

Harry Stobbs Memorial Lecture

Carbon sequestration: Science and practicality

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Abstract

Tropical grasslands are environmental resources that play a critical role in the water resources of large areas of the tropics, and offer other environmental benefits such as carbon offsets.

Introduced pastures of African grasses on the eastern plains of Colombia accumulate large amounts of C in the soil. Net aerial primary productivity (NAPP) is 33.3–33.5 t DM/ha/yr in well-managed pastures of introduced grasses without either an associated legume or N fertiliser. NPP below ground is only slightly less. Replacing lowly productive native pastures is a massive intervention and C accumulates because of the increase in NPP. This accumulation will continue until a new equilibrium is reached. In Africa, introducing a legume component is a possibility for increasing both production and C storage, but there are few examples. African grasses sown in Australia are generally different from those in South America and legume technology has received general adoption in Australia. In Brazil, the widespread pasture degradation can be reversed by a rotation of several crops followed by a pasture phase, with minimal C cost.

Measuring soil C by soil sampling and soil analyses makes little economic sense in the context of trading soil C. A suitable proxy for soil C might be liveweight turnoff, supplemented where necessary by soil analyses.

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Introduction

In 1998, my colleagues and I (Fisher *et al.* 1998) collated published data and anecdotal reports to answer some of the questions raised by our finding (Fisher *et al.* 1994; 1995) that introduced pastures of African grasses on the Colombian eastern plains accumulated large amounts of C in the soil. Two years ago, we collated subsequent work in Colombia and Brazil that answered some of the questions and speculations of that earlier review (Fisher *et al.* 2007). In the 2009 Harry Stobbs Memorial Lecture, I presented data from both the 1998 and the 2007 reviews, and it is inevitable that a good deal of the text in this paper, which is based on the Lecture, will be paraphrased from the Fisher *et al.* (2007) review. I will introduce some new data showing that the importance of tropical grasslands as environmental resources is much greater than commonly thought. In addition, I will suggest some possibilities for trading the ecological services (Constanza *et al.* 1997) that grasslands can provide.

Although this paper can stand on its own, I refer the reader to the more comprehensive reviews (Fisher *et al.* 1998; 2007) for discussion of the topic in more depth, in particular the mechanisms of C accumulation, net primary productivity (NPP) and the role of N cycling.

The tropical grassland resource

Grasslands cover about one-fifth, 3.4 billion (10⁹) ha, of the world's land surface (Hadley 1993; FAO 1993), with about 1.5 billion ha in the tropics, of which Pearson and Ison (1987) considered 0.7 billion ha to be 'improvable grasslands'. There are some improbable claims for the total area of tropical grasslands. For example, "... tropical grasslands, which cover 50% of the earth's surface, are as important as forests for the sequestration of carbon" (Mannetje *et al.* 2008, back cover, my emphasis). A moment's thought

will show that 50% cannot be correct; the numbers above indicate the correct figure is about 9%. Few global-change experts would accept the remainder of the claim (see Watson *et al.* 2000 for a global analysis of land use, land-use change and forestry).

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 he used to obtain this estimate. In contrast, 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, and the data on soil C stocks presented below, also to a depth of 1 m, are 2–3 times Houghton's figure.

Tropical grasslands are environmental resources that rarely receive the attention they deserve. For example, in the water accounts of 10 tropical river basins studied in the Basin Focal Projects of the CGIAR Challenge Program on Water and Food, grasslands are the major water user in 8 of them (Indus, Karkheh, Limpopo, Niger, Nile, São Francisco, Volta and Yellow); the only exceptions are the Mekong and the Ganges (Figure 1). Not only do grasslands play a

critical role in the water resources of large areas of the tropics, but they also offer the possibility of providing other environmental benefits such as carbon offsets.

Given that grasslands in these river basins use more water than other land uses, it follows that they make a disproportionate contribution to the quality of the runoff in those basins as well. Indeed, as long as they are not degraded (unfortunately not certain), we can safely assert that they make positive contributions to water quality compared with agricultural land uses. Both natural and introduced grasslands are vulnerable to mismanagement worldwide, however, and in many places the causes are complex. Claret and Ogilvie (2009) give some interesting insights into the situation in the Volta basin of the sub-Saharan, where social conflicts and institutional weaknesses are key components. At least one component of the war and misery in Darfur is the conflict between migrant herders and sedentary farmers (Economist 2009). A complete discussion of this topic is outside the scope of this paper.

