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Role of legumes in providing N for sustainable tropical pasture systems

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Abstract

Forage legumes have long been lauded for their ability to fix atmospheric nitrogen and contribute to the sustainability of agricultural production systems. However despite the benefits they bring in terms of increased herbage and animal production they are not widely used in temperate or tropical regions. In this review the amounts of biological nitrogen fixation (BNF) needed to sustain the soil-plant-animal system are discussed and related to the amounts fixed in tropical pastures. The data suggest that tropical forage legumes have the capacity to meet the requirements to balance the N cycle of grazed pastures. The actual amounts required will depend on the rate of pasture utilization and the efficiency of recycling via litter, excreta and internal remobilization. The efficiency of nitrogen fixation (% of legume N derived from fixation) is usually high in tropical pastures (> 80%) and is unlikely to be affected by inorganic soil N in the absence of N fertilizer. Thus an estimate of the amounts of N fixed could be obtained from simple estimates of legume biomass provided tissue levels of other nutrients such as phosphorus and potassium are adequate. Key factors for the achievement of sustainable grass/legume pastures include the selection of appropriate germplasm adapted to the particular environment and the judicious use of fertilizers such as phosphorus, potassium, calcium, magnesium and sulphur on acid infertile soils typical of the sub-humid and humid tropics. The main constraints to the widespread adoption of forage legumes include a lack of legume persistence, the presence of anti-quality factors such as tannins, variable *Bradyrhizobium* requirements and lack of acceptability by farmers. Strategies for the alleviation of these constraints are discussed. Forage legumes can be used to recuperate degraded soils via their ability to improve the physical, chemical and biological properties of soils and these benefits could be of particular use for small-scale resource-poor farmers. The incorporation of forage legumes into agropastoral systems is discussed as an environmentally and economically attractive means to encourage the widespread adoption of legumes in the humid tropics.

Introduction

Twenty three percent of the world's total area or 3.4 billion ha are permanent grasslands (FAO, 1993). Around 1.5 billion ha of these grasslands are in the tropics as either wild or cultivated fodder plants (Pearson and Ison, 1987; UNESCO, 1979). In most developing tropical countries animal production from pastures is low compared with developed countries, e.g. beef production is around 20 kg per animal unit per year in developing countries compared with 96 kg per animal unit per year in developed countries (Henzell, 1983). At least 700 million ha of relatively unproductive grasslands in South America, Africa, Asia and Australia are considered to be "improvable grasslands" (Pearson and Ison, 1987). Technologies for the improvement of grassland production have been considered (Breman and de Wit, 1983; Sanchez and Salinas, 1981; Teitzel, 1992; Toledo and Nores, 1986) wherein the introduction of a legume into grassland systems features prominently (e.g., Toledo, 1985). The basis of this essentially low-input (but not zero input) technology is the reliance on legume-based pastures to provide N, via biological fixation, and hence higher quality forage on offer to grazing animals. The provision of N via BNF in tropical pastures is particularly important as grasses (mainly C_4 types) frequently contain levels of N of 1.3% or less which are inadequate for animal production (Humphreys, 1991) and fertilizer N is generally less readily available to farmers for logistic and/or economic reasons.

The grasslands of Latin American tropics frequently suffer from pasture deterioration and degradation due to a number of causes including overgrazing and subsequent soil erosion, mineral deficiencies, especially N and P, and occasional attacks from pests and diseases (Thomas et al., 1994a). In Australia the expansion of pastures peaked around 1971 and since then there have also been problems of declining pasture productivity due to acidification, salinization, waterlogging and compaction, lack of phosphorus fertilization and N deficiency (Blyth and Menz, 1987; Gramshaw et al., 1989; Myers and Robbins, 1991). In Sahelian pastures N and P limitations occur along with water shortages (Breman and de Wit, 1983). In SE Asia, savannas cover around 23 million ha and are dominated by the noxious, shallow rooting grass *Imperata cylindrica* (star grass or alang-alang), where nutrient cycling is incomplete and soils degrade (Von Uexkull and Mutert, 1993). These problems are often acute leading some to suggest that these areas should perhaps be left under extensive use (Pearson and Ison, 1987). However the constraints of these marginal areas, especially in terms of soil quality, are well known (Sanchez

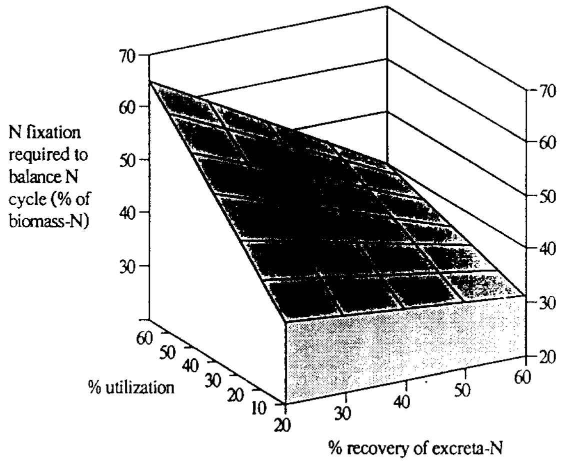

Fig. 1. Effect of variations in the % recovery of excreta-N and pasture utilization on the requirement for fixed-N.

and Logan, 1992) and it is possible to design technologies which would allow an intensification of grassland productivity using legumes (e.g., t'Mannetje, 1986; Thomas et al., 1992; Von Uexkull and Mutert, 1993). Such intensification should now consider the options for integrating more closely crop and livestock production in order to produce the additional food and fibre of animal and plant origin needed to satisfy the world's burgeoning population (Henzell, 1983; Worldwatch Institute, 1992).

