

Another dimension to grazing systems: Soil carbon

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Abstract

In 1998, Fisher *et al.* attempted to draw together published and anecdotal information to answer some of the questions raised by the findings of Fisher *et al.* (1994; 1995), that introduced pastures of African grasses on the eastern plains of Colombia accumulated large amounts of C in the soil. This review synthesises the work in both Colombia and Brazil over the last 7 years that answers some of the questions raised and speculations made by Fisher *et al.* (1998). The most important studies have shown that the rate at which litter decays at the soil surface has been grossly underestimated in the past. As a consequence, net aerial primary productivity (NAPP) was shown to be 33.3–33.5 t/ha/yr in well managed pastures of introduced grasses without either a legume component or N fertiliser. While data for soil C vary according to the past history and states of the pasture, well managed pastures do accumulate C in the soil to levels above that under the native grassland vegetation. Net primary productivity below ground was only slightly less than NAPP. Deficiencies of N and P are primarily responsible for the widespread degradation that occurs when introduced pastures are overgrazed and not fertilised. Heavy stocking rates profoundly change the N cycle and lead to N deficiency and hence degradation in the bulk pasture area by concentrating N recycling from faeces and urine in rest areas and watering points. Here the pasture is so damaged by trampling that it cannot take advantage of the increased fertility.

Introduction

Atmospheric carbon dioxide (CO₂) concentrations have increased from 270 ppm before the industrial revolution to 367 ppm in 1999 (IPCC 2001) and are continuing to increase at an average rate of about 1.5 ppm/yr. Without action to limit global CO₂ emissions, the concentration of CO₂ in the atmosphere could reach 550–1000 ppm by 2100. CO₂ is one of the main contributors to the so-called 'greenhouse effect', which the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report (IPCC 2001) concluded could lead to substantial warming of the global climate by 1.8–5.4°C by 2100.

In terrestrial systems, plants capture CO₂ from the atmosphere by photosynthesis. As dead plant material decomposes both within the soil and at the soil surface, plant C can be stored or sequestered in soil organic matter (SOM). The store of soil organic C (SOC) is almost 3 times that held in biota (1550 compared with 550 Pg) (*e.g.* Lal *et al.* 1995). Therefore, small increases in SOC could slow the increase in the concentration of CO₂ in the atmosphere (Schlesinger 1995), and in so doing have considerable effects on the global climate system.

African grasses introduced into savannas of the central lowlands of tropical South America can increase SOM and accumulate more C in the soil than the native grasses they replace (Fisher *et al.* 1994; 1995). In a review published in 1998, Fisher *et al.* explored the possible impact of this finding, and the role of 'management options that can increase the potential of tropical pastures as a significant C sink to mitigate global warming.' They went on to write, 'Neither the extent of this finding in the Latin American savannas nor understanding of the mechanisms in the soil-plant system by which it occurs are yet known.'

Over the 7 years to 2004, a project partly financed by the UK Department for International Development has allowed some of these issues to be addressed. In this paper, we attempt to update

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Fisher *et al.*'s (1998) review with recent information, some of which is unpublished or in the process of revision.

The potential of grasslands

Approximately one-fifth of the world's land, 3.4 billion ha, is covered by grasslands (Hadley 1993; FAO 1993), with about 1.5 billion ha in the tropics, of which Pearson and Ison (1987) considered as much as 0.7 billion ha to be 'improvable grasslands'. Houghton (1995) estimated the mean C content of the soils under tropical grasslands and pastures to be 48 t/ha, although it is not clear what depth of soil was used to obtain this estimate. Fisher *et al.* (1998) measured 1.5–5 times that amount of C in the soil to a depth of 1 m on the eastern plains (Llanos) of Colombia. The data on soil C stocks presented below, also to a depth of 1 m, are 2–3 times Houghton's figure.

Vegetation communities

Scholes and Hall (1995) estimated that tropical savannas, woodlands and grasslands occupy at least 11.5% of the global land surface. In calculating the C budget for these biomes, net annual C fixation in tropical tree-grass systems is about 7.6 Pg, which is about half of the net annual C fixation attributed to tropical forests, which have closed canopies and no herbaceous layer. The main factors that control C fixation are water, nutrient availability and vegetation composition and structure. The total C stock in tropical grasslands, savannas and woodlands is about 135 Pg, 80% of which is in soil (Scholes and Hall 1995).

Many of the generalisations about savannas have ignored the South American grasslands (*e.g.* Parton *et al.* 1995), so it is worth describing them briefly. The area of central Brazil known collectively as 'the Cerrados' covers 205 M ha. (In this paper, we use the terms with their common meanings. 'Cerrados' refers to the lands in central Brazil and 'cerrado *sensu strictu*' refers to the low scrubby vegetation that covers a large proportion of the Cerrados.) Fisher *et al.* (1998) asserted that most introduced pastures on the Cerrados were sown on the 24% (Haridasan 1992) that is either treeless or has only a few stunted trees and shrubs, concluding that: 'It is on these lands that most of the 50 M ha (Sano *et al.* 2000) of intro-

duced pastures are found.' This now appears not to be the case, in that most introduced pastures were in fact sown on lands that formerly carried cerrado *sensu strictu* vegetation. Any calculations of net carbon accumulations on the central lowlands of tropical South America (Fisher and Thomas 2004) must discount figures for C accumulation by the amount of C that is lost when the cerrado *sensu strictu* vegetation is cleared. Since cerrado *sensu strictu* vegetation covers a continuum from communities with scant arboreal component to near open forest (Cochrane *et al.* 1985), it is no trivial exercise to calculate historic C stocks on the lands sown to pasture. While we draw attention to this anomaly, further discussion is outside the scope of this paper. The savannas of Colombia and Venezuela (about 32 M ha) have not had, from historical times, a significant tree component (Moreno and Moreno 1989). Since their area is vast, any intervention in the savannas of the central lowlands of tropical South America that will increase their net primary productivity, and hence the stock of C in the soil, could be large enough to be of global significance.

Net primary productivity above ground

Long *et al.* (1989; 1992) found net primary productivity (NPP), *i.e.*, accounting for mortality of above- and below-ground organs, at 5 natural grassland sites in the tropics to range from 0.14 to 10 kg/m²/yr dry matter (DM), as much as 5 times greater than if they used the methodology of the International Biological Programme (Milner and Hughes 1968). Long *et al.* (1992) indicated that all 5 sites were potential sites of net C accumulation. In the absence of fires, their terra firma sites in Kenya, Mexico and Thailand accumulated 144 g/m²/yr C, and 40 g/m²/yr C with occasional fires (0.5/yr). They also found a net loss of 70 g/m²/yr C with more frequent fires and drought, suggesting that the balance, in terms of the sites being a sink or source of C, was delicate. Their studies indicated, however, that the grass-dominated communities have the potential to act as significant sinks for C.

Rezende *et al.* (1999) carried out an experiment on lands cleared from the coastal Atlantic forest at Itabela in southern Bahia state in central-eastern Brazil to determine the effects of introducing a forage legume (*Desmodium ovalifolium*) in pastures of *Brachiaria humidicola* at different

stocking rates. At monthly intervals over 3 years, amongst other measurements, they collected data on the rates of plant litter fall and decomposition by measuring litter already on the ground and the rate of litter fall over the subsequent 14 days. Doubling the stocking rate from 2 to 4 head/ha caused a highly significant decrease in litter fall, but the legume treatment had little effect (Table 1).

Their data showed that 15–18 t/ha of litter DM were deposited annually. However, the amount of existing litter was always relatively small (annual means were 0.8–1.5 t/ha DM), suggesting that litter decomposes rapidly, with calculated half-life of 22–33 days. Moreover, even this calculation must underestimate the true rate at which litter disappears, because a substantial proportion of it must have disappeared within the 14-day collection periods.

