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Nitrogen inputs from a pasture legume in rotations with cereals in the semi-arid tropics of northern Australia: experimentation and modelling on a clay loam soil

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Summary. Two experiments on a Tippera clay loam soil (alfisol) at Katherine, Northern Territory, investigated the nitrogen (N) benefit from legume pasture leys of Caribbean stylo (*Stylosanthes hamata* cv. Verano) to subsequent maize crops. Nitrogen uptake and yield of the maize crops were higher after the Verano leys than after a grass ley, the effect persisting into the second crop. The 1-year Verano ley was estimated to have increased N uptake by the maize crops by about 30 kg/ha, and the 3-year ley by about 55 kg/ha over that for the grass. Removing some of the Verano dry matter (DM) as hay at the end of each growing season reduced the subsequent benefit compared with treatments where the Verano DM was rotovated into the surface soil at the end of each growing season, or left standing. However, in all legume treatments, the additional N contributed by the legume was inadequate to fully meet the N requirement of the following crop.

The main features of the experimental results, through both the ley and cropping phases, could be simulated adequately using the cropping system model APSIM. The model provided the opportunity to explore the fate of N in the system, and gave insights into aspects of system performance that could not be obtained from the experimental data.

Introduction

By the late 1970s, legume-ley farming systems had been widely and successfully practiced in southern Australia for decades, but there was no comparable system for the semi-arid tropics of northern Australia. Nevertheless, most of the essential components of such a system were available. Adapted and productive forage legumes had been found to replace the annual legume, Townsville stylo, which had succumbed to the fungal disease anthracnose (Gillard and Winter 1984). These legumes yielded more dry matter (DM) and nitrogen (N) than Townsville stylo and most of the N was presumed to have come from N_2 fixation. Cultivars of grain sorghum and maize adapted to the semi-arid tropics were also available. So too was the technology for no-tillage planting of crops into the erosion-prone sesquioxidic soils which dominate the potentially arable lands of the region (Williams *et al.* 1985). Dramatically increased animal production from improved pastures based on legumes had also been demonstrated (Norman 1970). The availability of these 4 components led to the concept of a hypothetical farming system for the semi-arid tropics (McCown *et al.* 1985) in which: (i) self-generating legume-ley pastures of 1–3 years duration are grown in rotation with maize or sorghum; (ii) cattle graze native grass pastures during the green season and leguminous pastures and crop residues in the dry season; (iii) crops are sown directly into the pasture, which is chemically killed at or shortly before sowing; (iv) the legume sward, which volunteers from hard seed after the pasture is killed, is allowed to form an understorey ('live mulch') in the main crop.

One objective of this study was to determine whether a short duration legume ley can contribute sufficient N to the system to largely satisfy the N needs of a subsequent grain crop. The physical and technical resources available to us were inadequate for the level of sampling and analysis that would have been required to accurately measure the N_2 fixation by the legume during a ley phase, and its mineralisation and subsequent fate during a cropping phase. Therefore, we adopted a field bio-assay approach in which the value of the ley phase was assessed from the N uptake and growth of the subsequent crops. Three experiments were conducted, each lasting 5 years and using Caribbean stylo (*Stylosanthes hamata* cv. Verano) as the ley legume. Two soil types of contrasting texture were used, and crops of either grain sorghum or maize were grown. In this paper, the results for maize on the heavier soil type (experiments 1 and 2) are reported.

In recent years, considerable progress has been made in modelling cropping systems (McCown *et al.* 1996). A second objective of this study was to test the adequacy of current models for simulation of this legume ley–cropping system, and for analysing and gaining insight into the performance of the system.

Materials and methods

Experimental design and treatments

The experiments used a split-split-plot design with 3 principal treatments: ley types (main plots); length of the ley phase (subplots); and year of cropping (sub-subplots).

Four ley types were chosen to provide a range of N inputs into the system. The Verano–rotovated ley was chosen to represent an upper limit of N input. In it, most of the material was mechanically chopped up and buried at the end of the wet season, when the N yield of the legume pasture would have been close to its maximum. It could be considered as a green manure treatment. The Verano–hay ley was chosen to approximate what might occur under grazing, with much of the N in the plant tops being removed from the system. The Verano–standing ley was chosen as probably being intermediate between these 2 types. The ley types were: (i) grass, a mixture of Pearl millet (*Pennisetum glaucum*) and Birdwood grass (*Cenchrus setigerus*) was sown in experiment 1, and perennial forage sorghum (cv. Silk) in experiment 2; at the end of each growing season, standing DM was cut at about 5 cm and removed; (ii) Verano–rotovated, Verano was rotovated into the top 5 cm of soil at the end of each growing season during the ley phase (in April or early May); (iii) Verano–hay, Verano was cut for hay at a height of about 5 cm at the end of each growing season (April or May) during the ley phase, and the hay removed; (iv) Verano–standing, Verano was allowed to stand from one season to another during the ley phase, with occasional trimming at 30 cm, but no removal of material.

The 2 ley lengths were: (i) short ley, 1 growing season of the 4 leys (year 1), followed by cropping in years 2 and 3; (ii) long ley, 3 growing seasons of the 4 leys (years 1, 2 and 3), followed by cropping in years 4 and 5.

