Nitrogen cycling in a pure grass pasture and a grass-legume mixture on a red latosol in Brazil

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Abstract

A nitrogen-balance method and a process-orientated approach, comparing a pure *Brachiaria decumbens* sward with a *B. decumbens-Calopogonium mucunoides* mixture, were used to discuss the major pathways of nitrogen in improved tropical grazing systems in the Cerrados of Brazil. Both methods predicted a drain of soil N with the pure grass pasture which could be reversed by introducing a legume into the pasture. The impact of legumes on the system was demonstrated both in terms of achieving a positive nitrogen balance by adding symbiotically fixed N_2 and by increasing plant available soil N through improved net mineralisation of litter and root materials. The magnitude of the latter effect depended on the palatability and decomposability of the legume which govern the animal-litter pathway and the addition to soil organic-mineral N. A legume N_2 fixation of 31–46% (depending on legume utilisation) of total sward above-ground nitrogen accumulation (equivalent to 60–117 kg fixed N_2/ha for this system) was considered to be sufficient to sustain the productivity of the system. This corresponded to a proportion of about 13–23% on a dry matter basis (2600–5200 kg DM/ha) provided that a high proportion of the legume N is derived from N_2 fixation.

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Management options that increase N_2 fixation and efficient N recycling include optimising grazing management (short rest periods to improve legume persistence), adequate stocking rate (to improve litter recycling), use of less palatable legumes (to improve persistence) which are easily decomposed, and alleviation of nutrient deficiencies (especially P).

Introduction

In stable, natural savanna systems where nutrient inputs from the environment balance the losses, secondary productivity is usually poor. Animal production may be increased by modifying the amounts of nutrients and their flow in such ecosystems. A better understanding of the processes involved in the recycling, losses and gains (biological N_2 fixation) and utilisation of nutrients through the various components of the grazing system is likely to lead to the development of sustainable forage production systems. In the case of nitrogen, although savanna soils contain a large amount of N in organic forms, little is released by mineralisation for plant uptake. The productivity of newly-sown grass pastures generally declines after a few years — a phenomenon commonly referred to as pasture degradation in Latin America or pasture run-down in northern Australia — which appears to be due to reductions in nutrient mineralisation rates. Inclusion of persistent forage legumes in pastures can increase the sustainability of pasture production largely due to the inputs of N from N_2 fixation by the legume.

Here we describe an initial assessment of legume use in the Brazilian Cerrados. An existing data set, in which pure grass and grass-legume swards were compared, has been used for description of the N cycle using a balance approach and by using a process-orientated computer model. These approaches allowed us to estimate the proportion of legumes needed in the pasture in order not to drain soil nitrogen pools, and highlighted important processes for further research.

Case study: A nitrogen-balance approach

To illustrate the major pathways of nitrogen in improved grazed pastures, data from two contrasting grassland systems of the Cerrados of Brazil (Campo Grande, Mato Grosso do Sul) were selected (Seiffert *et al.* 1985). The chosen systems were: a pure *Brachiaria decumbens* sward; and *B. decumbens* in association with *Calopogonium mucunoides*. The plot size was 1.6 ha with 3 replicates, and swards were continuously grazed at a stocking rate of 2.2 AU/ha (AU = 450kg) during the dry season and 2.5 AU/ha during the wet season. The initial average animal live weight was 205 kg and liveweight gains were 487 kg/ha/yr in the grass only and 535 kg/ha/yr in the grass-legume mixture. The increased animal production from the mixed pasture was due to higher gains during the wet season (October–March) than on the pure grass sward (0.51 *vs* 0.44 kg/hd/d). Data related to net primary plant production (Y) were calculated from data of Seiffert *et al.* (1985) as $Y = \Delta G + \Delta D + X$ where ΔG and ΔD are green and dead material accumulated in protected areas (30 cages of 1 m^2/plot) and X is the amount of dead material disappearing (Wiegert and Evans 1964). Data for X were not directly available and were therefore assumed to be 0 in periods where ΔD was positive (dry season, Figure 1) and $X = \Delta D$ when ΔD was negative (decomposition during the wet season). The above-ground net