To resolve these issues, Rezende *et al.* (1999) developed an equation to correct for the loss of litter between sampling dates. The correction gave constants for litter decomposition of 0.037 to 0.097 g/g/d, equivalent to litter half-lives of 9–20 days. They summed these data, together with estimates of animal consumption, to calculate net aerial primary productivity (NAPP) of the pastures at 30–36 t/ha/yr (Table 1). These are astonishing figures, even compared with Long *et al.*'s (1989) estimates, but are consistent with Fisher *et al.*'s (1998) reasoned hypothesis that NAPP of sown *Andropogon gayanus* pastures on the eastern plains of Colombia was likely to be as much as 43 t/ha/yr. It is also worth pointing out that Long *et al.*'s data came from naturalised grasslands, which usually have much lower NAPP than sown pastures of introduced species

to which some fertiliser has been applied (Fisher *et al.* 1992).

Rezende *et al.* (1999) also experimented with litter bags, and a 'covered litter' system, which allowed soil fauna to access the litter. This experiment showed that soil fauna had little impact on the rate at which litter disappeared. Moreover, these techniques, commonly used to estimate litter decomposition, actually underestimated true rate of litter decomposition at least 10-fold, because, in contrast to litter bags, in the open field fresh litter is being added continuously. As this material consists of both easily degradable ('active') and recalcitrant fractions, the easily degradable fraction fuels an active microbial biomass that continuously degrades the less decomposable material. They noted in conversation that, when they went to the field in the early morning at Itabela, 'the litter felt warm' (R.M. Boddey, unpublished data). In this seminal paper, they concluded that their approach gives more realistic, and much higher, estimates of the NAPP of tropical grasslands and pastures than the techniques used until now.

The approach by Rezende *et al.* (1999) used a mathematical adjustment to take account of presumed degradation losses during the 14-day measurement interval, which may not be accepted by all. The result could be confirmed, albeit rather laboriously, using the techniques of tissue turnover developed by Hodgson and his colleagues at the former Hill Farming Research Institute in Scotland (Hodgson 1990). The method depends on determining the rate of leaf emergence coupled with taking a census of the number of tillers and

Table 1. Annual means of existing litter, litter deposited in 14 days and litter decomposition parameters in pastures of *B. humidicola* in monoculture under three stocking rates of crossbred Brahman cattle in the period January–December 1995 at Ceplac station, Itabela. The values are means of 12 monthly evaluations, from 10 quadrats per paddock, and 3 replicate paddocks per treatment.

Stocking rate	Means of existing and deposited litter		Decomposition constant k	Total litter deposited in 12 months		Consumption	Annual NAPP ³
	Existing	Deposited in 14 days		Estimate ¹ 14 days	Corrected ²		
(An/ha)	(g/m ²)		g/g/d			(t/ha/yr)	
2	116.6	72.5	0.0706	18.9	29.7	7.8	35.5
3	105.8	66.4	0.0734	17.3	27.5	9.1	33.3
4	73.7	49.1	0.0797	12.8	21.3	12.4	30.6
Mean	98.7	62.7	0.0746	16.3	26.2	9.8	33.1

¹ Calculated from [(litter deposited in 14 days)/14] x 365.

² Allowing for losses during the 14 days of deposition (See Rezende *et al.* 1999 for details).

³ Annual NAPP (net aerial primary productivity) = total deposited litter + forage consumption + change in standing biomass. The change in standing biomass during the year was –2.0, –3.3 and –3.1 t/ha for the stocking rates of 2, 3 and 4 animals/ha, respectively.

Data from Rezende *et al.* (1999) and Boddey *et al.* (2004).

Table 2. Mean net below-ground primary productivity calculated from ingrowth tubes of a native savanna (NS) grassland compared with a degraded *Brachiaria humidicola* pasture (Bh) and well managed pastures of *B. dictyoneura* alone (Bd) and in association with the legume *Arachis pintoi* (Bd+Ap). Data from Trujillo *et al.* (2005).

Parameter	NS	Bh	Bd	Bd+Ap
		(t/ha/yr)		
Sum of short-term tubes	2.42 c ¹	5.33 b	9.74 a	9.99 a
Last long-term tube	1.22 c	2.89 b	8.03 a	7.91 a
Peak in long-term tubes	2.88 b	3.47 b	8.63 a	8.96 a
Turnover	5.88 c	5.11 c	11.06 a	7.66 b
Last long-term tube + Turnover	7.10 c	8.00 c	19.09 a	15.57 b

¹ Within rows, treatment means followed by the same letter did not differ significantly ($P>0.05$).

the number of leaves on each. In many cases, the number of leaves per tiller is constant (5 or 6 in many *Brachiaria* species), implying that old leaves must die at the same rate as new ones appear. Data of mean mass of newly fallen leaves, multiplied by tiller density per unit area and multiplied by the rate of leaf appearance, would provide an independent estimate of litter fall ($\text{g}/\text{m}^2/\text{d}$).

Net primary productivity below ground

Although Long *et al.* (1989; 1992) broke new ground by including roots in their estimates of NPP, they limited their measurement of roots to the surface 15 cm. At the time, this was thought reasonable, because most measurements of plant behaviour were dominated by studies on sown crops (Fisher *et al.* 1998). However, the emphasis in the Tropical Pastures Program of the Centro Internacional de Agricultura Tropical (CIAT) for many years was to select tropical grasses with deep and abundant root systems that can exploit nutrients and water at depth in the soil. In many environments, especially in the semi-arid tropics, deep roots can also confer ecological advantages, for example, adaptation to drought. Fisher *et al.* (1994) speculated that deep-rootedness was at least part of the mechanism by which C was accumulated¹ by pastures of introduced grasses in the neo-tropical savannas. However, there are few measurements of the contribution of grass roots at depth to NPP.

Trujillo *et al.* (2005) estimated the net below-ground primary productivity (NBPP) on

the eastern plains of Colombia. They assessed the rate of root decomposition and calculated the annual input of soil organic carbon under native savanna vegetation (NS), a degraded pasture of *B. humidicola* (Bh) and well managed pastures of *B. dictyoneura* alone (Bd) and in mixture with the legume *Arachis pintoi* (Bd+Ap). Standing root biomass in Bd (8.6 t/ha) was about 3 times that in NS (2.9 t/ha), reflecting the low growth rates reported for the savanna species (Fisher *et al.* 1992). NBPPs of the well managed pastures were 30.0 and 31.3 t/ha/yr for Bd and Bd+Ap, respectively, compared with only 12.5 t/ha/yr for NS. Turnover losses of Bd and Bd+Ap were 1.5–2.5 times those in either NS or Bh (Tables 2 and 3). The decomposition constant of roots of Bd was lower than that of either NS or Bd+Ap, which resulted in a longer residence time for Bd roots. The amount of NBPP remaining in the soil after one year of decomposition under well managed pastures was about 2.3 times that under NS.

In a complementary study, Trujillo *et al.* (2007) estimated macro-organic matter ($>150\ \mu\text{m}$, MOM) in the soil under the same pastures described above. They separated the MOM into light (LF), intermediate (IF) and heavy fractions (HF), using solutions of differing specific gravity, and analysed each fraction for C and N. The C:N ratios of the MOM fractions decreased in the order $\text{LF} > \text{IF} > \text{HF}$ in all pasture treatments (data not presented). While the MOM fraction in NS and Bh accounted for a small percentage (8%) of the total SOC pool, the contribution increased to 21% under Bd+Ap and 30% under Bd. Trujillo *et al.* (2007) concluded that the MOM represented only a small percentage of the total soil organic carbon pool, because it turns over rapidly as indicated by the decrease in C:N ratios as the density fraction increased. They further pointed out that the

¹ Soil carbon is often described as 'sequestered'. Since we do not know the exact form of the newly accumulated C, we prefer to refer to it as 'accumulated'. Where we quote from earlier work, in which the authors used the term 'sequester' and its derivatives, we have substituted the alternative of 'accumulate' enclosed in square brackets [].

Table 3. Mean net below-ground primary productivity (NBPP) of a native savanna grassland (NS) compared with well managed pastures of *Brachiaria dictyoneura* alone (Bd) and in association with the legume *Arachis pintoii* (Bd+Ap), calculated from a compartment-flow model. Data from Trujillo *et al.* (2005).