Following each ley (type x length) there were 2 seasons of cereal cropping. Sub-subplots were: (i) crop 1, detailed measurements of responses to fertiliser N were made on the first crop after the leys; these sub-subplots were then discarded; (ii) crop 2, crops were grown without fertiliser N in the first year after the leys, then detailed measurements of responses to freshly applied fertiliser N were made on the second crop.

The sub-subplots measured 8 by 9 m. When cropped, they accommodated 12 rows of crop with an inter-row spacing of 0.75 m. In the cropping year when detailed measurements were made, a systematic arrangement of 8 fertiliser N rates, ranging from 0 to 180 kg/ha, was applied to adjacent rows.

The experiments were on recently cleared land in S Block at the Katherine Research Station. The soil at the site is classified as Tippera loamy red earth (Paleustalf), although it is somewhat lighter textured than other related soils on the Station. Experiment 1 ran from December 1978 until May 1983. In the cropping phase, 2 of its 4 replicates were sown with sorghum (cultivars Monsoon in years 2–3, and Texas 610 in years 4–5) and 2 with maize (cultivars XL99 in years 2–4, and Sergeant in year 5). Experiment 2 was a replication in time and ran from December 1979 until May 1984. It was located on an adjacent virgin site. In its cropping phase, all 4 replicates were sown to maize (cultivars XL99 in years 2–3, and Sergeant in years 4–5). Only the results for maize are reported here.

Pasture and crop management and measurements

Additions of phosphorus (P), potassium (K), sulfur, copper (Cu), zinc (Zn), and molybdenum (Mo) were made to the soil before the pasture phase to ameliorate known or possible nutrient deficiencies (Jones *et al.* 1985). Characterisation of this soil is provided by Williams *et al.* (1985, Appendix II, pp. 72–3). Depending on ley type, the leys were kept free of either legume or grass during the growing season, using a combination of herbicides applied through rope wick applicators and hand weeding. At the end of the season (usually in early April) when Verano was beginning to drop leaves and seeds, measurements were made of DM yield and N content of all ley types, and the rotovation and hay treatments were imposed. Measurements were also made of the residues below cutting height from the grass and Verano–hay leys. No further management was applied to the leys during the dry season.

Crops were sown into surface trash consisting of recently killed re-growth and residues from the previous ley or crop, using no-tillage. Favourable sowing conditions usually occurred in late December or early January, but in 1983 the early-sown crop failed because of drought and high temperature, and was re-sown in late February. As this crop was sown too late in the season to produce grain, only total DM yield and N content were measured.

Additional P, K, Cu, Zn and Mo were applied to subplots just before cropping. Nitrogen was applied as a solution of ammonium nitrate dribbled onto the soil surface within 10 cm of the base of the young crop plants. Rows 1 and 12 in each sub-subplot were border rows; rows 2–11 received 0, 0, 0, 20, 40, 60, 80, 100, 140 and 180 kg N/ha in sequence across the sub-subplot.

The first part of the N (up to 80 kg/ha) was applied 10–14 days after sowing and the balance 7–13 days later. Weeds and insect pests were controlled with appropriate chemicals during the cropping phase. The main data collected from the crop were anthesis date, and DM yield and N content of grain and stover at maturity.

Modelling ley–cereal rotations

The experiment described here provided data against which the performance of models of the crop–soil system could be evaluated. We attempted to simulate both ley and cereal components of the rotation. The attraction of this approach is that the modelled systems only have to be initialised once, before establishment of the leys, and all ley systems are assumed to commence with identical soil conditions. (An alternative would have been to simulate only the cereal crops following the leys. However, this would have required information on how the leys had modified the system, in order to re-initialise the model prior to each crop. Whilst some soil water and nitrate-N data were available, major assumptions would have been required about the effects of the leys on components of the soil organic matter.) The approach we have adopted allows soil properties to change in response to the growth of the leys under the imposed managements. We then evaluated the simulated system by comparing the simulated performance of the following cereal crops with the observed crop data, and by exploring other facets such as water use, denitrification and leaching.

The model used for simulating the experimental observations was APSIM (McCown *et al.* 1996) which was configured to simulate the ley–cereal system as described by Carberry *et al.* (1996). The soil properties used in defining the water characteristics of the soil are given in Appendix 1. The model included modules for the soil water balance (SoilWat V1.0), soil organic matter and N transformations (SoilN V1.0), surface residue dynamics (Residue V1.0), and for maize, sorghum and Verano (Maize V1.0, CSSAT V0.1 and Stylo V1.0). The current lack of a grass module was overcome by using the sorghum module at a high plant population, with genotypic parameters chosen to prevent grain production (P. S. Carberry pers. comm.). The sorghum and stylo modules were not able to 're-grow' as perennial pastures, so the leys had to be 're-sown' each year. In addition, grass and Verano were 'sown' in the storm period which