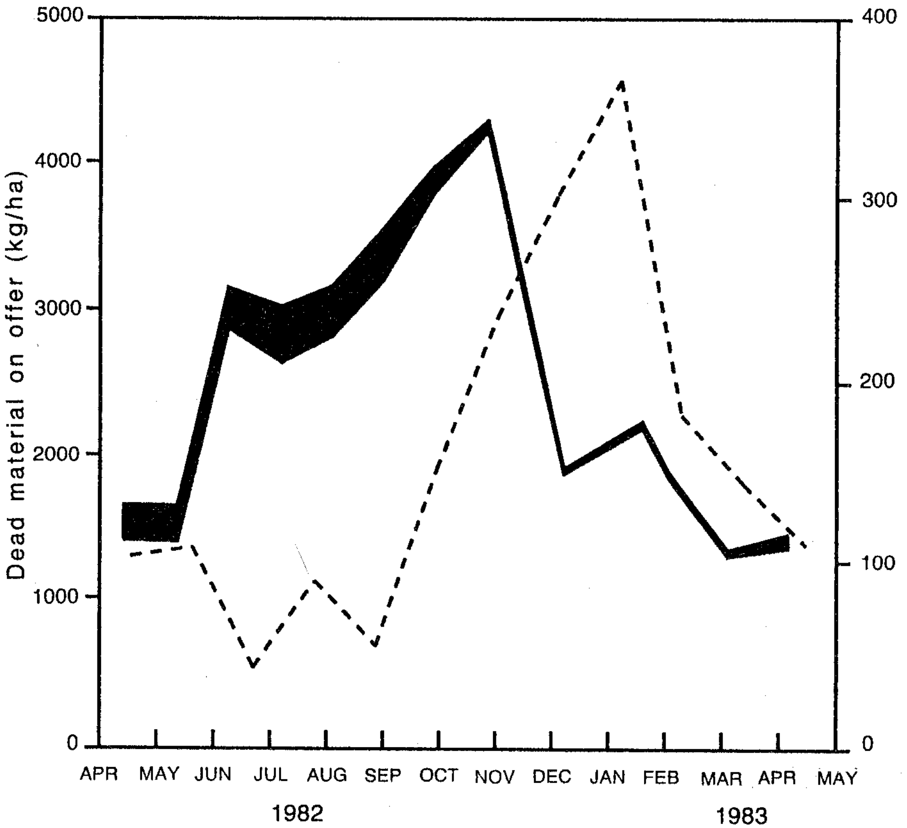

Figure 1. Seasonal pattern of rainfall (--), dead grass (white area under graph) and legume (■) component of material on offer in a *Brachiaria decumbens/Calopogonium mucunoides* sward in the Cerrados of Brazil (adapted from Seiffert *et al.* 1985).

primary production of the *B. decumbens* sward was calculated at about 15 000 kg/ha/yr. In contrast, yield of the mixed sward was 21 000 kg/ha/yr mainly due to the contribution of the legume component (4200 kg). The green dry matter production of *B. decumbens* in both swards of about 10–11 000 kg/ha/yr was comparable with other values (9–16 000 kg/ha/yr) cited for Brazil (Buller *et al.* 1972; Simão Neto and Serrão 1974).

Estimations of the above-ground plant nitrogen biomass (Figures 2a, 2b) were made by multiplying the net primary production by the respective N contents of green material (1.11 %N for *B. decumbens* alone, 1.06%N for *B. decumbens* in the mixture and 2.17 %N for *C. mucunoides*). The total N contribution of the legume in the mixture was 93 kg N/ha/yr of which 84 kg were derived from symbiotic fixation, assuming that 90% of the total amount of N assimilated by the legume was derived from atmospheric N_2. Such high fixation rates have often been observed in tropical pasture legumes associated with grasses (Vallis and Gardener 1985; Cadisch *et al.* 1989, 1993). The contribution of fixed N_2 by the legume-*Bradyrhizobium* symbiosis as well as the greater production of the mixed sward increased the plant biomass N pool compared with the grass-alone sward. Inputs of N through dry and wet deposition (dust and rain) of 7–14 kg N/ha/yr were assumed as reported for Brazilian conditions (Malavolta 1990).