Parameter	NS	Bd	Bd+Ap
		(t/ha/yr)	
Change in live roots	3.14 b ^{1,2}	7.28 a	7.92 a
Change in dead roots	1.82 b	6.32 a	5.16 a
Amount of decomposition	7.50 b	16.41 a	18.26 a
Turnover	9.32 b	22.72 a	23.42 a
NBPP	12.46 b	30.00 a	31.34 a
Inputs of SOC ³	4.99 b	10.30 a	11.58 a

¹ Within rows, treatment means followed by the same letter did not differ significantly ($P>0.05$).

² The figure in Trujillo *et al.* (2005) is 1.92, which is a typographical error. The correct value is 3.14 (W. Trujillo, personal communication, January 29, 2007).

³ Soil organic carbon.

amount and C:N ratios of the LF were most sensitive to differences in soil depth, vegetation type and pasture management.

Relation between root mass and pasture health

Embrapa-Agrobiology have measured root mass under pastures in various states from productive to degraded. Degraded pastures in the Cerrados are commonly identified as having a discontinuous grass cover, invasion of shrubby and other weeds and many termite mounds. The data seem to show that root mass increases as fertility declines up to a critical point, after which there is a cataclysmic decline in root mass as the roots disappear and the area becomes infested with termite mounds. They speculate that the dead roots are feed for the termites.

In severely degraded pastures, root biomass is often far lower than in productive pastures. In a chronosequence of *B. brizantha* pastures near Goiânia, a 7-year-old pasture had a larger root-stock (10.4 t/ha DM to 100 cm) than either a pasture established 1 year before (5.2 t/ha DM) or a heavily utilised pasture established 9 years previously (4.6 t/ha DM, Figure 1, Renato, personal communication). A 20-year-old heavily degraded *B. decumbens* pasture showed the lowest root-stock of only 2.9 t/ha DM.

Oliveira *et al.* (2004) studied 3 pastures established under well controlled conditions at the Embrapa-Beef Cattle Centre near Campo Grande. The root-stocks to 40 cm were compared in a newly established pasture and two 13-year-old pastures (all *B. brizantha*), one of which had been well fertilised including additions of N, and one grazed without fertiliser application since

its establishment. The results showed that the unfertilised 13-year-old pasture had the highest stock of roots (Table 4).

A further study (R. Schunke, personal communication) at Fazenda² Ribeirão, Chapadão do Sul in a large grazing experiment with *B. decumbens* pastures regularly fertilised with P and K (but not N), showed that increasing stocking rate

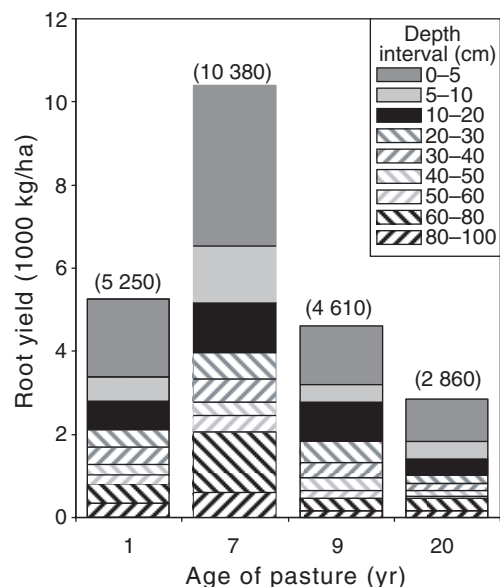


Figure 1. Root stocks in three *B. brizantha* pastures of increasing age and a 20-year-old degraded pasture of *B. decumbens*, Fazenda Barreirão, near Goiânia. Data are means of 4 replicates. Values in parentheses above the stacked bars are the total root stocks (kg/ha DM) to 100 cm. (Renato, personal communication).

² Fazenda is the Brazilian equivalent of the US ranch or the Australian station.

Table 4. Root biomass (t/ha) in soil under *Brachiaria brizantha* pastures at Campo Grande site. Data are means of 4 replicates.

Depth (cm)	Treatment		
	4 months	Fertilised	Not fertilised
0–10	3.2	8.3	12.2
10–20	0.7	1.9	2.4
20–40	0.7	1.9	3.1
Total in profile	4.6 b ¹	12.1 c	17.7 a

¹ Means followed by the same letter are not significantly different ($P>0.05$).

from 0.6 to 1.0 animal units/ha (1 AU = 450 kg live weight) had no significant effect on rooting density (g root DM/kg soil). A further increase to 1.4 AU/ha increased rooting density by approximately 50% (data not presented). These data suggest that, as soil fertility declines or demand on the pasture increases, initially the grasses increase their root mass, presumably to increase their capacity to capture nutrients from the soil. We hypothesise that finally the photosynthetic apparatus of the plants is unable to support such a large root system and there is a massive shedding of roots, leading to the low values typical of severely degraded pasture.

Oliveira *et al.* (2004) also monitored root biomass under a range of pastures at the Fazenda Barreirão near Goiânia (Table 5). A newly established pasture of *B. brizantha* showed a total root biomass to 40-cm depth of about 17 t/ha DM, which was very similar to a 4-year-old pasture at the same site. However, a 6-year-old pasture had more than double this root biomass (39.7 t/ha), while a 9-year-old pasture had only 11.4 t/ha. These are on-farm data and not from long-term experiments. Grazing pressure on the different pastures was not monitored nor was it necessarily the same for each pasture. Despite these limitations, the data are broadly consistent.

With the ongoing decline of pasture productivity, there may be important consequences of this behaviour of roots for the understanding of C accumulation under grazed pastures. While the application of generous levels of fertiliser to *Brachiaria* pastures almost certainly results in increased aerial productivity and allows increased stocking rates, root biomass may well be lower than in pastures that receive little or no maintenance fertiliser. This conclusion is certainly surprising, likely to be controversial, and needs con-

Table 5. Root biomass (t/ha) in soils under a chronosequence of recuperated *Brachiaria brizantha* pastures of different ages (5 months, 4, 6 and 9 years), Fazenda Barreirão, near Goiânia. Data are means of 4 replicates.

Depth (cm)	Pasture age			
	5 months	4 years	6 years	9 years
0–10	13.6	13.5	34.5	8.8
10–20	1.7	2.0	2.3	1.2
20–40	2.0	1.6	2.9	1.4
Total in profile	17.3 a ¹	17.1 a	39.7 b	11.4 c

¹ Means followed by the same letter are not significantly different ($P>0.05$).

firmation from long-term experiments and studies of root turnover, *i.e.*, NBPP.

A further conclusion would be that, for under-fertilised (or as is most usual, completely unfertilised) pasture, root biomass, and presumably inputs of C derived from roots, will increase with time. Root biomass should reach a peak, followed by a large deposition of dying roots as the system collapses. Under this hypothesis, the maximum rate of C deposition will occur at this time, but subsequently C stocks will gradually decline, and, if the area is not cultivated or fertilised, the C stocks will decline to levels below those originally present under the native vegetation.

The role of introduced grasses in C accumulation

Fisher *et al.* (1994) reported that African grasses introduced into the savannas of Colombia could accumulate organic carbon at depth in the soil compared with the native savanna vegetation. They reported that SOC from 0 to 80 cm depth in a grass-legume and a pure grass pasture exceeded that in savanna by 7.04 and 2.59 kg/m² C, respectively. More than 75% of the additional soil C was found below 20 cm, or below the plough layer. They concluded that 'this C should therefore be less prone to oxidation, and hence loss, during any cropping phase that might be undertaken in integrated crop and pasture systems. Indeed, such systems should be able to accommodate rotations with annual crops and still contribute to C [accumulation].'

Total amounts of SOC to 80 cm depth ranged from 19.7 kg/m² C under the native savanna to 26.7 kg/m² C under *B. humidicola*-*A. pintoi* grass-legume pastures (Fisher *et al.* 1994; Figure 2). These values of SOC represent the upper range for

tropical soils including Oxisols, which generally range from 2–22 kg/m² C (Moraes *et al.* 1995 and the references therein).