The purpose of this review is to demonstrate the role that forage legumes and BNF can play in both improved pasture production and in the recuperation of degraded pastures, and to outline the main constraints that retard the adoption of legume-based pastures in regions of the developing world where they are needed the most.

The review is not comprehensive but attempts to complement several recent articles on BNF in pastures (Giller and Wilson, 1991; Ledgard and Steele, 1992; Peoples and Herridge, 1990; Peoples et al., 1995).

How much BNF is needed to sustain the soil-plant-animal system?

The amount of legume needed in a pasture is an old question that has generally been addressed from the herbage or animal production standpoint. For example, estimates of the amounts of above-ground legume biomass necessary in a pasture to maximize herbage production are in the order of 30–50% dry matter (DM) content (Harris and Thomas, 1973; Martin, 1960) with a range of 20–40% for maximum animal live weight gain (Simpson and Stobbs, 1981; Stewart, 1984; Watson and Whiteman, 1981). The question of how much legume and BNF is needed to maintain the N balance in the soil-plant-animal system has seldom been addressed. It has been estimated that to maintain the N reserves of the soil in pastures receiving no N fertilizer, a range of legume biomass of 20–31% of the pasture DM is needed for moderately grazed pastures with a 10–40% utilization (consumption by animals). This range increases to 35–45% DM in intensively used pastures with a range of utilization of 50–70% (Thomas, 1992). Others have indicated however, that as little as 10% legume could maintain the N requirements of temperate ryegrass/white clover swards (Sheehy, 1989).

The estimates by Thomas (1992) included the effects of likely variations in the recovery of N by plants via the main recycling processes, viz., excreta, plant litter decomposition and internal remobilization during senescence, on the requirement for fixed N to balance the N cycle without invoking a net drain on soil organic N (e.g. Fig. 1). Generally, as pasture utilization increases losses from the system also increase as more N passes through the animal and is excreted. Losses from excreta can be high via leaching and volatilization (e.g. 60–80%; Ball and Ryden, 1984; Simpson, 1987; Steele and Vallis, 1988) and constitute the "leaky" processes of the N cycle (in the absence of N fertilizer application). Consequently the requirement for inputs via BNF must similarly increase with increasing utilization to balance the cycle (Fig. 2).

These estimations did not include recycling via the root biomass, which can be large in N-deficient tropical pastures. Preliminary data from tropical grass/legume pastures in Colombia indicate a root:shoot ratio of approximately 1 in newly established pastures which are not excessively N-deficient. This ratio increases as deficiency increases (IM Rao, pers. commun.). Assuming a complete turnover of the root system per year and a N concentration in the roots of 0.5% N compared with 1% N in shoot tissue (Rao, unpubl.) then a 10 t ha^{-1} above ground DM will contain 100 kg N ha^{-1} shoot tissue plus 50 kg N ha^{-1} root tissue. Table 1 shows what effect the inclusion of root biomass-N would have on the requirement for legume-N to balance the cycle assuming a complete root turnover each year and a 50% recovery of root-N by growing plants. The effect varies from an additional 5% of the total plant biomass-N to 3% less depending on the % pasture utilization.

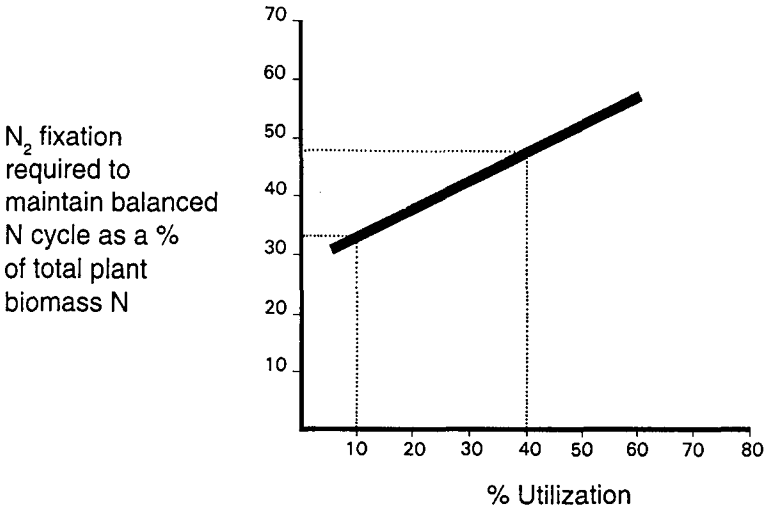

Fig. 2. Amounts of N_2 fixation required to balance the N cycle as a function of pasture utilization.

Table 1. Effect of the inclusion of roots on the requirement for legume-N to balance the N cycle of pastures grazed at different levels of utilization

	A	B[b]	C	D	E	F	G
Pasture utilization	Amount of[a] shoot-N needed to balance N cycle (% of shoot-N)	Amount of shoot-N available for recycling	Amount of shoot N available for recycling assuming complete root turnover and 50% recovery	Total amount of N (root + shoot) available for recycling	Amount of N needed to balance cycle	Amount of N needed to balance cycle as a % of total plant biomass	Difference in estimates of % biomass-N needed to balance cycle between shoot only estimates and shoot + root estimates
				(B + C)	(150–D)	E/150 × 100	(F–A)
10	34.3	65.7	25	90.7	59.3	39.5	+ 5.2
20	38.6	61.4	25	86.4	63.6	42.4	+ 3.8
30	42.9	57.1	25	82.1	67.9	45.2	+ 2.3
40	47.2	52.8	25	77.8	72.2	48.1	+ 0.9
50	51.5	48.5	25	73.5	76.5	51.0	- 0.5
60	55.8	44.2	25	69.2	80.8	53.9	- 1.9
70	60.1	39.9	25	64.9	85.1	56.7	- 3.4

[a] Data derived from Figure 4, Thomas (1992).