The N intake of animals (Figures 2a, 2b) was estimated in two ways. Firstly, it was calculated indirectly through animal liveweight gains. The animal body has an average N content of 2.4% (Spain and Salinas 1985) which led to a N retention by the animal of 12 and 13 kg N/ha/yr in the grass alone and the mixed sward, respectively. Wetselaar and Ganry (1982) suggested that, in beef production systems, approximately 10% of the fodder N taken up is incorporated into the animal body, whereas up to 90% is excreted again. This would suggest that the animals ingested about 117 and 128 kg N/ha/yr from the pure *B. decumbens* and the *B. decumbens-C. mucunoides* sward, respectively. The second estimate of animal N intake was based on an average fodder consumption of 2% of live weight with a nitrogen concentration in the diet of 1.5% (0.4% N more than green plant N concentration due to selective grazing) for the grass alone and 1.8% for the mixture. Thus the animal N intake becomes 118 and 142 kg N/ha/yr for the grass alone and the mixed pasture, respectively. In the case of the pure grass treatment, the two estimates of N intake were almost equal and similar to the N production of the green herbage (123 kg N/ha). In the legume-based pasture, the fodder-consumption calculation exceeded the estimate based on animal retention but was still less than the N accumulated in the green material (187 kg N). Seiffert *et al.* (1985) noted that the legume, *C. mucunoides*, was not eaten by cattle during vegetative growth (wet season) but was accepted at flowering (May–June). Consequently, the major part of the legume N remained in the plant-soil system. A low legume palatability strongly increased the amount of N cycled through the litter component in the mixture (99–113 kg N/ha/yr) compared with the grass alone sward (17 kg N). In the absence of an actual litter evaluation, these estimates were obtained by calculation of the difference between the plant biomass N and the amount of N ingested by the animal (calculated in the two ways described above). This difference was then partitioned between litter and N recycled within the plant by using the average ratio of the N content of the dead material (0.36% N for *B. decumbens* alone and 0.46% N for *B. decumbens* in the mixture) to that of the green material. The estimated amount of litter N in the pure grass sward (17 kg) appears small as it would result in a high utilisation rate for tropical pastures (73% on a dry matter basis), although it was similar to the value obtained through the accumulation of dead material (14 kg N) in standing crop during the dry period. However, the latter underestimates the true litter accumulation, especially during the wet season when intensive litter decomposition occurs (Figure 1). This is especially true for the N-rich legume litter material which presumably decomposes more easily than grass litter.

The main N losses from a pasture system occur via volatilisation of NH_4^+ leading to a loss of about 50% (9–80%) of the N in excreta from the system (Vallis 1985). Denitrification losses would appear to be limited in the red latosol of the case study as this soil is mostly well aerated and low concentrations of soil nitrate were present (0.3–2 ppm NO_3^-). McGarity and Rafaratnam (1973) suggested that intense