Tarré *et al.* (2001) reported the use of stable C isotope (¹³C) analysis to determine the source of soil C in the 20 years following clearing of the Atlantic forest vegetation at a site in southern Bahia state of east-central Brazil. Eleven years after clearing in 1977, *B. humidicola* was established and subsequently regularly fertilised with P and K. After 9 years of pasture, soil (Typic Paleudult) C levels under the original forest and under the sown pasture were similar, but the source of the C had changed, with 9 t/ha of the original C lost from the 0–30 cm layer and replaced with C derived from the sown grass. Stocks of soil C to 100 cm (corrected for compaction caused by grazing by calculating the C stock in a mass of soil equal to that under the forest–Neill *et al.* 1997) under the sown grass were not significantly different from those under the forest.

Where the legume *Desmodium ovalifolium* had been introduced into the sward, the mean rate of accumulation of soil carbon almost doubled from 0.66 to 1.17 t/ha/yr C. Although these rates are far lower than those reported by Fisher *et al.* (1994) on the Colombian Llanos, the results confirmed

the positive effect of the legume. However, the ¹³C abundance data showed that little C derived from *B. humidicola* was deposited below 40 cm depth. This suggests that, in this biome where rainfall is fairly evenly distributed throughout the year, *B. humidicola* did not root deeply. This contrasts with the deeper rooting of the same grass species in the Llanos of Colombia (Rao 1998), which has a higher annual rainfall (~2200 mm) than Bahia (~1400 mm), but also has a strong 3–4 month dry season.

Until recently, very few studies from the Cerrados region of Brazil had evaluated the impact of substituting pastures of *Brachiaria* spp. for native vegetation. Corazza *et al.* (1999) studied the soil C stock under a *B. decumbens* pasture established in 1976 on an Oxisol (49–59% clay) near Brasília. In 1982, a single crop of soybean was planted with intensive tillage and the pasture was then resown. The stock of soil C was found to be 150 t/ha to a depth of 100 cm, 16.6 t/ha C more than that under the cerrado *sensu strictu* community, although this may be an overestimate, as no correction was made for differences in soil bulk density in the 2 profiles (Neill *et al.* 1997).

Freitas *et al.* (2000) compared the stocks of C to 40 cm depth under the native vegetation and a productive and a degraded sown pasture on an Oxisol (36–46% clay) near Goiânia. They presented data for bulk density, but did not correct the data for equal soil mass between the 2 pastures. Recalculating the data shows that both sown pastures had less soil C than was originally present under the cerrado *sensu strictu* vegetation. The correction for compaction by grazing animals shows the importance of correcting for equal mass of soil in the profiles (Table 6).

A third, very recent study compared the soil C stocks under an area of cerrado *sensu strictu* vegetation and 6 areas of different forage species on an Oxisol at the Embrapa-Cerrado Centre near Brasília (da Silva *et al.* 2004). The area of native pasture, which was regularly grazed, contained 99.7 t/ha C to a depth of 100 cm. The carbon stocks, also to 100 cm, under:

- Grazed *Panicum maximum* established 7 years before sampling,
- A grazed mixed pasture of *Stylosanthes guianensis* with *B. brizantha* established 3 years before sampling, and
- Two ungrazed fields of *B. brizantha* and *Paspalum atratum* established 4 years before sampling and used for seed production,

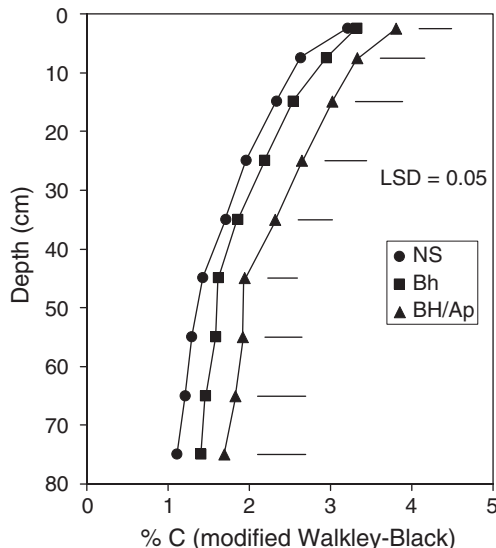


Figure 2. Soil organic C distribution by depth in introduced pastures of the grass *Brachiaria humidicola* alone (Bh) and with the legume *Arachis pintoi* (Ap) compared with native savanna pasture (NS) on a clay loam Oxisol at Carimagua on the eastern plains of Colombia. From Fisher *et al.* (1998).

Table 6. Carbon concentration, bulk density and C stocks (as presented and corrected for equal mass of soil) in an Oxisol (36–46 % clay) near Goiânia under cerrado *sensu strictu* vegetation compared with productive and degraded pastures. Means of 9 replicate samples per depth in each plot. Adapted from Freitas *et al.* (2000).

Depth	Carbon	Soil bulk density	Soil carbon stock (t/ha C)	
(cm)	(g/kg)	(kg/dm ³)	Presented ¹	Corrected ²
NVC Native vegetation of the Cerrado ³				
0–10	22.6	1.19	26.9	26.9
10–20	19.6	1.24	24.3	24.3
20–40	13.7	1.12	30.7	30.7
0–40	—	—	81.9	81.9
PP– Productive pasture				
0–10	22.0	1.10	24.2	25.6
10–20	16.1	1.32	21.3	19.9
20–40	10.8	1.33	28.7	24.2
0–40	—	—	74.2	69.8
DP–Degraded pasture				
0–10	19.0	1.10	20.9	22.4
10–20	16.4	1.23	20.2	19.9
20–40	12.2	1.23	30.0	27.3
0–40	—	—	71.1	69.6

¹ C concentration \times soil bulk density \times depth.

² Corrected for same mass of soil to 100 cm as under native vegetation (Neill *et al.* 1997).

³ The term used by Freitas *et al.* 2000; cerrado *sensu strictu* vegetation in the terminology we use here.

all showed significantly increased soil C stocks, which reached 110–113 t/ha C. No significant increase in C stocks was observed under a *B. decumbens* pasture, nor under a mixed legume-*Andropogon gayanus* pasture, both of which were grazed, but which had been established for only 3 years. Considering the short period of this study, and that soil C stocks are generally significantly reduced at the time of land clearing and pasture establishment, these data indicate a considerable potential for accumulation of soil C under productive pastures.

The source of the accumulated C

The C accumulated in the soil must originate in the C fixed by the pasture, that is, it must come from the pasture's NPP. Fisher *et al.* (1998) pointed out that, unlike the synchronised development of short-cycle annual crops, pastures have a continuous cycle of initiation, growth and death of individual units (tillers in grasses and branches in legumes). As the volume of herbage in a pasture increases, the rate of senescence and death of the older units also increases until finally they equal the rate of initiation of new units, leading to the so-called maximum yield that is commonly measured by agronomists and others.

Unless there is some environmental constraint (drought, nutrient deficiencies, pests or diseases) or the grasses flower, which they rarely do in well managed sown pastures under grazing in the central lowlands of tropical South America, primary growth probably continues at something close to the maximum measurable rate for the whole growing season. Fisher *et al.* (1998) estimated that yearly NAPP of *A. gayanus* on the Colombian eastern plains, where rainfall is abundant (~2200 mm annually with at least an 8-month growing season) and temperatures are uniformly high throughout the year, may be 4.3 kg/m². We emphasise that these conditions are for the central lowlands of South America and may not be typical of other regions with less favourable climates.

On the Colombian Llanos, Rao (1998) estimated standing root biomass during the growing season under grazing of introduced pure grass and grass-legume pastures at 570 and 380 g/m², respectively, compared with 140 g/m² for a native savanna. Root turnover in pure grass pasture was estimated to be twice and in grass-legume pasture 3 times that in native savanna. Based on these data, Fisher *et al.* (1998) concluded that, 'we can safely assume that roots turnover at about the same rate as above ground material, and apply that to the maximum measured yield of roots [to estimate NPP]'.