[b] For a 100 kg shoot N ha^{-1} pasture this value is 100–A.

Estimates are based on a 10 t DM ha^{-1} pasture with a shoot:root ratio of 1 and 1% N in shoot, 0.5% N in roots i.e. 100 kg shoot N + 50 kg root N ha^{-1} = total biomass-N is 150 kg N ha^{-1}.

Less N is needed at higher rates of utilization as the calculations assume no effect of increased grazing on root biomass-N. This may be a questionable assumption but the data illustrate that the absence of root data may not have a large effect on the estimated amounts of BNF required to balance the cycle. In addition the % N concentrations in shoot tissues of a grass/legume pasture are likely to be greater than the value of 1% used here. Values for shoot N of greater than 1% or a greater difference between %N in shoots and roots than that used in the estimations may further diminish the contribution of root N to the N balance. Data on root production and turnover of both organic matter and nutrients are urgently needed to verify these estimates particularly as it is known that root systems of tropical grasses have the capacity to immobilize substantial amounts of N resulting in pasture degradation (Bushby et al., 1992; Robbins et al., 1987).

Notwithstanding the limitations of the above analyses (Thomas, 1992) it would appear that the amounts of legume required in a pasture to balance the N cycle in terms of soil reserves are not too different from the amounts needed to maximize herbage production and individual animal performance. Thus there may not be much of a trade-off between the apparently conflicting demands for BNF in pastures for agricultural production (meat and milk) and for the replenishment of soil reserves. The key factors will be the stocking rate of animals and the rate of utilization of the pastures, i.e. factors that are controlled by the land manager and which are discussed later.

How much N can be fixed?

Reliable estimates of the amounts of N fixed in tropical pastures have appeared only relatively recently with the increasing use of ^{15}N isotope methodologies. These are summarized in Table 2 and the range reported matches the estimated annual inputs of 15–158 kg N ha^{-1} required to sustain soil-plant-animal systems producing 3–22 t forage DM ha^{-1} yr^{-1} (Thomas, 1992). There seems little doubt therefore that tropical forage legumes have the potential to sustain the N requirements of a pasture.

Noticeable in these estimations were the high proportions of legume-N derived from fixation (% Ndfa) under varying pasture conditions (average 84%). However there has been little systematic research on the effects of factors such as soil type, soil nutrients, pasture age or grazing on the % Ndfa in tropical pastures.

Factors affecting BNF in pastures

Factors affecting BNF have been extensively covered by recent reviews (Giller and Wilson, 1991; Ledgard and Steele, 1992; Sprent and Sprent, 1990) and include soil inorganic N, acidity, salinity, nutrient deficiencies (P, K, Ca, Mo, Zn, Co, Fe) or toxicities (Al, Mn), water stress, high or low temperatures, pests and diseases. The reader is referred to the cited reviews for further details and only some pertinent recent points are discussed here.

Inorganic soil N

Inorganic nitrogen in the soil is well known to be able to reduce BNF but generally in pastures and especially in the absence of N fertilizer, levels are low and are unlikely to have an inhibitory effect (Simpson, 1987). Sylvester-Bradley and Mosquera (1985) showed a reduced response to inoculation in terms of plant N in ploughed soil with subsequent higher nitrate-N levels compared with unploughed soil, but there were no differences between treatments in nodulation evaluations. In these experiments there was little competition for soil N from grasses. In rice (*Oryza sativa*)-pasture associations applications of up to 80 kg urea-N ha^{-1} (in three split applications) to rice - *Brachiaria dictyoneura-Centrosema acutifolium* mixtures sown after three different types of land preparation, had little or no effect on the nodulation of the legume (Thomas, unpubl.). In these oxisols levels of nitrate-N remain below 2 μg nitrate-N g^{-1} soil after N fertilizer applications. Thus inorganic-N may not be a significant problem for BNF in relatively infertile acid-soils.

Phosphorus and potassium fertilization

Cadisch et al. (1989) reported a marked decrease in % Ndfa from a range of 70–88 with P and K fertilization to 44–84% with no added P or K for eight tropical forage legumes that were grown in strips cleared of native savanna. The same authors showed that P fertilization had a greater effect on the % Ndfa than K with *Centrosema acutifolium* and *C. macrocarpum* (Table 3 adapted from Cadisch et al., 1993).