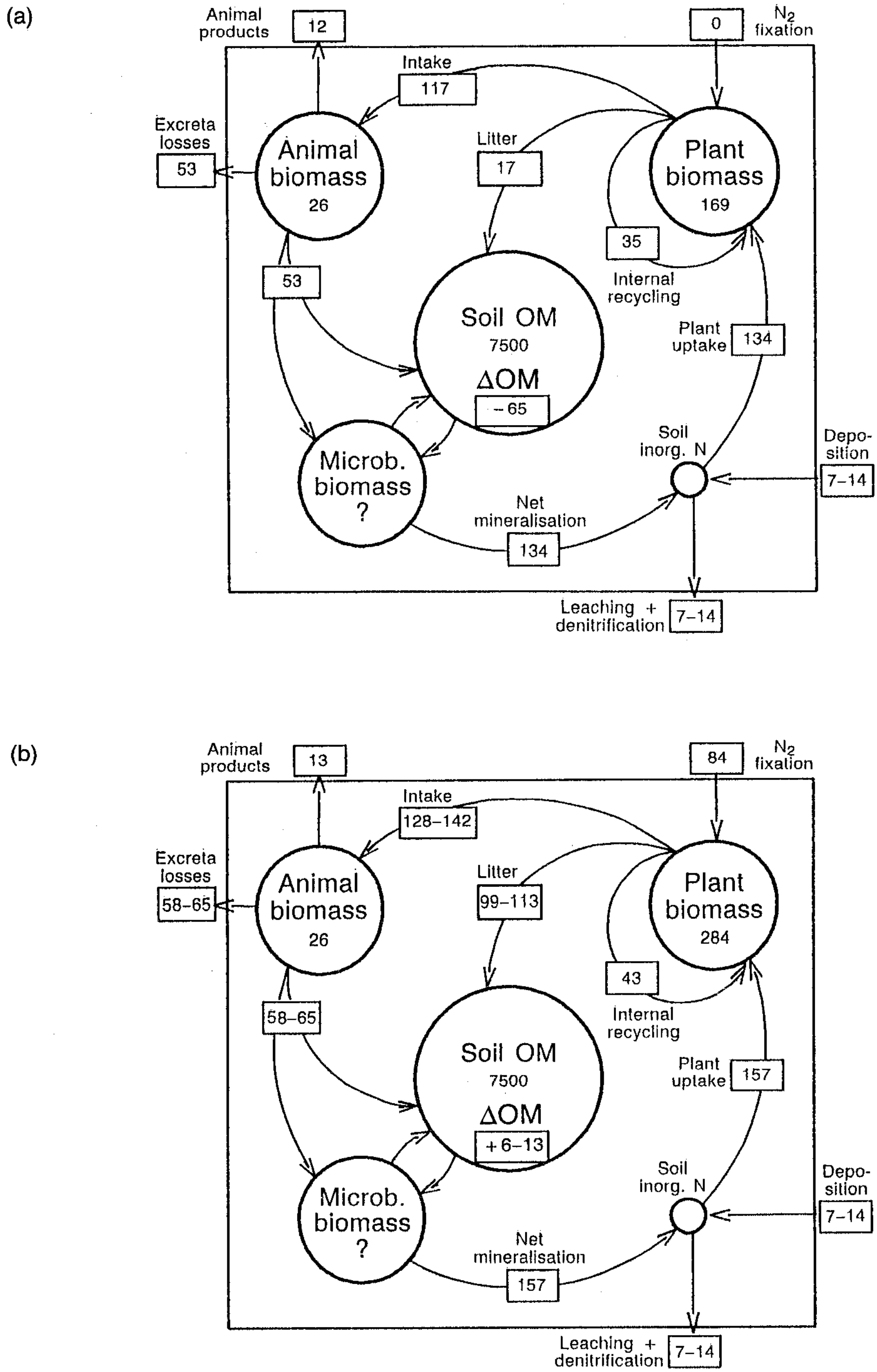

Figure 2. Nitrogen cycle case study for a) a pure *Brachiaria decumbens* and b) a *Brachiaria decumbens-Calopogonium mucunoides* sward on a red latosol in the Cerrados of Brazil (Campo Grande, MS). Circles represent the main pools of N in the system with the amount of N given in kg N/ha; the rectangles represent the major N fluxes with the amount given in kg N/ha/yr; ΔOM = predicted annual change in organic matter N pool.

microbial activity following wetting of dry soils, where nitrate levels are slightly increased (Seiffert *et al.* 1985), may induce significant losses of N by denitrification. The potential for denitrification in grazed pasture is also increased by the localised high concentration of nitrate under urine patches (Vallis *et al.* 1982). The nitrate accumulated during the dry season, especially in the mixed sward (Seiffert *et al.* 1985), can also be leached by heavy rains at the start of the wet season when there is still little N uptake by plants. The magnitude and mechanisms of N losses in the Cerrados are not well known. In low-input systems (no N fertiliser), losses of N released by mineralisation from soil organic matter through leaching and denitrification are usually small (Sheehy 1989; Hetier *et al.* 1989) and we assumed they were equalled by inputs through deposition.