Fisher *et al.* (1998) then attempted to estimate C inputs to the soil of pastures under grazing,

assuming that plant dry matter is 40% C. They concluded that total C inputs from shoots and roots in a grazed pasture on the eastern plains of Colombia were likely to be about 2.6–3.2 kg/m²/yr. We can now draw together the experimental data of Rezende *et al.* (1999), Boddey *et al.* (2004) and Trujillo *et al.* (2005), discussed elsewhere in this paper, to obtain revised estimates of C inputs under grazed pastures. The data for litter fall of *B. humidicola* plus faeces return under the lower 2 stocking rates in the Itabela experiment were 3.1–3.2 kg/m². NPP of roots on the eastern plains of Colombia for the *B. dictyoneura* pasture was 3.0 kg/m². Summing these and converting them to C, we may safely estimate the total C inputs under reasonably well managed *Brachiaria* pastures to be about 2.4–2.5 kg/m²/yr, only slightly less than the lower end of Fisher *et al.*'s (1998) 'back-of-the-envelope' estimates. Moreover, because the present data come from widely distributed experiments, we can be confident that they apply more generally to the central lowlands of tropical South America.

Are there differences among tropical grass species?

All grasses that show a capacity to accumulate more C in soil than the native grasses are of African origin (Thomas and Grof 1986). Fisher *et al.* (1998) quoted data of sampling from pastures of *B. decumbens* in the Cerrados near Brasília that showed little or no C accumulation (J. Duxbury, personal communication; since rendered somewhat moot by the data of da Silva *et al.* 2004 summarised above). However, they added that, in the Llanos of Colombia at Carimagua Research Station, SOC accumulation to 100 cm depth in 13-year-old pastures of *B. decumbens* and *B. decumbens*-*Pueraria phaseoloides* was 25.6 and 34.1 t/ha C, respectively, greater than under native savanna vegetation.

Fisher *et al.* (1998) speculated that possible explanations for differences amongst species might be related to differences in the composition of litter, which in turn would affect their rates and patterns of decomposition. For example, the C:N ratios of leaf litter ranged from 88 for *B. decumbens* to 130, 126 and 117 for *A. gayanus*, *B. dictyoneura* and *B. humidicola*, respectively (Thomas and Asakawa 1993). Data from roots indicate a range of C:N ratios of 159–224 (Thomas, Ayarza and Celis, personal

communication), and although these differences were not reflected in short-term decomposition constants (Thomas and Asakawa 1993), they may affect longer-term decomposition and conversion to recalcitrant forms of SOC. Fisher *et al.* (1998) continued, 'The lower contribution of *B. decumbens*-based pastures to C [accumulation] may in part be explained by higher rates of decomposition of shoot and root litter of *B. decumbens* due to lower C:N ratios. Therefore the ability to [accumulate] C in soil may be species specific as noted for tree species (Sánchez *et al.*, 1985).' There does not appear to be any recent work that clarifies these speculations.

Demands on additional N supply

Fisher *et al.* (1998) discussed this issue in some detail, but because of the lack of data, much of it was speculation. We have summarised their arguments below. Boddey *et al.*'s (2004) paper on detailed studies of the N cycle of grazed pastures is broadly relevant to this topic, but they addressed the C cycle only indirectly. Boddey *et al.*'s (2004) paper, which gives understanding of the processes of pasture degradation, is discussed below in the section on grazing management.

Fisher *et al.* (1998) drew attention to anomalous C:N ratios of the soil organic matter under the grasslands of the Colombian eastern plains, which at 21.5 are much wider than the 10–12 found elsewhere (Schlesinger 1995). They pointed out that litter of introduced grasses in the sown pastures has extraordinarily wide C:N ratios (75–194 for above-ground litter and 158–224 for root litter), and that after only 9 years of a sown pasture on the eastern plains of Colombia, 6 of them with the legume *Arachis pintoii*, the C:N ratio to a depth of 80 cm had increased to 33.2. They concluded that further work was needed to develop an 'understanding of the processes of breakdown of plant material of high C:N ratios'.

Fisher *et al.* (1998) went on to speculate on the possible source of N to allow the accumulation of C at depth in the soil. By using known inputs of N from the legume component and associative fixation to be 200 kg/ha/yr N in grass-legume pastures and 40 kg/ha/yr N in pure grass pastures, they reasoned that the C:N ratios of the newly acquired SOM must be around 200, which is close to the values of the root and shoot litter. They concluded that this 'suggests that the

newly-acquired SOM is particulate plant material. How it gets to depth in the soil is unknown at present, but deep rootedness is a clear possibility'. Boddey *et al.*'s (2004) study on N cycling in grazed pastures, discussed below, is broadly consistent with this conclusion, although they did not address the issue of C:N ratios of SOM.

Relationship with soil moisture

Fisher *et al.* (1998) quoted Brown and Lugo's (1982) study of tropical forest soils, in which they reported a positive relationship between the amount of soil C and moisture, which was also associated with different plant communities and soil types. They further concluded that, 'Soils in wet climates exhibited greater variations in soil C content with changes in land use, in terms of both loss and recovery, than did soils in dry climates (Lugo and Sánchez, 1986).' There have been no recent studies that provide further evidence on this topic.

Management options to increase C accumulation

Introduction of forage legumes to improve N supply

In pure grass pastures on the eastern plains of Colombia, the amount of C accumulation is remarkably constant at about 3 t/ha/yr, and is 2.5–5 times this rate with a legume component (Fisher *et al.* 1994). The constant rate of C accumulation by pure grass pastures suggests that the process is rate-limited, and the increased rate with a legume suggests that the limitation is N. If this is so, sowing a legume component in pastures will clearly increase their capacity to accumulate C. If there is a new equilibrium value for the maximum amount of C that can be accumulated in the soil, increasing the rate of accumulation will mean that the equilibrium value will be reached sooner. However, the new equilibrium value is unknown, so that the role of increasing the rate is uncertain. There are other options to increase the N supply to a pure-grass pasture, such as application of modest amounts of N fertiliser and seeking means to increase associative N fixation (Fisher *et al.* 1998). The same arguments would also apply to them, except that there is a C cost in producing N fertiliser.

Use of fire

Much of the native tropical grasslands or savannas (as opposed to sown grasslands) are burned as frequently as annually, and they are rarely fertilised. Therefore, Long *et al.* (1992) suggested that soil C is at an equilibrium that is less than it would be if pastures were not burned and if some fertiliser was applied. Greenland (1995) hypothesised that, with these simple management options, the tropical savannas could be an even greater sink for C than is presently forecast. However, it is doubtful whether traditional sedentary or nomadic users of tropical grasslands would change their management practices without some strong economic incentive to do so. It is outside the scope of this paper to discuss the topic further.

It is worth noting that introduced pastures are rarely burned, except by accident, at least until they have become seriously degraded and invaded by undesirable woody weeds.

Increased activity of soil macro-fauna

Lavelle *et al.* (1994) pointed out that pastures usually have greater populations of soil invertebrates than other forms of land use and that these organisms require significant amounts of energy. An active earthworm community may consume the equivalent of 1.2 t/ha/yr C (Lavelle 1996), although, given the data that we quote in this review, this is only about 5% of NPP of a well managed *Brachiaria* pasture. On the other hand, Martin (1991) determined that rates of carbon mineralisation in earthworm casts may be 70% less than that of the bulk soil. In the acid soils of the eastern plains of Colombia, mass of soil macro-fauna in pastures of *B. decumbens* was 5 times, and in *B. decumbens*-*P. phaseoloides* was 10 times, (up to 60 g/m², Decaens *et al.* 1994) that in the native savanna. Earthworms dominate the soil fauna population and can ingest up to 10 times their body weight in soil each day, leading Fisher *et al.* (1998) to calculate that, within 3 years, 60 g/m² of earthworms have the potential to pass the whole of the soil volume to 1 m depth.

Fisher *et al.* (1998) postulated that earthworms must have considerable impact on the processes for moving C from the surface to depth in the soil, although there are no data to determine whether they are the only vehicle or whether other

processes are involved. It is known that earthworm casts have substantially different properties from the bulk soil, with more water-stable aggregates due to cementing of the soil particles (Guggenberger *et al.* 1996). Fisher *et al.* (1998) concluded 'We do not know for example if the benefits brought by earthworms in terms of soil improvement (*e.g.*, macro-aggregation, nutrient cycling) and hence increased NPP of the pasture, will outweigh the costs, in terms of carbon, of supporting the activity of earthworms. Available evidence indicates differences depending on the fauna species that dominate the populations (Lavelle *et al.*, 1994).' In this regard, Decaëns *et al.* (1999) showed that the casts of the large aneic (surface-feeding) earthworm *Martiodrilis carmaguensis* can account for the accumulation of as much as 8.6 t/ha/yr C.