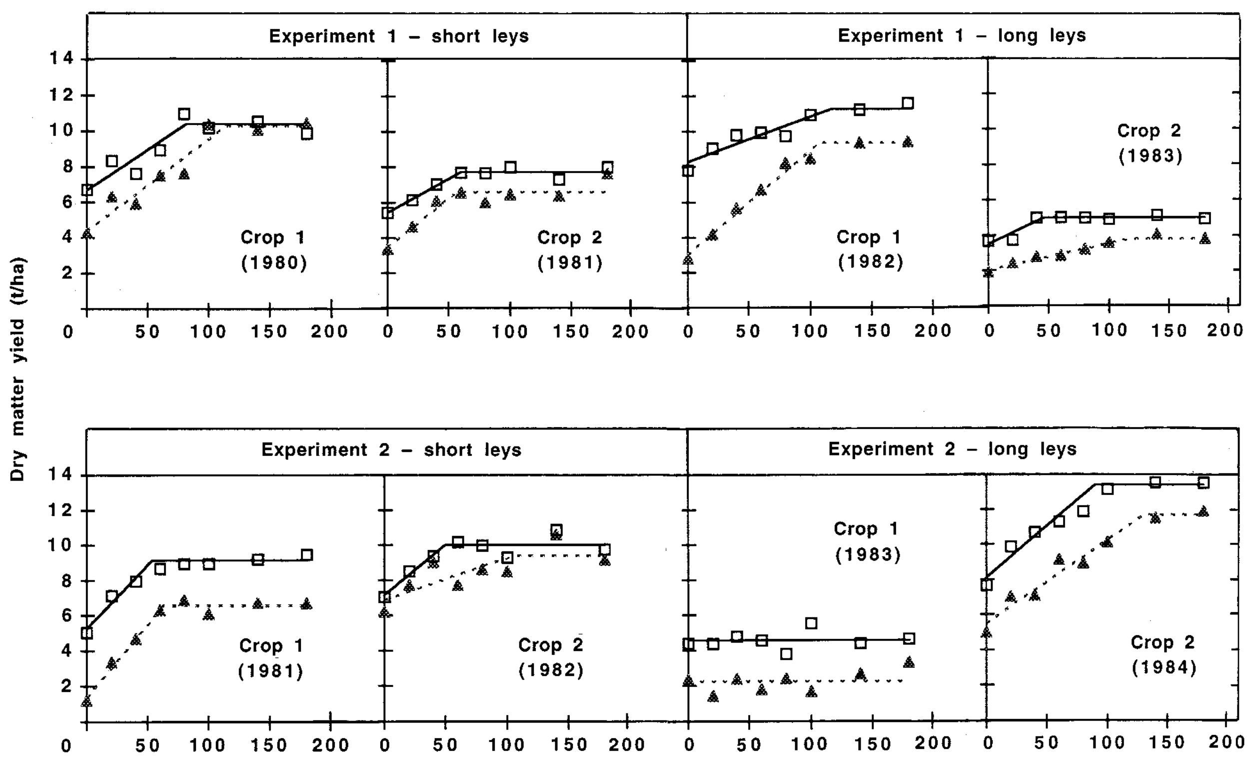

Figure 1. Total dry matter yield of two successive maize crops grown after short and long leys of grass (▲) or Verano (□). The Verano data are means of the three managements, rotovated, hay or standing.

usually preceded the wet season, in order to mimic regrowth of the ley species and weeds that occurred before sowing the maize. In the simulations, the grass and Verano–hay leys were cut and the material removed, and the Verano–rotovated ley was tilled, according to the schedule followed in the experiment. Management of the maize crops (sowing date, plant population density, fertiliser applications, removal of stover etc.) was directly specified in APSIM. Simulated crops were 'harvested' if or when they reached maturity.

Simulations were carried out for the 4 leys of both experiments 1 and 2. In each case, the short and long ley periods were modelled using 5 rates of N (0, 20, 40, 80 and 180 kg/ha) applied to the subsequent maize crops. In presenting the outputs of the simulations, however, we concentrate on experiment 1 (established in December 1978) because the findings are very similar for both experiments.

Results

Experimental data

The total above-ground DM yield of maize crops after either grass or Verano leys is shown in Figure 1. Crops after Verano leys generally produced a higher yield and a smaller response to applied N than those after the grass ley, and the effects of the legume carried through to the second crop. To attain near-maximum yield after Verano usually required 60–80 kg/ha of additional fertiliser N. After grass, it usually required at least 80 kg/ha, but in some crops, even 180 kg N did not bring the grass and Verano curves together. The poor growing conditions in 1983 clearly limited the effects of the leys in that year. Grain yield is not presented because it is even more subject to seasonal conditions than is total DM, as it represents only the reproductive portion of the crop. However, grain yield can be approximated from the harvest index values. For crops grown to maturity with an adequate supply of N (mean of the N_{100}, N_{140}, N_{180} rates), the harvest index was 0.42 (1980, short ley, crop 1), 0.34 (1981, short ley, crop 2), 0.47 (1982, long ley, crop 1) and 0.51 (1984, long ley, crop 2).