For the system to be in equilibrium, a net mineralisation of 134 kg N/ha/yr for the pure grass sward and 157 kg N for the grass-legume mixture would have to occur. This is likely to occur in the mixed pasture as the large proportion of legume in the litter with its low C:N ratio facilitates litter decomposition. Moreover, the overall N balance of the case study revealed that the legume-based pasture appeared to be in equilibrium, i.e. no net N drain from the soil organic matter. In the case of the pure *B. decumbens* sward, a net N drain as high as 65 kg N/ha/yr indicates pasture degradation in the long term. Additionally, the low litter quality (C:N $\approx$ 117) is likely to lead to a productivity decline through a reduction in available soil nitrogen (immobilisation). This nitrogen-balance study clearly demonstrates the benefit of introducing legumes into a pasture to maintain the sustainability of the system. The study also suggests that an average legume content of about 26% on a green dry matter basis can maintain pasture fertility which is in agreement with calculations of Thomas (1992).

Towards a process-orientated approach: SCUAF model

The above nitrogen-balance study demonstrated the importance of introducing N_2-fixing legumes into the pasture system to maintain a positive N balance but gave little information on the rates of nitrogen turnover actually occurring. To evaluate the impact of legumes on improving mineralisation processes and improving soil organic N, an adapted version of the SCUAF (Soil Changes Under AgroForestry) computer model (Young and Muraya 1990) was used with the above data. In the model, the transfer of nitrogen from litter to humus is governed by the principle that soil will accept new carbon and nitrogen only at its existing soil C:N ratio. Thus litter nitrogen that is not accepted by the soil is assumed to become mineral nitrogen. Table 1 shows characteristics of the system used in this simulation. Root estimates are included and thus slightly higher values are obtained than in Figure 2. The plant available soil N in the simulation was in close agreement with the N in plant biomass (±10%) except for the pure legume sward where the calculated N availability was much greater than the demand.

Table 1. Important characteristics used in the SCUAF model simulations.

Soil C:N	10:1[1]
Soil depth considered	1 m
Amount of total soil N to 1 m	7500 kg N/ha[2]
Soil humus decomposition	2.5%/yr[3]
Litter to humus carbon conversion loss	85%[3]
Root to humus carbon conversion loss	67%[3]
Dung to humus carbon conversion loss	67%[3]
Turnover rate of labile humus-litter	1 yr
Grass-legume root:shoot ratio	0.4/0.3[3,4,5]
Proportion of legume N from N_2 fixation	0.9[5]
Urine:dung N ratio	1.5
Leaching and gaseous losses from urine N	60%[6]
Leaching and gaseous losses from dung N	30%[6]
Losses of mineral N from organic origin	3%[3]

[1]Malavolta 1990; [2]Seiffert *et al.* 1985; [3]Young and Muraya 1990; [4]Chacon *et al.* 1991; [5]Cadisch *et al.* 1989, 1993; [6]Vallis 1985.

The simulation predicts losses of soil organic N in the order of 63 kg N/ha/yr in pure *B. decumbens* systems (Table 2). While high rates (45 kg N/ha/yr) of N_2 fixation associated with grass roots as suggested by Boddey and Victoria (1986) would improve the system N balance, the model predicts little improvement in soil organic N. The mixed grass-legume sward appears to be sustainable (equilibrated N balance) and also appears to increase soil fertility while providing sufficient available soil N for the growth demand of both grass and legumes. The difference in changes in soil organic N between pure grass and mixed pastures resulted mainly from the larger

Table 2. Simulations of soil nitrogen dynamics in tropical pasture systems on a red latosol using an adapted version of the SCUAF (soil changes under agroforestry) model.