Grazing management

Most studies on grazed lands have focused on aspects of animal production, herbage production and utilisation with little attention being paid to impacts on the soil resource base (Fisher *et al.* 1998). Fisher *et al.* (1998) concluded that results of evaluations of the effects of grazing on SOC are inconsistent, both increases and decreases being reported with increased grazing pressure, and that many factors are involved in the response of SOM to grazing (soil type, sward type, nutrient status *etc.*). They further asserted that there is a need to develop an indicator or some parameter of system state that reflects the overall result of the different factors involved in determining actual or potential C accumulation. They speculated that the concept of sward 'steady-state' as described by Hodgson (1990), which can be used to optimise growth, productivity and senescence in terms of a simple measurement of sward height in temperate ryegrass pastures, might be used in tropical pasture systems. They thought that such an estimate of sward state could be linked to the concept of Spain *et al.* (1985) in terms of the management of tropical pastures within a 'grazing envelope', which ensures sustainability of production and could optimise net accumulation of SOC. They added that 'This work is in its infancy for tropical pastures and requires much more attention.'

From the few investigations that have been performed, and from a theoretical point of view, it is evident that, if pasture productivity declines,

which almost invariably occurs because landowners rarely apply maintenance fertiliser and frequently overgraze their pastures, soil C stocks will be reduced. To this end, Embrapa-Agrobiology are engaged in studying soil C stocks under *Brachiaria* pastures of contrasting productivity compared with those under neighbouring native vegetation.

It is extremely difficult rapidly to assess the productivity or 'degree of degradation' of pastures. Traditional soil fertility analysis does not reveal the difference between productive pastures and even those in a fairly advanced state of decline. Lilienfein *et al.* (2003) made an intensive comparison of soil properties between 3 sets of areas of native vegetation, productive pastures and degraded pastures, all within an area of 100 km². They sampled the soil solution at 5 depths (5 replicate suction cups per depth) down to 2.0 m at weekly intervals through 2 wet seasons (October–April). All samples were analysed for P, K, Al, Ca, Mg and Na as well as Fe, Mn, Zn, NH₄⁺, NO₃⁻, total organic C and total S. There were no significant differences in the concentrations of these various elements/ions between the productive and degraded pasture with the exception of Ca, K and Mg. The authors suggested that the higher grass productivity in the productive pasture was due to the significantly higher concentrations of these 3 nutrients and concluded that maintaining constant productivity 'requires the regular application of Ca, K and Mg.'

This conclusion contrasts strongly with the consensus amongst pasture agronomists working in the Cerrados that N and P are the 2 nutrients that principally limit pasture growth in this region (Carvalho *et al.* 1990; Zimmer and Correa 1993; Macedo 1995). In Lilienfein *et al.*'s (2003) study, P and NH₄⁺ concentrations in the soil solution were below the limits of detection of their analytical techniques (0.2 and 0.05 mg/L, respectively) as were many analyses of NO₃⁻ (limit 0.01 mg/L). Furthermore, there was no significant difference between the productive and degraded pastures for the measurable values of NO₃⁻ in the soil solution.

Oliveira *et al.* (2004), working on a chronosequence of pastures of 2, 4, 7 and 17 years of age, could not rank their state of productivity using traditional analysis of either soil fertility or plant tissue. While soil mineral N was not evaluated, available P (Mehlich-I) in the soil under all pastures was at 1.0 or less mg/kg.

However, these same authors had previously shown at 3 different sites in the Cerrados that, while degraded pastures did not respond to P, K, S or micronutrient fertilisers and responded weakly to N application, most responded strongly when N was supplemented with P or full fertilisation with NPKS and micronutrients (Oliveira *et al.* 2001). In summary, these results vindicate the belief that generally P and N deficiency are the principal causes of pasture decline (Boddey *et al.* 2004), and furthermore the extremely high affinity of the dense mat of roots for P, NO_3^- and NH_4^+ means that, even in productive pastures, the concentrations of these elements/ions in the soil solution are extremely low, as they are absorbed by the roots as soon as they become available from mineralisation of soil organic matter.

The lack of simple analytical tests for evaluating the relative productivity of *Brachiaria* pastures on-farm was a major obstacle in the effort to determine the effects of pasture productivity on soil C stocks at a farm level. Cattle farmers often cannot provide accurate information on grazing history, as they normally rotate their animals through many paddocks during a single season. For this reason, Oliveira *et al.* (2004) investigated dynamic/biological indicators of the state of decline/degradation of pastures in the Cerrados. Their best indicators of pasture health, which should preferably be used together for more certainty in the assessment, were:

- rate of regrowth after cutting,
 - rate of litter fall after clearing all litter from the soil surface,
 - microbial biomass C, and
 - light-fraction of the soil organic matter,
- which is consistent with Trujillo *et al.*'s (2007) conclusions.

The work now in progress at Embrapa-Agrobiologia will examine different chronose-

quences of productive and degraded pastures on neighbouring areas for their apparent productivity using these indicators, and C and N stocks to a depth of 1 m and to identify the origin of the soil carbon (derived from C_3 native vegetation or from the C_4 *Brachiaria*) by evaluating the ^{13}C natural abundance of the C at each sampling depth.

Preliminary results are now available for 2 of these sites:

a) Fazenda Palota (soil 80% clay), near Luz in Minas Gerais state, and

b) Fazenda Ribeirão (soil 18% clay), near Chapadão do Sul in Mato Grosso do Sul state.

Both regrowth after cutting to a height of 5 cm and the rate of litter deposition were measured after 28 days (Table 7). The results confirmed the initial classification of the productivity of the pastures at both sites.

At Fazenda Palota, the area had been used for growing coffee since the 1930s and subsequently for extensive grazing, probably of *Hyparrhenia rufa* and *Melinis minutiflora*. While these grasses (also African introductions) are much less vigorous than *Brachiaria* spp., they are also C_4 and so have high ^{13}C abundance similar to *Brachiaria* spp. The productive pasture (*B. brizantha*) was established in 1995 with tillage and the application of lime and P fertiliser on an area that had been under *B. decumbens* since the 1970s. The area sampled was only lightly grazed and used as a reserve of forage in the dry season. The degraded pasture (*B. decumbens*) was established in an area of *H. rufa* and *M. minutiflora* in 1995, immediately after a crop of limed and fertilised upland rice, but was heavily grazed and at sampling had been heavily invaded by weeds. The soils were sampled in 2003.

The C stocks differed markedly between the vigorous and the degraded pasture, being 164.6 and 138.0 t/ha C (corrected for equal mass of soil to 100 cm depth under the native vegeta-

Table 7. Forage re-growth and litter deposition in putative productive and degraded pastures at two sites in the Brazilian Cerrados. Means of 4 replicate plots per pasture.

Site	Forage re-growth		Litter deposited on soil surface	
	Productive pasture	Degraded pasture	Productive pasture	Degraded pasture
	(g /m ² DM in 28 days)			
Fazenda Palota, Luz, MG	264** ¹	119	37*	27
Fazenda Ribeirão, Chapadão do Sul, MS	235ns	206	114**	35

¹ ** P<0.01, * P<0.05, ns P>0.05.

tion, whose C stock was 117.0 t/ha). The distribution of the C derived from the native vegetation and from the *Brachiaria* pastures for the 2 pastures and the native vegetation is shown in Figure 3.

At Fazenda Ribeirão in both pasture areas, the native vegetation was originally cleared at the start of the 1980s and sown to *B. decumbens*. The productive pasture is on an area that was cropped to soybean in 1991–94, and then sown to *B. brizantha* that is well managed. The degraded pasture was an area, which remained in *B. decumbens* with indifferent management.

The C stocks (0–100 cm) under these 2 pastures were, respectively, 62.6 and 53.1 t/ha C, the latter under the degraded pasture being lower than that under the neighbouring native vegetation (57.1 t/ha C). Distribution of the C derived from the native vegetation and the *Brachiaria* down the profile for the 2 pastures and the native vegetation is shown in Figure 4.