In field experiments on two differing soils, intimate mixtures of the grass *Brachiaria dictyoneura* and one of three forage legumes (*Arachis pintoi, Centrosema acutifolium, Stylosanthes capitata*) were given amounts of fertilizer normally used for the establishment of pastures in acid-soil savannas (kg ha^{-1}; 20 P, 20 K, 50 Ca, 20 Mg, 12 S, micronutrients and no N) and were compared with similar treatments receiving three times these amounts (Fisher et al., 1994). The % Ndfa were not significantly different between the two fertilizer treatments for any of the three legumes grown on either a sandy loam soil or a clay loam soil during the first year of establishment (Table 4). In the second year, in general, similar trends were noted with only

Table 2. Estimates of N_2 fixation and % plant N derived from fixation from tropical forage legumes using ^{15}N methodologies

Legume species	(Kg N fixed ha^{-1})	% Ndfa	Period of measurement	Reference
Calopogonium mucunoides	64	–	1 yr	Seiffert et al. (1985)
Centrosema acutifolium	43	82	17 wks	Cadisch et al. (1989)
C. macrocarpum	41	83	"	"
Desmodium ovalifolium	25	70	"	"
D. intortum	24–183	94	1 yr	Vallis et al. (1977)
Macroptilium atropurpureum	15–24	92	1 yr	"
"	23–79	83	1 yr	Shivaram et al. (1988)
Pueraria phaseoloides	9–23	82	3 mths	Zaharah et al. (1986)
"	115	88	17 wks	Cadisch et al. (1989)
Sesbania cannabina	121 - 141	80	1 season	Chapman and Myers (1987)
Stylosanthes capitata	38	87	17 wks	Cadisch et al. (1989)
S. guianensis	47	75	"	"
S. macrocephala	71	88	"	"
S. spp.	2–84	81	various	Vallis and Gardener (1985)
Zornia glabra	61	88	17 wks	Cadisch et al. (1989)

Table 3. Effect of different levels of P and K fertilizer on the % of legume-N derived from fixation in field grown *Centrosema acutifolium and C. macrocarpum*[a]

Fertilizer kg ha^{-1}		% legume shoot-N derived from fixation	
P	K	*C. acutifolium*	*C. macrocarpum*
5	60	84.9	79.2
40	60	94.6	91.6
75	60	94.5	94.0
75	30	94.8	93.0
75	0	94.3	92.9
LSD 0.05		3.1	

[a] Data from Cadisch et al. (1993), Fixation measured 14 weeks after sowing.

small differences in % Ndfa with fertilizer treatment (results not shown). The major effect of the lower level of fertilization was a reduction in legume biomass in the pastures at the two sites (Table 4).

These results suggest that the % Ndfa in forage legumes will decrease only where extreme deficiencies of nutrients such as P and K occur.

Efficiency of nitrogen fixation

The efficiency of nitrogen fixation (defined here as % Ndfa) in forage legumes has rarely been studied in grazed pastures for any length of time as most studies have dealt with the pasture establishment phase. Pasture legumes generally are poor competitors with grasses for soil N probably because of low root biomasses relative to grasses. Walker et al. (1956) and Eltilib and Ledgard (1988) showed that the proportion of nitrogen fixed by clover in a temperate pasture exceeded 80% over a wide range of mineral N supply. Vallis and Gardener (1985) showed with 10 accessions of *Stylosanthes* spp. that there were little differences in % Ndfa among accessions and little relationship between % Ndfa and total N uptake from the soil or with the age of the pasture up to 6 years old. Similarly Edmeades and Goh (1978) showed no change in the % Ndfa in grass/white clover pastures varying in age from 2 to 20 years. These results imply that the % Ndfa remains stable over time. However it should be noted that in these studies phosphate fertilizer was added either annually (Vallis and Gardener, 1985) or at the beginning of the measurement period along with other nutrients (Edmeades and Goh, 1978). Thus there remains the uncertainty of what level of efficiency (%Ndfa) can be expected from long term grass/legume pastures that do not receive maintenance levels of fertilizer as is the case for much of Latin

American pastures. The data of Cadisch et al. (1989, 1992, 1993) indicate that tissue analysis for nutrient deficiencies could be a useful guide to the likely level of % Ndfa in older pastures. Further research is needed to define the relationships between % Ndfa and mineral nutrient levels in tissues of different forage legumes.

Estimates of BNF from biomass measurements?

The bulk of the available data suggests that in tropical grass/legume pastures the %Ndfa remains relatively high (> 80%). If this is so then relatively simple estimates of legume biomass may be sufficient to estimate the amounts of nitrogen fixed using a value of around 80% for the plant N derived from fixation. In temperate grass/legume pastures Sanford et al. (1993) reported a range of % Ndfa of 0–100% with means for different species between 70–80% measured at over 200 sites. Such a comprehensive survey has not yet been reported for tropical legumes but is required to verify the use of legume biomass as a measure of N_2 fixation.

The data in Table 4 and other reports (e.g. Edmeades and Goh, 1978; Peoples et al., 1995; Vallis and Gardener, 1985) show that the amounts of nitrogen fixed will be dependent mainly on the amounts of legume present and legume productivity. Of paramount importance then is the maintenance of a legume population of 20% or greater to ensure a continued input of amounts of N that meet the requirements of both animal production and the soil N balance.

Fate of fixed N

Evidence for the transfer of fixed N to companion grasses was recently discussed by Ledgard and Steele (1992) and Giller and Wilson (1991). Generally levels appear to be low with around 25% of the legume-N being transferred to the grass via the decomposition of above- and below-ground tissues, leaching from tissues into the soil and gaseous effluxes with subsequent re-uptake by grasses, and perhaps direct transfer via mycorrhizal connections. Recent evidence has shown wide variation in the short term decomposition and release of N and other nutrients from six different tropical forage legumes and it was estimated that between 2–38% of a pasture's requirement for above-ground N could be obtained from recycling via above-ground litter (Thomas and Asakawa, 1993b). Transfer via animal excreta can also be an important although seldom quantified process in tropical pastures.