The corresponding N uptake by the crops is shown in Figure 2. In general, N uptake increased with increasing fertiliser N to N_{180} or N_{140}. The benefits from the Verano leys generally continued into the second year of

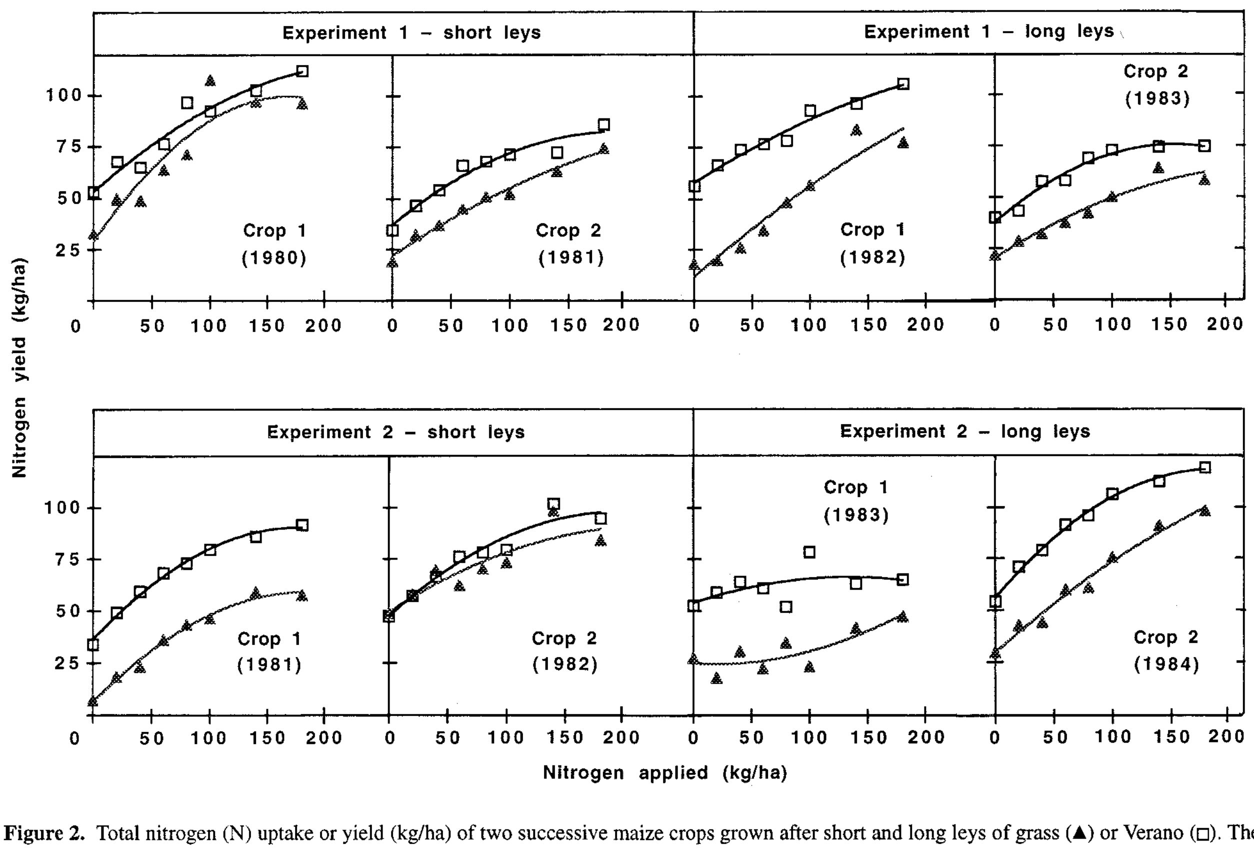

Figure 2. Total nitrogen (N) uptake or yield (kg/ha) of two successive maize crops grown after short and long leys of grass (▲) or Verano (□). The Verano data are means of the three managements, rotovated, hay or standing. Fitted response curves (2nd order polynomial) on rate of N application are shown.

Table 1. Nitrogen (N) uptake (kg/ha) in each year of the leys, and in the two subsequent crops of maize grown without fertiliser N

The legume benefit is the N taken up by the two maize crops following the legume leys in excess of that for the corresponding grass ley

Ley	Ley phase Year 1	Year 2	Year 3	Cropping phase Crop 1	Crop 2	Legume benefit
Experiment 1, short (1 year) ley						
Grass	16			33	19	—
Verano–rotovated	82			66	38	52
Verano–hay	78			50	28	26
Verano–standing	78			43	32	23
Experiment 1, long (3 year) ley						
Grass	16	35	13	17	23	—
Verano–rotovated	82	35	121	84	34	78
Verano–hay	78	29	120	37	34	31
Verano–standing	78	60	115	55	44	59
s.e.d.				10.6		21.8
Experiment 2, short (1 year) ley						
Grass	17			8	50	—
Verano–rotovated	53			39	55	36
Verano–hay	52			35	44	21
Verano–standing	55			33	48	23
Experiment 2, long (3 year) ley						
Grass	17	15	22	27	33	—
Verano–rotovated	53	159	218	54	75	69
Verano–hay	52	159	215	36	61	36
Verano–standing	55	160	212	71	55	66
s.e.d.				8.6		12.0

cropping, although little effect was found after the 1-year ley in experiment 2.

There are several possible approaches for estimating the additional N contribution from the legume leys over the grass ley system. Firstly, one could extrapolate fitted response curves to where they intercept the x-axes, and estimate the difference between the intercepts. This approach is very dependent on the choice of model to fit to the data. A second approach would be to estimate the amount of fertiliser N that would have to be added to the crops after the grass leys to achieve the same N uptake or DM yield as achieved by the unfertilised crops after the Verano leys. This approach is only strictly applicable if the different systems tend to a common asymptote at high rates of fertiliser application, which was not the case with our data in most seasons.