Three tentative conclusions can be made from these preliminary results:

1. Productive, lightly grazed pastures on soils high in clay content can eventually accumulate considerable quantities of soil C, well above the stocks under the cerrado *sensu strictu* vegetation.
2. Under productive pastures, considerable quantities of C can be stored at depth, as deep as 100 cm.
3. When pasture productivity falls due to lack of maintenance fertiliser and inappropriately heavy grazing, C derived from the grass is lost and appears to be almost entirely eliminated from depths greater than 40 cm.

Grazing management and pasture degradation

Pasture degradation, which is widespread on the Cerrados, has a profound influence on soil C stocks. Fisher and Thomas (2004) attempted to estimate the total contribution of introduced pastures in the tropical lowlands of tropical South America. They included the Amazon, which is not relevant to this review, so comments will be

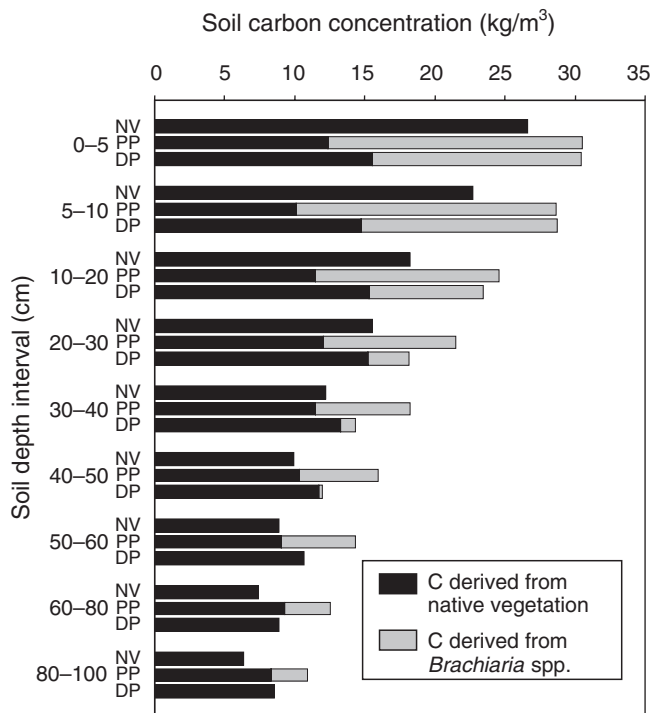


Figure 3. Carbon derived from C_3 native savanna vegetation and from C_4 *Brachiaria* spp. in a stand of cerrado *sensu strictu* vegetation (NV) compared with a productive *B. brizantha* pasture (PP) and a degraded *B. decumbens* pasture (DP). The soil has 80% clay and NV has 117.0 t/ha C to a depth of 1 m. Data are means of 4 replicates. Fazenda Palota, near Luz in Minas Gerais state. Note that the scale of the abscissa is about twice that of Figure 4.

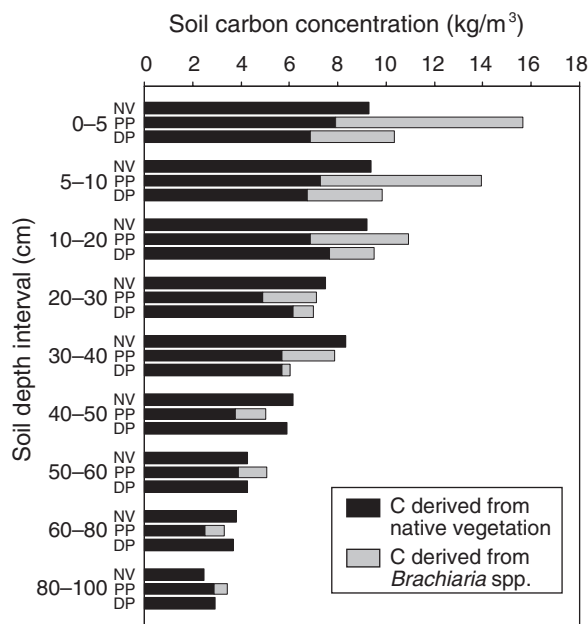


Figure 4. Carbon derived from C_3 native savanna vegetation and from C_4 *Brachiaria* spp. in a stand of cerrado *sensu strictu* vegetation (NV) compared with a productive *B. brizantha* pasture (PP) and a degraded *B. decumbens* pasture (DP). The soil has 18% clay and NV has 57.1 t/ha C to a depth of 1 m. Data are means of 4 replicates. Fazenda Ribeirão, near Chapadão do Sul in Mato Grosso do Sul state. Note that the scale of the abscissa is about half that of Figure 3.

limited to the Cerrados and the Orinoco basin of Colombia and Venezuela. They used the figure of 0.44 M km², recently updated to 0.50 M km² (Sano *et al.* 2000), of the treeless grasslands of the central lowlands that have undergone substantial conversion from the native vegetation to pastures, mainly *Brachiaria* spp., in the last 30 yr. By using the extensive descriptions of the land systems of the central lowlands of Cochrane *et al.* (1985), they extrapolated data for C accumulation in the soil under introduced pastures on the eastern plains of Colombia (about 3 t/ha/yr C) to similar soils and topography elsewhere to estimate the probable change in C stocks as a result of conversion to pasture in the grasslands as a whole. They pointed out that losses of above-ground C on conversion of the former treeless grasslands are negligible.

Fisher and Thomas (2004) addressed the issue of pasture degradation, and by using a simple model of a declining ramp function (Figure 5) to calculate mean rate of C accumulation for a number of scenarios, they calculated a 'degradation index' (DI). DI is the time-averaged amount of C accumulated in pastures that degrade and are recuperated compared with well managed pas-

tures that do not degrade, expressed as a percentage. They concluded that, if pastures were recuperated soon after they degraded, they probably accumulated as much as 50% of the C of a well managed pasture (DI=50), and that 'It requires draconian mismanagement of rapid degradation and long-delayed renovation for the [DI] to fall below 30.'

Fisher and Thomas (2004) estimated the mean time since land conversion started in the tropical lowlands and discounted the calculated C accumulation with a mean DI of 50. They concluded that introduced pastures on the former grasslands have been a net sink for about 900 Mt C. Although there were many uncertainties in the study, the authors detailed all assumptions made. With more reliable data, the study can be readily updated.

Although only broadly concerned with soil C, a recent paper by Boddey *et al.* (2004) gives the first definitive understanding of the processes involved in pasture degradation. Since degradation so profoundly affects soil C, it is appropriate to discuss it in some detail here. Boddey *et al.* (2004) studied the effect of increasing stocking rate on the fluxes of nitrogen (N) though the

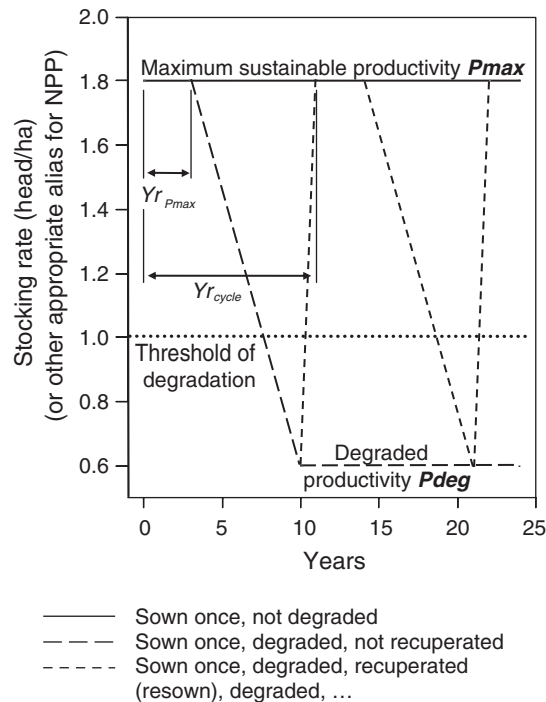


Figure 5. A conceptual model of pasture degradation expressed in terms of stocking rate of beef cattle. The pasture is assumed to remain at its maximum productivity P_{max} for $Yr_{P_{max}}$ years and to decline linearly to a degraded state whose productivity is P_{deg} at which stage it is recuperated and returns to productivity P_{max} , which completes the cycle of Yr_{cycle} years. The cycle is then repeated. The time-averaged productivity is the integral of the area under the curve over the period Yr_{cycle} . From Fisher and Thomas (2004).

animal (forage consumption, production of faeces and urine) and through the plant pathways of growth and senescence in *B. humidicola* pastures grazed by beef cattle in the Atlantic forest region of the south of Bahia state in Brazil. The experiment was the same one reported in the study of NAPP by Rezende *et al.* (1999).