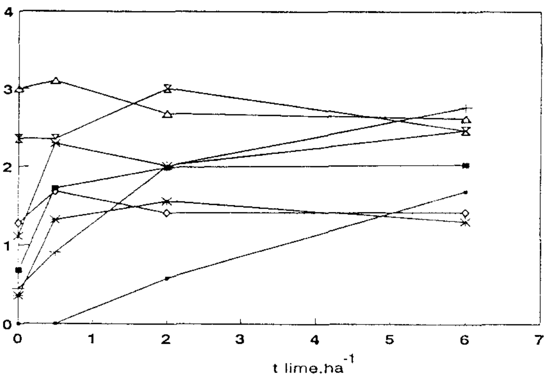

Fig. 3. Effect of lime on legume dry matter production in the field. -■- *Centrosema plumieri*, -+- *Centrosema* sp. CIAT 442, -*- *Centrosema* sp. CIAT 438, -□- *Centrosema pubescens*, -×- *Desmodium ovalifolium*, -⌑- *Pueraria phaseoloides*, -△- *Zornia* sp. - - *Stylosanthes capitata*.

The benefits of fixed N in terms of increased forage production and quality and gains in animal performance (liveweight, milk production and reproduction) have been reviewed recently (Thomas et al., 1992, 1994a; Thomas and Lascano, 1994) and were highlighted by spectacular 10-fold increases in productivity per hectare and 2-fold liveweight increases per head of cattle from grass/legume pastures compared with unimproved native savanna grasses.

How can sustainable grass/legume pastures be achieved?

Some strategies for achieving sustainable grass/legume pastures with a continuing input of N via BNF are discussed in this section along with the major constraints that need to be addressed.

Selection of appropriate forage legumes

The key to the success of forage legumes in providing N for tropical pastures is firstly the selection of germplasm adapted to the edaphic and environmental conditions and resistant to pests and diseases. In most of the tropics, soils are acid (pH <5.5) and consequently the soil constraints include acidity and often the associated toxic levels of aluminum and low availability of other plant nutrients (Sanchez and Logan,

Table 4. Amounts of N_2 fixed over 12 weeks, legume biomass and % N derived from fixation (% Ndfa)*. Values followed by same letter under each parameter are not significantly different, $p < 0.05$

		A. pintoi			*C. acutifolium*			*S. capitata*		
Site	Fertility	(kg N fixed ha^{-1})	Biomass (kg DM ha^{-1})	% Ndfa	(kg N fixed ha^{-1})	Biomass (kg DM ha^{-1})	% Ndfa	(kg N fixed ha^{-1})	Biomass (kg DM ha^{-1})	% Ndfa
Sandy	Low	0.8a	89.9a	81.5a	1.7a	130.5a	88.9a	21.0a	1510.4a	85.6a
Loam	High	7.4b	619.7b	87.1a	2.5a	143.8a	91.7a	40.0b	2528.5b	90.2a
Clay	Low	0.9a	96.8a	71.7a	3.5a	248.0a	91.4a	14.8a	1390.1a	79.7a
Loam	High	6.8b	607.8b	85.6a	5.2a	340.9b	92.9a	31.0b	2808.6b	89.1a

*N_2 fixation measured by ^{15}N isotope dilution (Thomas and Asakawa, 1993a).

Table 5. Forage legumes for different Latin American ecosystems[a]

	Ecosystem			
Legumes	Savannas Colombia/Venezuela	Savannas Brazil	Humid tropics	Subhumid tropics
Arachis pintoi	+[b]	-	+	-
Centrosema acutifolium	+	+	+	-
C. brasilianum	+	+	-	+
C. macrocarpum	-	-	+	+
C. pubescens	-	-	+	-
Calopogonium mucunoides	-	+	-	-
Cratylia argentea	+	-	+	+
Desmodium ovalifolium	+	-	+	-
D. velutinum	+	-	+	-
Pueraria phaseoloides	+	-	+	-
Stylosanthes capitata	+	+	-	-
S. guianensis var. *pauciflora*	+	+	-	-
S. guianensis var. *vulgaris*	-	+	+	+

[a] Data from Miles and Lapointe (1992).
[b] + = adapted to the ecosystem; - = not adapted

1992). A large collection of over 18,000 herbaceous and woody legume accessions from over 100 genera and 600 species is maintained at CIAT, Cali, Colombia along with a collection of over 4000 strains of *Bradyrhizobium* (Franco et al., 1993). Other sources of *Rhizobium* and *Bradyrhizobium* are listed in Bushby et al. (1986). The majority of the forage legumes in the CIAT collection have been selected from acid infertile soils of Latin America and are extremely tolerant of low acidity. For example there was little response to liming when legumes were grown in an oxisol with pH 4.5 and 90% aluminum saturation (Fig. 3, adapted from Spain, 1979). Most of the legumes produced maximum growth at 0 or 0.5 t lime ha^{-1}. The promising species have been evaluated in a multi-institutional decentralized network operating throughout the Latin American region (Toledo, 1985, 1986) and a summary of their adaptation to different ecosystems in Latin America is presented in Table 5. Note that there is not a legume that is adapted to each of the four ecosystems. Thus although a wide adaptation to climate, soil and management has been advocated, especially for forage legumes introduced into native Australian pastures (Miller and Stockwell, 1991), legumes for targeted niches would seem a more appropriate objective. For the humid tropical areas of Australia *Centrose-*

ma pubsecens, C. schiedianum and *Pueraria phaseoloides* have been selected for productive and persistent grass/legume mixtures on relatively fertile soils and *Calopogonium mucunoides, Arachis pintoi* and *Centrosema* spp. have been suggested as better alternatives for pastures on poorer soils with a tendency for poorer drainage and grazing mismanagement (Teitzel, 1992).