Pasture system	Green dry matter production	Changes in soil organic N	Changes in soil mineral N: Net[6] mineralisation – Litter + roots	Changes in soil mineral N: Net[6] mineralisation – Excreta	Changes in soil mineral N: Losses – Leaching + gaseous	Plant available soil N	N_2 fixation	System N balance
	kg/ha/yr	kg N/ha/yr						
Pure grass	11 000[1]	−44	−58	74	57	152	0	−63
Pure grass[2]	11 000	−44	−58	74	57	152	45	−18
Grass-legume[3]	10 000 + 3 600[1]	+26	−59	110	87	158	95	−4
Grass-legume[4]	10 000 + 3 600	+25	−14	73	63	189	95	+26
Pure legume	7 000[5]	−83	+40	92	73	252	227	+145

[1]Seiffert *et al.* (1985).
[2]Pure grass including 45 kg N/ha/yr input from associative N_2 fixation (Boddey and Victoria 1986).
[3,4]Assuming all (3) or only 20% (4) of legume green dry matter production eaten by animals.
[5]CNPGC (1988).
[6]Additional 188 kg N/ha/yr soil humus N mineralisation.

amount of carbon in the mixed pasture and thus more humification from litter and excreta. Substantial immobilisation from grass litter material is predicted by the model with net mineralisation occurring only when its C:N ratio decreased below 65. This agrees closely with the findings of Robbins *et al.* (1989) who found small net N release below C:N = 75:1 with *Panicum maximum*. Improved net mineralisation with the inclusion of the legume is a direct result of the smaller C:N ratio of this plant material. However, the alleviation of the strong N immobilisation occurring with grass litter (Figure 3) will depend strongly on the amount of legume material which is cycled through the litter pathway rather than taken up by the animal. Although with legume materials there is net mineralisation, some initial immobilisation in the soil microbial biomass always occurs (Figure 3).

Pure legume protein banks appear not to be favourable as the plant available soil N pool strongly exceeded the plant N demand which will result in both losses and reduced N_2 fixation. Problems with legume persistence are a major constraint in mixed tropical pastures. An alternative to increase legume survival in mixed swards is to use less palatable legumes. This approach leads to increased N cycling via the litter pathway which is less subject to losses and hence increases the legume contribution to soil fertility. Increased soil organic N occurs when the palatability is coupled with reduced litter decomposition as is often the case with litter which has a high content of polyphenolic substances (Vallis and Jones 1973; Palm and Sanchez 1991). Otherwise the plant available soil N pool mainly increases due to improved mineralisation rates of legume residues compensating for the immobilisation effect due to poor quality grass residues (Table 2). Thus the legume production required to sustain both the N balance and productivity of the system, is strongly dependent on the utilisation and quality of the legume. The simulations suggest that a legume proportion of 13–23% of the total above-ground dry matter production is required to sustain productivity (Figure 4). This value obviously depends on the N accumulation by the legume and the ability to fix N_2. In this case, 13–23% of *C. mucunoides* is equivalent to 2600–5200 kg DM/ha, fixing an estimated total of 60–117 kg N_2/ha. The simulated N_2 fixation required to provide a sustainable pasture system is close to the 125 kg/ha estimated by Myers and Robbins (1991) for a *P. maximum* sward and corresponded to 31–46% of total sward above-ground N accumulation depending on legume utilisation which approximates that suggested by Thomas (1992).

The large soil N pool in these deep soils (up to 8700 kg N/ha from 0–2 m depth; Seiffert *et al.* 1985) may make it difficult to measure small net N gains or losses from the soil organic matter, perhaps with the exception of the upper soil layer