As stocking rate increased from 2 to 4 head/ha, liveweight gain decreased from 153 to 120 kg/head/yr but overall weight gain per hectare increased from 305 to 360 kg/yr. N exported in the animal weight gain increased only from 7.3 to 8.6 kg/ha. Pathways of N cycling were radically changed by increasing the stocking rate from 2 to 4 head/ha (Figures 6 and 7). Total N consumed by the animals increased from 94 to 158 kg/ha/yr, which resulted in increases in N deposited as urine and dung in the pastures from 50 to 90 and 37 to 59 kg/ha, respectively. N in plant litter deposited on the soil decreased from 170 to 105 kg/ha.

A large proportion of the animal excretions was deposited in rest areas and around drinking troughs, where the grass was so trampled that it could not take advantage of the N and other nutrients they con-

tained. Data from complementary studies showed that N losses from urine could be 35–80%, being much higher in areas without vegetation. Boddey *et al.* (2004) concluded that pasture decline is hastened by increasing stocking rates because of these losses of N and the decrease in N and other nutrients available for grass growth over the pasture as a whole.

Fertiliser management

In small plot experiments referred to above (Oliveira *et al.* 2001), conducted at 3 widely separated sites in the Brazilian Cerrados on degraded pastures of either *B. decumbens* or *B. ruziziensis*, there were no growth responses to P, K or S, alone or in combination, in the absence of N, nor were there more than minor responses to N alone. However, the application of NPK fertiliser with micronutrients gave good recovery, suggesting that pastures may be rejuvenated by the use of chemical fertilisers alone. Moreover, one can conclude that the cause of degradation in the first place is principally nutrient deficiency.

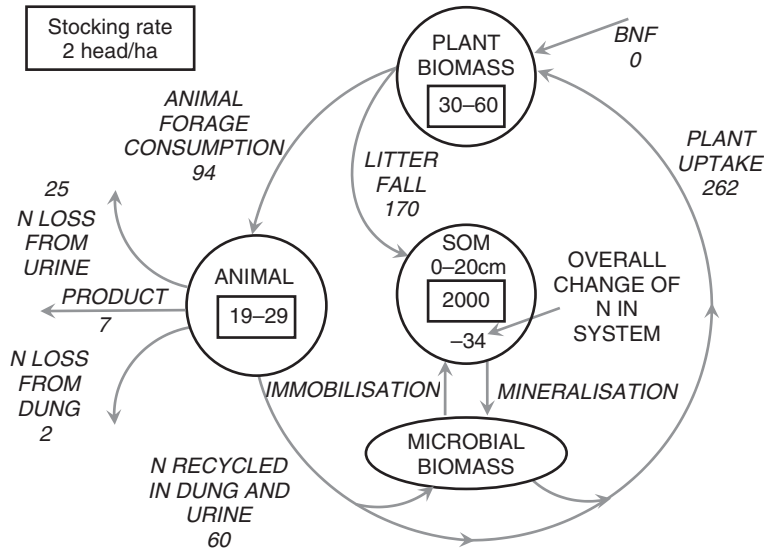


Figure 6. Schematic diagram of the nitrogen cycle in a *B. humidicola* pasture grazed by crossbred Zebu steers at a stocking rate of 2 head/ha. Values in rectangular boxes are pool sizes (kg/ha N) and other values are annual fluxes of N in kg/ha/yr. SOM is soil organic matter. Redrawn from Boddey *et al.* (2004).

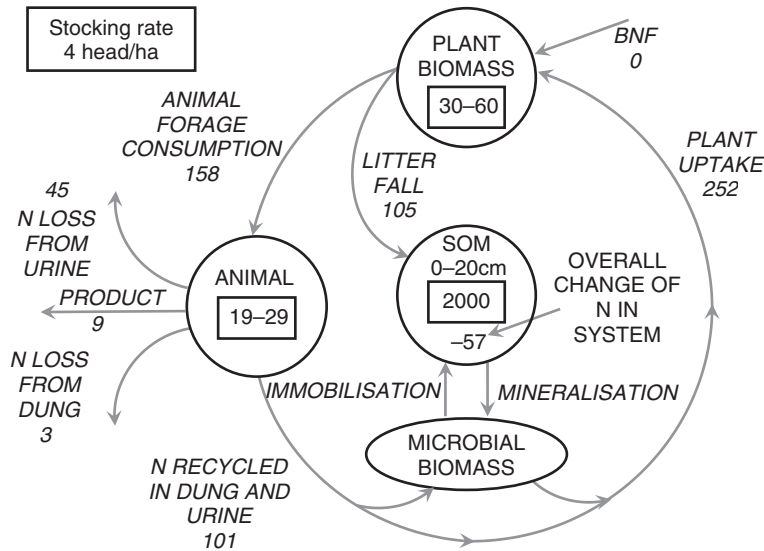


Figure 7. Schematic diagram of the nitrogen cycle in a *B. humidicola* pasture grazed by crossbred Zebu steers at a stocking rate of 4 head/ha. Values in rectangular boxes are pool sizes (kg/ha N) and other values are annual fluxes of N in kg/ha/yr. SOM is soil organic matter. Redrawn from Boddey *et al.* (2004).

Very little fertiliser is applied to sown pastures in the neo-tropical savannas. In contrast, in mixed agro-pastoral systems, fertiliser is applied to crops, which need higher levels of fertility than do pastures. The pastures can then make use of the residual fertility from the cropping phase (Thomas *et al.* 1995). In this context, it is

the crop, not the pasture, that bears the financial and environmental costs. As Fisher *et al.* (1998) noted, ‘In agro-pastoral systems, then, the use of fertilizer to increase both agricultural production and C accumulation may be economically viable and a “win-win” option.’

Summary and Conclusions

In the 7 years since Fisher *et al.* (1998) reviewed the questions of carbon accumulation by introduced pastures on the acid soils of the grasslands of the central lowlands of tropical South America, a considerable amount of work has been done to overcome the uncertainties and fill the knowledge gaps they identified. We know now that:

- litter is a key component of net aerial primary productivity that was previously seriously underestimated,
- the NAPP of introduced African grasses in the tropical lowlands of South America is much higher than previously thought,
- NBPP is about three-quarters of NAPP, data that were previously only surmised, and
- pasture health is a key component of C accumulation in the soil and degraded pastures in general have soil C stocks little different from the native vegetation that they replace.

On the other hand, well managed pastures of *Brachiaria* species almost always have more soil C than native vegetation communities. Soil C accumulation under introduced pastures in Brazil is substantial, but a maximum of half that measured on the eastern plains of Colombia. To date NAPP on the Colombian eastern plains has not been measured, so we can only speculate that climatic differences may be responsible. The eastern plains of Colombia have uniformly high temperatures throughout the year, in contrast with southern Bahia, which has a cool season during April–October.

We have gained valuable insights into the reasons for pasture degradation, which is so common in introduced pastures in the central lowlands of tropical South America. It is primarily caused by over-utilisation of the pasture, which fundamentally alters the nitrogen cycle. We conclude that this is not an inevitable process, but with judicious application of fertiliser and prudent grazing management it could be averted.

It seems possible to rejuvenate degraded pastures simply by the application of fertiliser, although at present we do not know how widely useful this may be. However, there may be a requirement to recuperate pastures periodically in some version of the ley-farming practices of temperate systems. These so-called agropastoral systems have received attention in the last decade and appear to be as successful on the tropical lowlands as they are elsewhere (Guimarães

et al. 1999). There are no definitive data of their impact on C accumulation in the soil, but by recuperating a vigorous pasture it should be substantially positive.

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