The introduction of a new legume into an area can be very successful as exemplified by *Stylosanthes guianensis* which is grown on over 13,000 ha in tropical China 8 years after its introduction in 1982 (CIAT, 1991). In 1993 over 5,200 ha were sown in Guangdong province alone (Devendra and Sere, pers. commun.). In Australia two legumes, *Stylosanthes hamata* cv. Verano (Caribbean stylo) and *Stylosanthes scabra* cv. Seca (shrubby stylo), introduced from Venezuela and Brazil respectively, were released in 1973 and 1976. At the end of 1991 it was estimated that these legumes had been sown on 500,000 and 300,000 ha respectively (Cameron et al., 1993). These examples should encourage further selection trials.

Use of fertilizers

The second important factor in sustainable grass/legume pastures is the judicious use of fertilizers. As pointed out by Sanchez and Salinas (1981) the low-input soil management technology associated with grass/legume pastures does not imply the elimination of fertilizer use but rather a more rational and efficient use of limited amounts of fertilizer, especially phosphorus, which farmers can afford. Even with a compatible grass/legume mixture there is a need for maintenance levels of nutrients, particularly phosphorus but also in some instances, potassium, sulphur, calcium, magnesium and micronutrients. In the Australian humid tropics for example, a reapplication of 30 kg ha^{-1} of soluble P every 2 years and an application of trace elements every 4 years is recommended for productive and persistent grass/legume pastures (Teitzel, 1992). However further work is needed on maintenance fertilizers for different grass/legume pastures on different soil types based on long term evaluations.

Alleviation of constraints

The most serious constraints to the widespread use of forage legumes in pastures include problems of lack of persistence, anti-quality factors, variable *Rhizobium* requirements and poor acceptability by farmers.

Legume persistence

Lack of legume persistence is common to temperate and tropical pastures. For example in spite of early work showing that the composition of grass/white clover swards could be manipulated by timing and pressure of grazing (Jones, 1933), it is only relatively recently that guidelines have become available for the management by grazing of ryegrass-white clover pastures. These include longer resting intervals between grazing, integration of cattle and sheep grazing with conservation cuts and maintenance of sward heights around 6 cm (Evans et al., 1992; Grant and Barthram, 1991; Orr et al., 1990; Wilkins, 1982). Emphasis appears to be on the maintenance of white clover growing point numbers and avoidance of burial during wet periods (Laidlaw et al., 1992). Little or no information of this type exists for tropical species which have only been domesticated recently. Clements (1989) demonstrated the increasing susceptibility of some twining tropical legumes to loss of growing points as grazing pressure (animals per unit green DM) increased compared with more prostrate legumes which suggests that a similar strategy, i.e. maintenance of growing points under grazing, is likely to contribute to a better persistence of tropical forage legumes.

Tropical legumes show a variety of responses to grazing ranging from a rapid disappearance, e.g. *Centrosema acutifolium,* to legume dominance in *Desmodium ovalifolium* (e.g. de Santana et al., 1993). The latter contains high levels of tannins thus reducing its palatability to animals and digestibility (for discussion see Humphreys, 1991). Clements (1989) also reported that the low acceptability of the more prostrate species *Cassia rotundifolia* was a more important factor in its tolerance to grazing than the disposition of its growing points.

One of the most persistent and promising legumes to date is the forage *Arachis species, A. pintoi.* In grazing experiments in the eastern plains of Colombia this legume has persisted under heavy grazing pressure for over 6 years in association with the grass *Brachiaria humidicola* and formed good associations with three other *Brachiaria* species (Lascano, 1994). Similarly *A. glabrata* cv. Florigraze has persisted for 8 years in association with *Cynodon dactylon* and *Hemarthria altissima* in Florida (Dunavin, 1992). Possible reasons for the persistence of forage *Arachis spp.* include a prostrate stoloniferous habit (similar to white clover), an ability to flower and set seeds profusely and bury the seeds via fruiting pegs. Furthermore *A. pintoi* is easily propagated via vegetative stolons which may be detached from the mother plant by trampling. It is shade tolerant, rapidly re-establishes its leaf area index after defoliation and can survive relatively long dry periods even though it loses its leaves and appears desiccated (Fisher and Cruz, 1994). An ability to acquire aluminum-bound phosphorus from acid soils (Rao and Kerridge, 1994) may also be a factor in the superior persistence of *A. pintoi.* All the features listed above are consistent with the legume ideotype necessary for a persistent forage legume (Marten, 1989).

Grazing management is the most readily available tool to the land manager whereby a target legume content can be maintained. However a blanket recommendation cannot be made because of differences in grass and legume behaviour under grazing. Studies at CIAT have suggested that the grazing system (i.e. continuous, rotational and deferred grazing) is as important as the grazing intensity (animals/unit green biomass) with respect to maintaining an appropriate grass/legume balance (Lascano, 1991). A system of flexible grazing management has been proposed (Spain et al., 1985) for the evaluation of grass/legume mixtures which depends upon:

1. the adjustment of stocking rate (animals ha^{-1}) to maintain the amount of forage on offer between 3–6 kg DM 100 kg^{-1} liveweight day^{-1} and
2. the alteration of the grazing system to maintain the legume content between 15 and 50%.