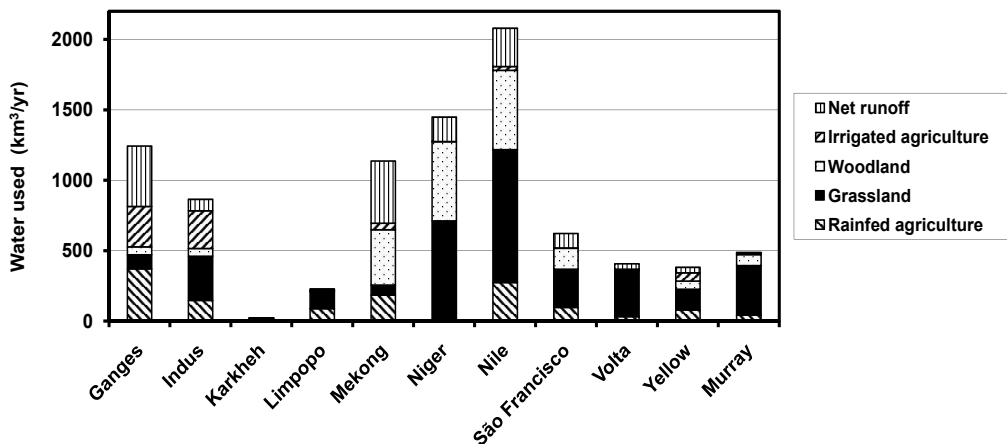


Figure 1. Water consumption by various land uses in 10 river basins (Kirby *et al.* 2009), with the Murray-Darling included for comparison (M. Kirby, personal email communication March 19, 2009). Consumption in the Karkheh Basin is a little over 24 km³/yr (grassland 50%). The data do not represent a complete water accounting; in particular they do not include evaporation or seepage losses, notably from the Akasombo Dam on the Volta, the Aswan Dam on the Nile or the Sud and Inland Delta wetlands on the White Nile and the Niger, respectively. Lake Volta loses about 6 km³/yr (Condappa *et al.* 2009), while Lake Nasser loses 7–20 km³/yr depending on the level of the Lake (Sutcliffe and Parks 1999). The data for the Murray-Darling were from different sources and so should be treated with caution.

Carbon accumulation

I caution that the term *C sequestration* is used very loosely in the literature, and usually *C stocks* and *C accumulation* would be more accurate terms for what is described. In the case of forests, for example, the C stored remains only until the forest is logged, which is occurring widely in the tropics. Unless one has identified the soil fraction with which the accumulated soil C is associated, one cannot assume that any additional accumulation has indeed been "sequestered", that is, become part of either the slow or the passive pools. In the case of pastures on the Colombian Llanos, the newly accumulated organic matter had C:N ratios greater than 30 compared with the normal ratio for humus of about 10–12. Although this was only indirect evidence, it suggested that the new organic matter was probably particulate plant material. Its residence time would therefore be uncertain, although at depths greater than 20 cm, where we measured 70–86% of the accumulation (Fisher *et al.* 1994), it would probably be less labile than material in the surface horizons.

The C accumulated in the US Conservation Reserve Program, which costs the US taxpayer US\$ 1 billion/yr, was proposed *inter alia*, as a "C-sequestration" activity. Most of the C accumulated in these soils is in the top 7.5 cm, rarely as deep as 20 cm (see, for example, Huggins *et al.* 1998). It will remain only until the land is cultivated to grow corn for ethanol in the biofuels program, which emphasises the importance of perverse incentives.

We need to know what management options can increase the potential of tropical pastures as an important C sink to reduce atmospheric C levels. When we reviewed the situation in 1998, we did not know the areal extent of C accumulation under pastures in the South American savannas, nor did we know the mechanisms in the soil-plant system by which it occurs (Fisher *et al.* 1998). I discuss this aspect below.

In considering the potential for grasslands to accumulate C, the important issues are the baseline (from where do we start?), the rate of accumulation and what controls it, permanence (how long will it be there?) and leakage (will the old activity, such as deforestation or agriculture, be transferred elsewhere?).

On the face of it, the concept of a baseline is straightforward. If establishment of the new system requires destruction of the C in the

present vegetation (and soil), the store of C in the new system will have to be discounted by that amount. This raises the issue of when the baseline should be established.