We estimated the legume 'benefit' from the total yield of above-ground N in the 2 successive crops grown without fertiliser N (Table 1), expressed as the extra N taken up in excess of the corresponding grass ley. The Verano–rotovated ley always gave substantially greater benefits to subsequent crops than the other Verano leys, particularly Verano–hay. When averaged over ley types in the 2 experiments, the benefits were about 30 kg N/ha for the 1-year ley, and about 55 kg N/ha for the 3-year ley. These estimates of the legume benefit consider only 2 crops grown in succession. Additional, but declining, benefits can be expected for subsequent crops. The estimates represent the benefits of the legume expressed in terms of the additional N actually taken up by the following crops, not in terms of the additional fertiliser N that would be required to produce those additional N uptakes.

In comparing the fertiliser N requirements of the cropping phase in a legume ley–cereal rotation with continuous cropping, the grass ley treatment may not be an adequate yardstick. Inputs of carbon to the soil through

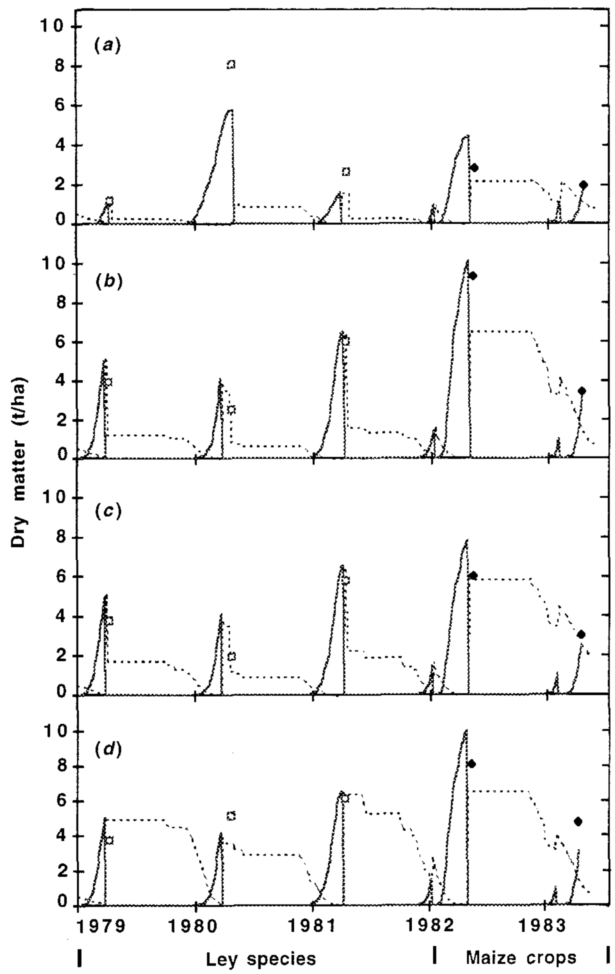

Figure 3. Simulated dry matter yield of the ley species and the subsequent maize crops, grown without fertiliser nitrogen (N), for the four ley systems: (*a*) grass; (*b*) Verano–rotovated; (*c*) Verano–hay; (*d*) Verano–standing. The simulated above-ground residues are also shown (- - - -). In the simulations, soil conditions (water, mineral-N and soil organic matter) were initialised only once, on 30 September 1978 at the start of land preparation. Symbols denote the measured biomass yield of ley (open) and crop (closed).

roots and residues may be greater under a grass than under cereals, thereby causing a higher immobilisation demand. The N requirements for a continuous cereal system, therefore, might be lower than is indicated by our results for crops grown after grass leys.

Simulations

Figure 3 gives an overview of the simulated output for the 3-year ley systems. It shows the DM yield of the grass and Verano leys followed by the 2 maize crops in 1982 and 1983 without application of fertiliser N, together with the above-ground surface residues. The simulation of the production of the leys is in reasonable agreement with the observed data. The maize yield, especially in the first crop after the ley, responds to the preceding ley, with yield after Verano being substantially higher than after grass. The effect of management of the Verano leys on subsequent growth of maize is not as pronounced in the simulations as in the observed data, but nonetheless does exhibit some reduction in maize growth where the Verano has been removed in the hay treatment. The simulations show only minor differences between the Verano–rotovated and Verano–standing treatments. The 1983 maize crop was re-sown (hence the double peak in the simulated plots) and had not reached maturity when it was harvested. Simulation of this crop was terminated on the actual date of harvest. The model suggests that effects of the preceding ley are carried over into the second maize crop, which is in close agreement with the observed data.