With a high legume content an increase in the rest period from grazing is thought to increase the grass component whereas at low legume levels increased grazing via reductions in the rest period is thought to encourage the legume component at the expense of the grass component. While this experimental methodology has had some success with *Desmodium ovalifolium,* a vigorous, prostrate and unpalatable legume (de Santana et al., 1993), it has yet to be translated into management options for contrasting grass/legume pastures that are based on some simple evaluation of the state of the pasture such as the use of sward height in temperate ryegrass pastures (Hodgson et al., 1985; Parsons, 1984). Studies on the ecophysiology of tropical grass/legume pastures are required to determine if a simple indicator of sward state exists which could be used as a guideline for the persistence of a forage legume. Such an indicator will probably need to be different for associations with either the prostrate grasses (e.g., *Brachiaria*) or with the more erect bunch types (e.g., *Andropogon*).

Fisher and Thornton (1989) hypothesized that because grasses in tropical pastures are predominantly C_4 types whilst the legumes are C_3 types it is inevitable, other factors being equal, that grasses will dominate the pasture as a result of their superior rates of photosynthesis and growth. In order to obtain legume persistence the above authors argued that the legume must have some competitive or demographic advantage or that the grass must be preferentially grazed. Decision rules for grazing should therefore take these objectives into account in order to maintain the legume in the pasture even if there is a penalty in terms of animal production.

Anti-quality factors

The presence of anti-quality factors such as tannins in many tropical legumes (Humphreys, 1991; Swain, 1979) can be thought of as both advantageous and disadvantageous. Preferential grazing of the grass in a grass/legume mixture due to the unpalatability of a legume which contains anti-quality factors can result in an increase in the proportion of the legume in the pasture. It could however result in poor animal intake and production and a lower rate of litter decomposition and hence slower nutrient recycling (Thomas and Asakawa, 1993b). The latter could be a disadvantage if there is a need for a rapid release of nutrients for a subsequent crop, for example.

Is there a need to inoculate tropical forage legumes?

The previous classification of tropical forage legumes into three groups, viz., promiscuous effective, promiscuous ineffective and specific with only the latter two requiring inoculation (Date, 1977) has tended to lose its usefulness as more legumes are tested and more exceptions are reported. For example legumes previously classified as promiscuous effective such as *Pueraria phaseoloides, Centrosema macrocarpum,* and *Arachis pintoi* (Sylvester-Bradley, 1984; Sylvester-Bradley et al., 1988, 1991) responded to inoculation when grown in infertile acid soils (oxisols). Lack of an ability to generalize about the inoculation requirements of a particular forage legume is due to many factors including the wide variation in both numbers, competitiveness and effectiveness of the indigenous rhizobial population, environmental factors such as soil acidity, temperature, moisture, and microbial predators all of which can affect the survival and success of the inoculant strain. Models have been developed to predict the native rhizobial population, based on factors such as % legume cover, rainfall and extractable bases in soils (Woomer and Bohlool, 1989) and also to predict the likelihood of success of inoculation based on indigenous rhizobial populations and availability of soil mineral N (Thies et al., 1991). However there has been little or no verification of these models in tropical pastures. As suggested by Date (1977) the simplest approach, in the absence of an ability to predict an inoculation response, is to conduct simple need-to-inoculate tests. Details of these tests are available (Brockwell et al., 1988; Date, 1977; Sylvester-Bradley, 1984; Vincent, 1970) and some have been discussed further by Giller and Wilson (1991). Briefly, these tests compare the growth of uninoculated and inoculated plants with a third treatment receiving doses of N fertilizer of 30 kg ha^{-1} every 2 weeks. The uninoculated control will reveal the presence of native rhizobia and their effectiveness when compared with the other treatments. The inoculated treatment will examine the effectiveness of the inoculant strain(s) and the N fertilized treatment will indicate the growth potential in the absence of N limitation.

Acceptability of forage legumes by farmers

Farmers are generally reluctant to invest the time and resources into the establishment of legumes in pastures. There is abundant research evidence available which demonstrates the benefits of legumes to beef production e.g. in the eastern plains of Colombia on-farm trials showed an increase of between 32 to 61% in beef production from grass/legume pastures compared with grass only pastures (Ferguson, 1992). Constraints to the adoption of forage legumes include the inherent slowness of the adoption of a novel component by pastoralists, an unawareness of the relevance and benefits to beef and milk production (let alone soil improvement), low availability of commercial legume seed, limited availability of technical assistance, lack of capital and credit requirements, lack of experience in identifying "niches" for particular legumes (Ferguson, 1992). All these issues need addressing as well as a need for suitable policy incentives to improve the adoption of forage legumes by farmers (for discussion of the latter point see Bohlool et al., 1992).

One can conclude from the information presented above that the long-term success of a grass/legume pasture will be a function of the persistence of the legume and that this is a complex interaction between plant types, relative growth rates of the grass and legume, shade tolerance of the legume, relative palatability of the grass and legume or grazing preference of the animals, capacity for recruitment via legume seed or vegetative material, ability to withstand trampling and burial. In addition the socio-economic factors need to be more favourable to encourage the widespread adoption of forage legumes by farmers.

Role of forage legumes in recuperation of degraded land

Pastures can stabilize soils mainly by the complete ground cover conferred by the grass species. Legumes can also fulfill this role if they can cover the ground rapidly. Figure 4 shows that the % area covered by a number of forage legumes can be sustantial after 12 weeks growth on a hillside site in the coffee growing region of Colombia. The forage *Arachis* species, *A. pintoi*, was the most successful legume in this experiment achieving 80% ground cover.