In considering baselines in the context of the South American savannas, where land-use change is likely to continue for many years, we need to know what the native savanna vegetation was. The vegetation communities of the savannas in South America are dominated by the *Cerrados* of central Brazil, which cover 205 M ha. Of these about 50 M ha are virtually treeless in the *campo limpo* and *campo sujo*. The remainder is mostly covered by low scrubby vegetation (*cerrado sensu situ*), although it is a continuum to the closed woodland of the *cerradão*, typical of Cuiabá in Mato Grosso state. The savannas of Colombia and Venezuela cover 32 M ha and are virtually treeless.

In the Australian context, it is undoubtedly intellectually challenging to attempt an historic census of soil C, but apart from the academic interest, it is irrelevant to C trading. The important data are current levels of soil C and how these might be increased to offset C emissions. The Australian Greenhouse office carbon programme is undertaking a massive inventory of soil C over the whole of Australia.

Any system of consistent long-term management is likely to be more-or-less stable, at least as far as pastures are concerned. Any losses as a result of changing land use (= clearing, ring-barking) occurred long ago and in most cases we can accept the current status as the baseline. Note, however, that many cropping systems, such as on the US Great Plains, continue to lose soil C, even though more than 30% of the soil C that existed, when cultivation started about 100 years ago, has already been lost (see, for example, Paustian *et al.* 1996). Change from continuous arable systems to minimum- and zero-till and pasture-ley systems can have a spectacular effect by greatly increasing C inputs in cropping systems (Peterson *et al.* 1998). Since the theme of this paper is pasture systems, I shall refer to cropping systems again only when they are relevant to pastures.

Soil C status may be thought of as a simple balance sheet. If inputs exceed losses, soil C will accumulate, but if inputs are less than losses, soil C levels will fall. Pasture systems that have been under constant management for many years are likely to be in dynamic equilibrium; dynamic

because of fluctuations caused by seasonal differences. For a system in dynamic equilibrium to accumulate C, some change in management that will either increase inputs or decrease losses will be required. In long-term, stable pasture systems, there are probably few opportunities to do either.

Increasing the C inputs to a system can cause soil C to increase, but the process cannot continue in perpetuity and sooner or later a new equilibrium will be reached. The question is: what controls that new equilibrium? In our tropical pasture systems, I know of no data that give a definitive answer.

Net primary productivity

Individual units of a pasture (tillers in grasses and branches in legumes) have a continuous cycle of initiation, growth and death. As the amount of herbage in a pasture increases, the rates of senescence and death of the older units also increase, until finally they equal the rate of initiation of new units, leading to the so-called maximum yield that is commonly measured. This methodology was enshrined in the International Biological Programme (IBP) (Milner and Hughes 1968).

The pasture continues to grow, however, unless it is constrained by nutrient deficiency or drought. Therefore, net primary productivity (NPP) is substantially higher than maximum yield. Long and his colleagues (Long *et al.* 1989; 1992) showed that, by ignoring mortality of above- and below-ground organs, the IBP methodology underestimated NPP by as much as 5-fold. Subsequently, Rezende *et al.* (1999) found the half-life of litter in their *Brachiaria humidicola* pastures in central coastal Brazil was only 9–20 days. Accounting for this rapid decay of litter gave annual above-ground NPP of 30–36 t/ha DM, or 3 times greater than the highest NPP that Long *et al.* (1989; 1992) estimated.

Studies of root turnover on the eastern plains of Colombia showed similar below-ground NPPs (Trujillo *et al.* 2005). Total potential NPP of pastures of introduced African grasses in the central lowlands of tropical South America is therefore likely to be over 60 t/ha DM or a C input (assuming DM is 42% C) of 25 t/ha per year. Of course, not all of this C will be converted into forms that might be thought “sequestered”, that is, part of the slow (residence times of 10–100 yr) or the passive (residence times of 100–1000+ yr)

pools (see Fisher *et al.* 1998; 2007 for a discussion of the conceptual pools of soil C as applied to soil C under tropical pastures). This C input does indicate that the maximum rates that we measured (about 15 t C/ha/yr, Fisher *et al.* 1994) are consistent with the NPPs of introduced pastures in the central lowlands of tropical South America.