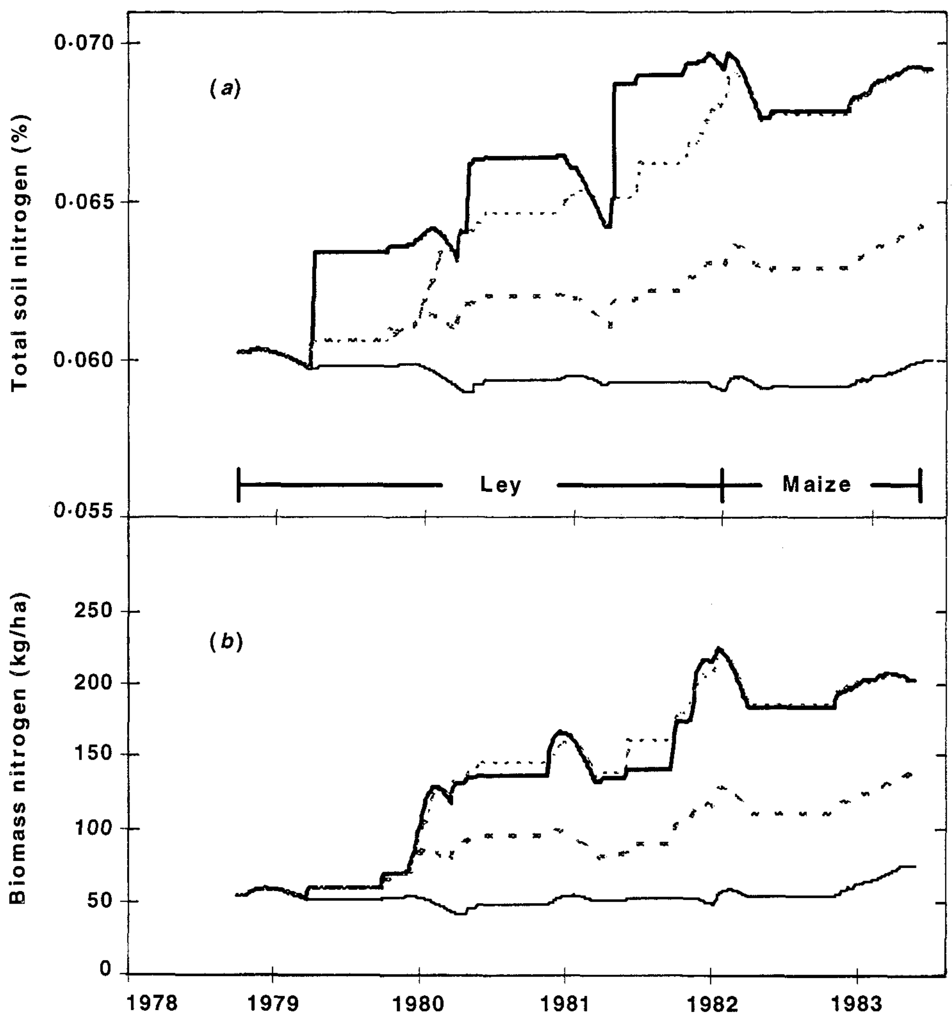

Figure 4. Simulated changes in (*a*) total soil nitrogen (N) (%) and (*b*) biomass-N (kg/ha) in the surface 0–15 cm layer of soil during the three-year leys (— grass; —— Verano–rotovated; – – – Verano–hay; · · · Verano–standing) followed by two maize crops.

Unfortunately, there are very limited experimental data for soil water and nitrate-N to compare with the output from the simulations (data not shown). Simulated total soil water in the profile varies little between the grass and Verano ley systems. Each year, the simulations indicate that the leys use almost all of the available soil water. The simulations also indicate that little nitrate-N remains in the soil at the end of the growing season for both the leys and the maize crops. The only exception to

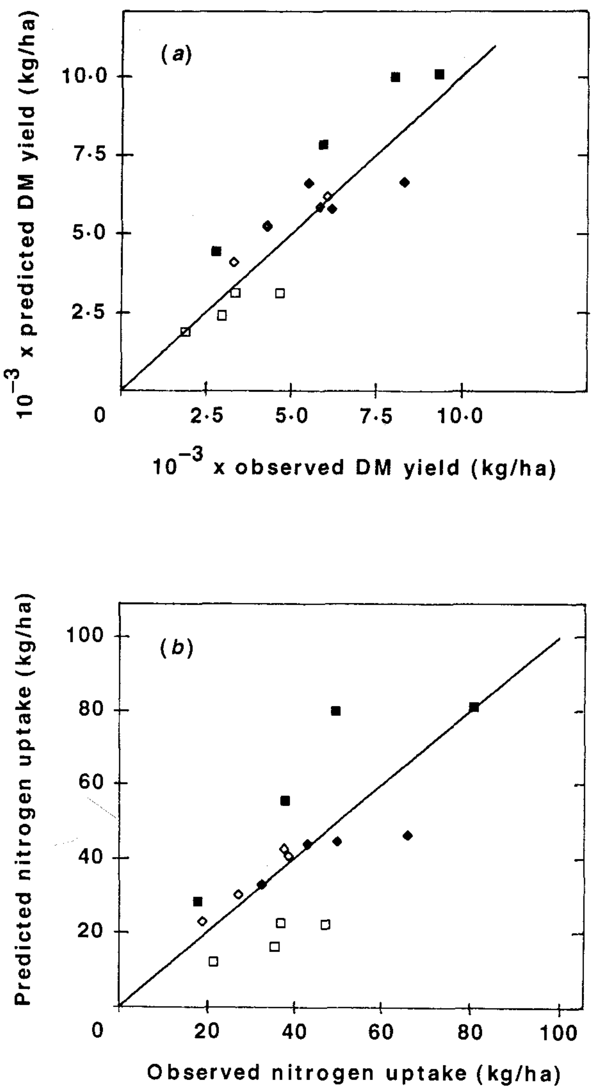

Figure 5. Comparison of observed and simulated data for (*a*) total dry matter (DM) yield (kg/ha) and (*b*) nitrogen (N) uptake (kg/ha) of maize grown without fertiliser N following the short ley (◆ first crop; ◇ second crop) and long ley (■ first crop; □ second crop). The second crop following the long ley was harvested before it reached maturity and simulated yield is that for the harvest date (day 109). Other crops were harvested at maturity.