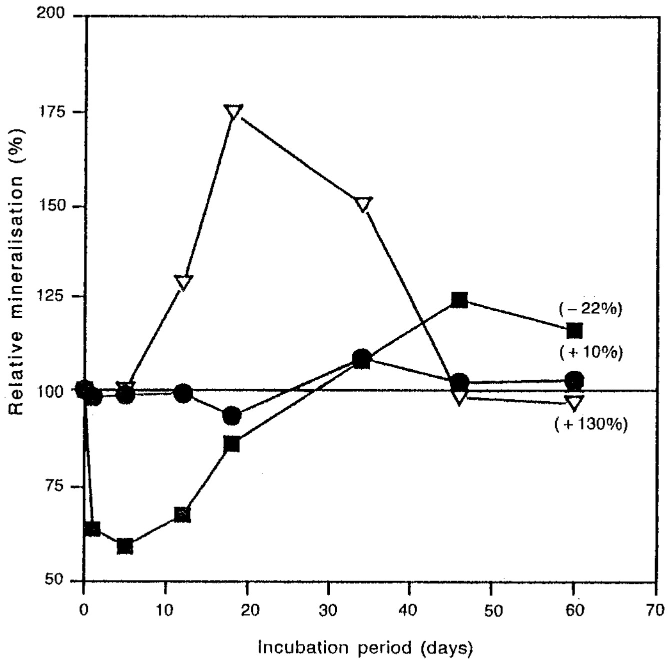

Figure 3. Relative (100% = soil) net mineralisation rates of leaves of (■) sorghum (C:N = 48:1) and (●) *Canavalia* (C:N = 23:1) mixed with a red latosol or surface applied (▽) $(NH_4)_2SO_4$ fertiliser at a rate of 50 kg N/ha. Values in brackets are accumulated amounts of net N mineralisation relative to input above native soil mineralisation.

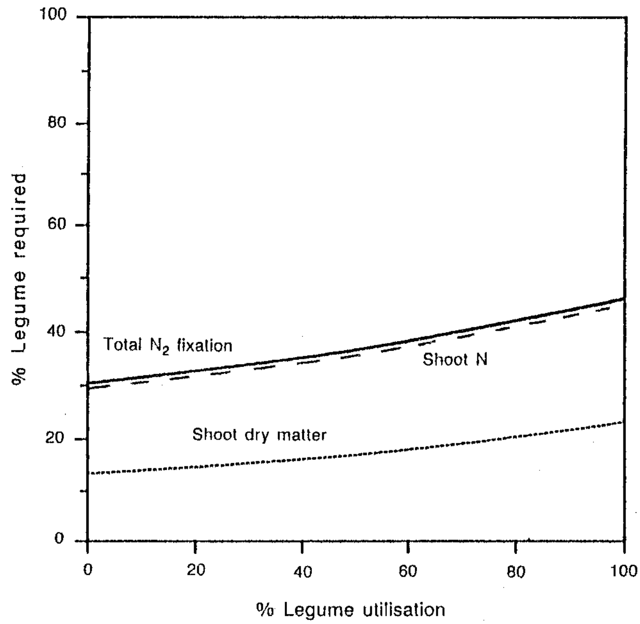

Figure 4. % Legume dry matter production (...), shoot-N accumulation (---) and total (shoot and root) N_2 fixation (_____) (as % of total above-ground) required to sustain the system N balance and productivity. SCUAF simulations at constant grass production and utilisation (59%).

where N-rich legume litter accumulates. However, the key step in the N cycle for maintaining plant productivity is the amount of soil N which is mineralised, and whether this occurs at the right time and in the right amount to match the plant N demand. There is a need for direct *in situ* measurements of mineralisation as proposed by Raison *et al.* (1987) in order to compare actual rates in undisturbed soils with plant demand (Alves *et al.* 1993). Such measurements would also serve to validate outputs from applied simulation models. Changes in soil fertility are more likely to be detected soon after changes in management by assessing and modelling microbial processes than by analysis of total soil N contents.

Management options to improve N cycling

The above studies confirmed the potential contribution of a high quality, N_2-fixing pasture legume in a grazing system to maintaining or improving soil fertility. In the following section we will explore how much N_2 may be fixed under Cerrado conditions and what management options are available to increase its contribution to the system.