The potential of tropical pastures to accumulate C

The key consideration in determining whether a pasture system will accumulate soil C is how the system under consideration compares with the baseline. In the Colombian Llanos, the baseline is the treeless native savanna grassland under extensive utilisation (0.1–0.2 cattle/ha), with frequent fires (at least 1/yr). While we have no data on NPP of these pastures, growth rates following defoliation (an indicator of NPP) are low, so that C inputs are also likely to be low. In contrast, when introduced African grasses are sown following a fertilised pioneer crop (usually dryland rice), and grazed fairly intensively (2–3 head/ha), this represents a massive intervention. The amount of C input to the system is at least 20-fold, so C must accumulate in the soil. The important questions, to which we do not yet have answers, are: how long will the accumulation continue?; and what will control the new equilibrium?

Management options to increase soil C accumulation

Whether pasture systems accumulate C or not depends on how the management applied to the system compares with the management it formerly received, irrespective of whether we are talking of South America, Africa or Australia. While data for soil C vary according to the past history and states of the pastures, well-managed sown grass pastures in tropical South America do accumulate C in the soil to levels above that under the native grassland vegetation. The mean rate of C accumulation over a wide range of sites and management systems seems to be about 1 t C/ha/yr, which is far less than the potential levels mentioned above. The accumulation will continue until a new equilibrium is reached.

In contrast, there appear to be fewer opportunities for accumulation of soil C in Africa, where the grasses introduced to South America originate. Introducing a legume component is one possibility for increasing C inputs, but there have been no outstanding successes. Australia has possibilities with (different) African grasses and where legume technology has been adopted with some success. The key is management to maintain higher levels of NPP than the original vegetation.

Introduction of forage legumes to improve N supply

On the eastern plains of Colombia, grass pastures accumulated 3 t C/ha/yr in the soil in formal experiments (compared with the 1 t C/ha/yr commonly measured in commercial pastures), while the rate in a grass-legume pasture is 2.5–5 times greater (Fisher *et al.* 1994). This suggests that C accumulation is rate-limited, and the increased rate with a legume suggests the limitation is N. It is easy then to conclude that a legume component will increase the rate at which the soil accumulates C, but any maximum level of soil organic carbon (SOC) will be reached sooner rather than later. We do not know what the new equilibrium value might be. Moreover, we know that N is a key issue in pasture degradation, which I discuss below.

Increased activity of soil macrofauna

On the Colombian Llanos, a *B. decumbens* pasture had twice as much soil macrofauna as the native savanna, while a *B. decumbens*-Kudzu (*Pueraria phaseoloides*) pasture had twice as much again. Earthworms were over 80% of the macrofauna, more than 50 g/m² or 500 kg/ha, equivalent to the live weight of 2 weaner steers. Earthworms can ingest up to 10 times their body weight of soil each day, so that in 3 years 50 g/m² of earthworms could pass the whole soil volume to 1 m. Their beneficial influence on soil processes in general earned them the title “nature’s plow” (Jiménez and Thomas 2001).

Fire

Long *et al.* (1992) showed that SOC under pastures would increase without burning and with fertiliser. Most native tropical grasslands or savannas are burned annually, however, and are very rarely fertilised. With these simple management changes, tropical savannas in Africa could be a greater sink for C than is presently forecast (Greenland 1995), but it is doubtful if traditional users would change their management without cash incentives. The fertiliser component is irrelevant to Colombia, as savanna species do not respond to fertiliser (Fisher *et al.* 1992). Introduced pastures are rarely burned, except by accident, until they are very degraded and invaded by woody weeds. As I discuss below, there are probably better options for managing degraded pastures than fire.

Grazing management

The effects of grazing on SOC are inconsistent, with both increases and decreases as grazing pressure increases. It seems that many factors are involved, including soil type, sward type and nutrient status. It is clear that we need indicators of system state that reflect the overall C accumulation to maximise SOC. We do not yet have these, but possibilities include the “sward state” of temperate pastures indicated by sward height as proposed by Hodgson (1990), which could be linked to the “grazing envelope” proposed by Spain *et al.* (1985) to ensure sustainable production of tropical pastures. This is an area that obviously needs more investigation.

Fisher *et al.* concluded that productive, well-managed pastures on clay soils in Brazil can accumulate considerable amounts of SOC compared with the native cerrado, and that the accumulation can be as deep as 100 cm. Moreover, when pastures degrade as a result of heavy grazing and the absence of fertiliser inputs, C derived from the grass is lost and disappears from depths below 40 cm.