this was the grass ley in 1979 which produced very little DM, and the simulations indicate that it would not have exploited all the mineral-N available. As a result, the grass ley in 1980 had a better N supply than might have been expected and, in that year, did produce a higher DM yield than Verano (Fig. 3).

The simulations indicate that the most pronounced effect of the different leys is in the soil organic matter. Figure 4*a* shows the simulated total soil N in the uppermost soil layer (0–15 cm). The model indicates that the legume leys increase total soil N relative to the grass ley, with the increase being smaller for the Verano–hay ley where 65% of the above-ground Verano DM was simulated to have been removed. The most sensitive component of the soil organic matter is the BIOM pool which is notionally the soil microbial biomass. This increases year by year under the legume ley (Fig. 4*b*). The smaller inputs of carbon and N from the Verano–hay treatment result in a smaller increase in the BIOM pool. In the model, the only difference in the transfer of carbon and N from surface or incorporated residues to the soil pools is their different rates of decomposition. Thus, the ultimate effects of the rotovated and standing Verano treatments (assuming they produce similar yield and N content) must be similar also, as shown in Figure 4.

The N supply to the following maize crops depends on mineralisation of N from the residues, and from the increased soil organic matter that accumulated during the legume leys. Figure 5 presents a comparison of the observed and simulated DM yield and N uptake by the 2 maize crops (without fertiliser N) that followed both the short and long leys. The goodness of fit of the model to the observed data is very satisfactory. For both total DM yield and N uptake, the fitted line between simulated and observed data has an intercept that is not significantly (P>0.05) different from zero and a slope that is not significantly different from unity. The regression accounts for 78% of the variation in the DM yield data, with a root mean squared deviation, i.e.

$$\sqrt{[\Sigma(\text{observed–predicted})^2/n)]},$$

of 1118 kg/ha. For N uptake, the corresponding statistics are 47% and 13.9 kg/ha.

Discussion

The key question posed earlier was whether a legume ley could contribute sufficient N to the system to largely satisfy the needs of a subsequent grain crop. Experimentally it was found that there was a substantial effect of the type of ley on the subsequent growth of maize crops in terms of total above-ground DM (Fig. 1), N uptake (Fig. 2) and grain yield (data not shown). The DM yield of maize after Verano leys was greater than after grass, and the effect persisted into the second crop. The N contributed by Verano, over and above that measured after a grass ley, depended on the management of the Verano (Table 1). Where the Verano was cut as hay and removed (to mimic cattle grazing a hypothetical system), the N contribution to the following crops was less than for the rotovated or standing treatments. Considered overall, the 3-year legume leys were estimated to have increased N uptake by the crops by 55 kg/ha and the 1-year leys by 30 kg/ha. To achieve these N uptake values in a soil–climate environment where the 'apparent' recovery of fertiliser N by crops rarely exceeds 50% (Fig. 2; Myers 1979; Thiagalingam *et al.* 1993) would require the application of 2–3 times these amounts as fertiliser N. However, the additional legume-derived N was generally insufficient to satisfy the full need of the crops.

A second question posed was whether current modelling capability is adequate for analysing and gaining insight into system performance. The simulations attempted here, through 1 or 3 years of ley pasture followed by 2 maize crops grown with different inputs of fertiliser N, are a demanding test of a model. Acknowledged weaknesses of the model are its inability to simulate the perennial nature of the leys (necessitating that both the grass and Verano had to be 're-sown' each year), and especially the use of a sorghum module to mimic the behaviour of the grass ley. One shortcoming of the latter is that sorghum probably does not put enough of its carbon below ground into roots. Whereas the stylo module directs one third of its total biomass to roots, the simulated grass ley had only 23, 10 and 17% of its total biomass in roots in 1979 through 1981. This is well below the amount of roots measured under grass pastures in this environment by Dimes *et al.* (1996).

Despite these limitations, the model adequately captures the principal effects, especially so in terms of the extra N taken up by the maize crops after the Verano leys compared with the grass ley, and the persistence of the effect of the legume leys into at least the second maize crop. In making this judgement, we rely entirely on the simulated growth of the maize crops, since there is insufficient measured data to verify the reasonableness of the simulated changes in the soil variables.