The amount of N derived from fixation is based on 3 factors: herbage yield, N concentration in plant tissue and percent nitrogen derived from the symbiosis. Using an efficient legume-*Bradyrhizobium* symbiosis under conditions in which nutrient supply is sufficient and grasses are competing for soil N, herbage yield is normally the most variable parameter contributing to N_2 fixation among pasture legume species (Cadisch *et al.* 1989). Current production levels of adapted legumes in pure stands (small plots) in the Cerrados with a 3-5-month dry period are (t/ha/yr): 7.5 t for *C. mucunoides*; 3.9 t for *Centrosema macrocarpum*; 7.8 t for *Stylosanthes guianensis*; and 5.7 t for *S. capitata* on a red latosol in Campo Grande (Seiffert *et al.* 1985; CNPGC 1988); and 5.2 t for *Centrosema brasilianum*; and 1.8 t for *C. acutifolium* in Chapado, Planaltina (wet season production only; CIAT 1989). This would lead to above-ground N_2 fixation potential at current management levels of about 60–200 kg N/ha/yr in legume-dominant swards in the Cerrados, assuming 80% fixation. Thomas and Andrade (1984) reported fixation rates of only 3–46 kg N/ha/yr for *Stylosanthes* spp. in mixed swards under Cerrado conditions. This is because tropical pastures are mostly grass dominant. Although initial legume proportions may be high (34–84%), legume persistence is often poor. Legume content may decrease within 2–4 years to 0–14% when growing with aggressive grasses such as *Brachiaria decumbens* and *B. brizantha* (CIAT 1988; CNPGC 1989). Selection of more competitive legumes and/or less aggressive grass species or accessions for the association with legumes and use of low stocking rates (CIAT 1988) as well as short rest periods (Spain and Pereira 1985) favour maintenance of a high legume proportion in these pastures. Moderate stocking rates also enhance cycling of plant residues via the litter pathway which contributes to the sustainability of the system. The use of less palatable legumes as an alternative approach to increase legume persistence under grazing is succesfully practised in the more humid areas using *D. ovalifolium* and its contribution to soil fertility is discussed above.

The proportion of fixed N_2 of established forage legumes is normally high and varied little (70–88%) between species established in the native savanna of the Llanos Orientales of Colombia (Cadisch *et al.* 1989). By using grasses which compete more strongly for soil mineral N, the proportion of N_2 fixed may be increased (Vallis *et al.* 1977; Cadisch *et al.* 1993) but the legume content is likely to decrease. In contrast, the proportion of fixed N_2 decreases in pure legume swards due to suppression of nodulation, and N_2 fixation induced by accumulation of soil mineral N (Table 2). The latter favours nitrate leaching from the system. Thus mixed swards should be preferred over pure legume swards. *C. mucunoides* and *S. guianensis* form an effective legume-*Bradyrhizobium* symbiosis with indigenous strains in many areas of Brazil and no or only small inoculation responses are obtained. However, other species like *Centrosema* spp. strongly benefit from specific inoculation (CNPGC 1988; Sylvester-Bradley *et al.* 1990).

The ability of legumes to fix N_2 is strongly affected by plant nutrition, and nutrient deficiencies are likely to occur in low-input systems. Phosphorus deficiency, one of the major soil constraints of the Cerrados, reduced the proportion of N_2 fixed and considerable differences (44–84 %N derived from fixation) between species were observed (Cadisch *et al.* 1989; 1993). Combined P/K fertilisation increased the amount of N_2 fixed by up to 66 kg N/ha in the wet season in these experiments. Supplying P to pastures instead of as a mineral supplement to animals is not only economically advantageous but also increases litter recycling and root biomass production and hence more efficient recycling of nitrogen (Schunke *et al.* 1991). To justify costs involved with fertilisation, pasture establishment in Brazil is often combined with an initial cash crop such as upland rice or soybean. Adequate fertilisation and animal management as well as selection of adapted species or ecotypes would help to maintain high rates of N_2 fixation under such nutrient-limited conditions.

Conclusions

Comparison of N cycles of tropical pasture systems using a N-balance and a process-orientated approach resulted in similar predictions. Both methods foresee a drainage of N from the system for a pure grass sward which could be reversed by introducing a legume into the pasture. The amount of total legume N_2 fixation needed in mixed pastures to sustain the system ranged from 60–117 kg N_2/ha depending on legume utilisation. The way the legume contributes to the long-term productivity of the pasture depends strongly on the palatability (governing the animal-litter pathway) and decomposability (addition to soil organic-mineral N) of the legume material.

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