Forage legumes have also been shown to improve the physical, chemical and biological properties of soils by increasing factors such as organic matter, cation exchange capacity, aggregate stability, infiltration rates, moisture retention, mineralisable N and P fractions and numbers of earthworms (Dalal et al., 1991; Lal et al., 1979; Mytton et al., 1993; Thomas et al., 1994b; Wilson et al., 1982). These are essentially the reversal of the degradative processes occurring in many tropical soils. The effect of forage legumes on the soil fauna may be particularly valuable for small-scale farmers as a relatively simple and cheap means to initiate remedial treatment of degraded soils and

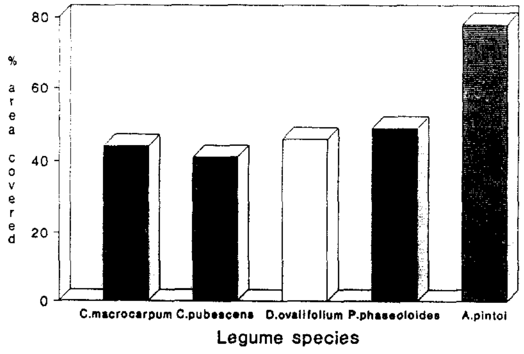

Fig. 4. Percentage soil cover with forage legumes after 12 weeks growth.

this topic merits further research (e.g., Lavelle et al., 1989).

The potential use of forage legumes in agropastoral systems

The use of agropastoral systems similar to the classic ley farming systems of the pre-fertilizer era has been discussed as an option for land management in the tropics (Saleem and Fisher, 1993). The introduction of a relatively short-term pasture phase of 3–5 years with a forage legume component is attractive from the viewpoint of the constraints noted above to the widespread use of legumes. Such a system is currently being tested in the savanna lands of Brazil, Colombia and Venezuela where a grass/legume mixture is sown simultaneously with an acid-soil tolerant upland rice variety (Sanz et al., 1994; Vera et al., 1992; Zeigler et al., 1994). The rice crop is harvested after 105–120 days and the pasture establishes at a much faster rate than the traditional methods as a result of the residual fertilizer not removed by the rice crop. Grazing of the pasture is possible after 3–5 months compared with one year using the traditional low-input pasture technology. Other advantages include a more efficient land preparation (less machinery operations), reduced soil erosion and leaching by establishing a ground cover more rapidly and completely compared with either rice or pasture alone (Thomas et al., 1994a). The pasture phase can be of short duration of 3–5 years and can be followed by another crop which can benefit from the input of N via BNF. In this system the persistence of the forage legume assumes less importance as it can be re-introduced or replaced by another forage legume or legume mixture with each crop phase. The use of rice as a pioneer crop for a grass/legume pasture is environmentally and economically attractive. An analysis of the cash flow for example indicates a net return after 3 years with rice-pasture compared with a least 5 years with pasture alone (Vera et al., 1992) and, in addition, the costs of establishing the rice-pasture association are recovered in the first year with income generated from selling the rice crop (Rivas et al., 1991).

Ley farming systems have also been estimated to be a profitable option for subtropical Australia on soils with low fertility although the lack of suitable tropical forage legumes is a current limitation (Lloyd et al., 1991). In semi-arid regions of Australia, germplasm is available but the economics of cropping and the increasing complexity of the management skills required in these areas with greater risks of crop failure due to the vagaries of climate, appear to be constraining the widespread adoption of legume-based leys (Jones et al., 1991).

The use of forage legumes in agropastoral systems holds great promise for the humid tropics and is considered to be one of the sustainable land use options currently available which can bring benefits such as improved control of pests and diseases through rotations, more efficient nutrient cycling, less loss of soil and increased productivity (National Research Council, 1993). Agropastoral systems also offer a means to overcome some of the constraints noted above for the widespread adoption of forage legumes. Further research is needed on increasing the number of crop options, on the competition between crops, grass/legume pasture and weeds in different environments, on improvements in fertilizer use efficiency and integration with the use of biologically fixed N.

Conclusions

Forage legumes can provide sufficient amounts of biologically-fixed N to increase herbage and animal production and maintain the N balance of the soil provided the legume content of the pasture is maintained at a minimum value of around 20%. As utilization of the pasture increases the requirement for legume N also increases. Careful grazing management using different grazing systems as well as grazing pressure can ensure the persistence of an adequate legume content but further research is required to define the management options for different tropical grass/legume associations.

The % Ndfa is usually greater than 80% in tropical pastures but can decline below this value if other mineral nutrient deficiencies occur. Further research is necessary to define the critical nutrient concentrations for maintaining % Ndfa above 80% especially in long-term pastures which may not receive maintenance levels of fertilization.

The forage species *Arachis pintoi* appears to be closest to the plant ideotype required for a persistent pasture legume in the tropics and an examination of the characters that confer persistence in this species is warranted.

At present the variable requirements for inoculation of forage legumes cannot be predicted with accuracy and the use of simple need-to-inoculate tests is encouraged.

Perhaps the greatest challenge for researchers is to address the issue of the poor acceptability of forage legumes by farmers and use this experience to redirect the large amount of effort currently undertaken on improving the knowledge base of the processes of biological nitrogen fixation. The latter has yet to result in any practical improvement of BNF in farmer's fields.

The integration of grass/legume pastures with cropping appears to be a promising option for increasing agricultural production, recuperating degraded soils and facilitating the wider use of forage legumes in environments where fertility is inherently low and where the use of N fertilizer is restricted by availability or cost.

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