However, there was a marked tendency for the model to overestimate the uptake of fertiliser N by the maize crop (data not shown). Measured recoveries of fertiliser N by the maize crops that grew to maturity decreased from about 50% at low rates of application to 30% at the highest rate of application (see Fig. 2). Simulated recoveries by maize, however, averaged 63% after the grass ley and 47% after Verano leys, at the highest rate of application. The reason for this discrepancy is perplexing. Such an effect has not been encountered in using APSIM to simulate wheat crops grown with varying inputs of fertiliser N (e.g. Probert *et al.* 1995).

The low recovery of fertiliser N by the crop means that the applied N must either have been lost from the system or have remained in the soil after the crop had been harvested. The model provides an opportunity to explore the fate of water and N during the experiment (Table 2). The simulations indicate that very little nitrate-N was left in the soil at harvest at rates of application up to 80 kg/ha, though some remained at the 180 kg/ha rate. Some nitrate-N is simulated to be leached below 180 cm, the amount lost increasing with the rate of application, but the biggest loss, which occurred in 1979–80, only amounted to about 15% of the applied N. Similarly, the

Table 2. Simulated runoff (mean of all well-fertilised treatments) and loss of nitrogen (N), either as leaching below 180 cm or by denitrification, during each cropping season, and nitrate-N remaining in the 0–180 cm profile at harvest of the maize crops

Data are for the grass and Verano–rotovated leys at three rates of fertiliser application and refer to the years in which fertiliser was applied

	1979–80		1980–81		1981–82		1982–83	
	Grass	Verano	Grass	Verano	Grass	Verano	Grass	Verano
Rainfall (mm)	1165		971		1025		746	
Runoff (mm)	72	64	64	57	16	12	19	5
Nitrogen leached (kg/ha)								
N_0	15.1	12.5	12.7	17.1	2.2	1.8	4.0	6.0
N_{80}	28.7	26.8	14.0	19.3	2.7	4.4	3.7	5.9
N_{180}	42.0	40.9	16.0	21.3	8.3	10.6	3.7	5.9
Denitrification (kg/ha)								
N_0	0.6	0.6	0.7	1.1	0.3	0.4	0.4	0.5
N_{80}	2.8	2.9	2.0	2.7	1.3	2.3	0.8	1.2
N_{180}	5.7	5.8	4.4	5.0	4.2	5.4	1.2	1.6
Nitrate-N in profile at harvest (kg/ha)								
N_0	1.5	2.6	1.6	2.6	1.6	4.3	1.7	2.8
N_{80}	1.5	2.6	2.6	3.8	1.8	9.3	2.4	4.2
N_{180}	29.5	43.3	49.6	69.9	29.0	89.3	74.6	91.4

simulations indicate that loss via denitrification is small; the largest loss by this process also occurred in 1979–80 and amounted to about 3% of the applied N. Leaching and denitrification losses under the conditions of this experiment, where concentrated solutions of ammonium nitrate were applied to the moist soil surface, are not known.

Other work on similar soils at Katherine has shown that N loss through leaching can be large (Wetselaar 1962; Day 1977). Thus the model may be underestimating loss of N especially through leaching. More rapid loss of nitrate before it can be taken up by the crop would be expected to reduce the recovery of applied N by the crop. The 1983 crop, however, raises some doubt as to whether this is the cause of the discrepancy between the model and observed N uptake data. This crop was re-sown and the fertiliser was not applied until 10 March, after which only 138 mm of rain fell before harvest (largest daily fall of 25 mm). It seems unlikely that this could result in a large loss by either leaching or denitrification, yet N uptake was overestimated in this year as in other years.

One of the features of the hypothetical farming system that we were not able to incorporate into the original experimental design, was the grazing of the leys and the crop residues during the dry season. In an attempt to address this, we managed the verano leys in 3 different ways to span what might happen under grazing, with the rotovated and standing treatments expected to contribute more N, and the hay treatment less N than grazed leys. How successful we were in spanning realistic grazing options is impossible to tell, because the hypothetical system has not been adequately tested in the region, either experimentally or at a farm scale. The one experiment in which the complete hypothetical system was implemented, using 2-year leys of 3 different legumes, did not incorporate a very satisfactory grass ley as a control (McCown *et al.* 1986). However, it did demonstrate that the leys produced sufficient N for quite good maize grain yield (2.7–4.7 t/ha, which was well above what could have been expected after grass leys on this soil). As in our experiments, however, the crops were still responsive to additional fertiliser N up to about 80 kg/ha.

The system model simulated the system reasonably well, given that it was initiated only at the commencement of the leys and was required to simulate DM yield and N uptake by crops 4–5 years later. With some further development, it should prove useful in examining the viability of pasture legume–cereal rotations in other environments and seasons. It should also prove useful in simulating the role of other productive legumes such as *Centrosema pascuorum* in such systems, as reported on by Thiagalingam *et al.* (1993).

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Appendix 1. Soil profile and volumetric soil water contents used to initialise the model on day 274 in 1978

	Layer number						
	1	2	3	4	5	6	7
Layer thickness (mm)	150	150	300	300	300	300	300
Lower limit	0.18	0.18	0.185	0.20	0.21	0.21	0.23
Drained upper limit	0.27	0.29	0.30	0.29	0.29	0.29	0.29
Saturated	0.38	0.38	0.38	0.39	0.39	0.38	0.38
Air dry	0.08	0.13	0.185	0.20	0.21	0.21	0.23