Pasture degradation and rejuvenation

In Brazil, pasture degradation is widespread as a consequence of overgrazing, which interrupts the N cycle, and lack of fertiliser. As pas-

tures degrade, their carrying capacity falls, and the live weight that they produce falls even more. Boddey *et al.* (2004) showed that, as stocking rate increased from 2 to 4 animals/ha, liveweight gain per animal decreased from 153 to 120 kg/yr. The pathways of N cycling were radically changed, with increases in N consumption by the cattle from 94 to 158 kg/ha/yr, and in N deposited as urine from 50 to 90 kg/ha and as dung from 37 to 59 kg/ha.

Most animal excreta were 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 contained. Complementary studies showed that N losses by volatilisation from urine could be from 35 to 80%, and were much higher in areas without vegetation. The authors concluded that pasture decline was hastened by increasing stocking rates because of these volatilisation losses of N and the decreases in N and other nutrients available for grass growth over the pasture as a whole.

Rejuvenation of the pasture is possible using a variation of the ley-farming concept, and a rotation of several crops followed by a pasture phase appears to be a viable system. Given that most C accumulates at depth in the soil, the C cost of such a rotation may be minimal, and with zero-till the rotation may even contribute C.

We hypothesised (Fisher *et al.* 2007) that, as soil fertility declines, or demand (grazing pressure) on the pasture increases, grasses increase their root mass, to increase their capacity to capture nutrients. This process continues until the photosynthetic capacity of the plants can no longer support a large root system, causing roots to shed and reducing the capture capacity in a downward spiral. The system collapses, leading to massive root shedding, giving the low root

masses typical of severely degraded pasture and abundant dead litter for foraging termites.

Fisher *et al.* (2007) concluded that, as pastures degrade, "root biomass ... will increase with time. Root biomass should reach a peak, followed by a large deposition of dying roots as the system collapses." There is some evidence to support this hypothesis (Table 1). It is therefore of great interest that Thompson (2009) reports anecdotal information for buffel grass pastures on his property near Roma, Queensland, that behave similarly. They go through a cycle of vigorous growth followed by declining productivity over a period of 5–7 years. Thompson (2009) concluded that, "an improved pasture (especially buffel) is not a permanent pasture and, like any other 'crop', it needs to be managed by means other than varying stocking pressure. If the pasture is treated like a crop and managed in 5 [to] 7-year cycles, productivity is enhanced, while the plants grow for long enough to store significant organic matter at depth."

We have no data on what might happen on our pastures in a degrade/rejuvenate sequence as reported by Thompson. However, it seems that it should lead to considerable C accumulation in the soil, although in what form we cannot say. Does it accumulate as particulate plant material?; or does the C from root material move along the pathway to humification?; and what are the processes involved? Degraded pastures on both the Colombian Llanos and the Brazilian Cerrados typically have large populations of termite mounds, from which we conclude that termites are taking advantage of the large amount of dead root material. There is no information of similar changes occurring in Australia. This is an area that clearly needs research and I urge my Queensland colleagues to follow this up.

Table 1. Root biomass (t/ha) in soils under a chronosequence of rejuvenated *Brachiaria brizantha* pastures of different ages (5 months, 4, 6 and 9 years), Fazenda Barreirão, near Goiânia. Data are means of 4 replicates. (From Fisher *et al.* 2007).

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 ($P>0.05$).

Fertiliser management

In small plot experiments, at 3 widely separated sites in the Cerrados on degraded pastures of either *B. decumbens* or *B. ruziziensis*, there were no responses to P, K or S, alone or in combination, in the absence of N, and only small responses to N alone (Oliveira *et al.* 2001). N with P, K and micronutrients produced good pasture recovery, however, suggesting that pastures may be rejuvenated by the use of chemical fertilisers alone. The cause of degradation in the first place is principally nutrient deficiency, as discussed above. Very little fertiliser is applied to sown pastures in the neotropical savannas. In contrast, in mixed agro-pastoral systems, fertiliser is applied to the crops, which need higher levels of fertility than pastures do. 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. "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." (Fisher *et al.* 1998).

Summary of the science

Some of the uncertainties and knowledge gaps about carbon accumulation by introduced pastures on the acid soils of the grasslands of the central lowlands of tropical South America (Fisher *et al.* 1998) have been resolved in the last decade.

Litter is a key component of net aerial primary productivity and was previously seriously underestimated. Largely because of this, 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.

Pasture health is a key component of C accumulation in the soil. Degraded pastures in general have soil C stocks little different from the native vegetation that they replace, but in contrast, soil C under well-managed pastures of *Brachiaria* species is almost always greater than under native vegetation communities. While data for soil C accumulation under introduced pastures in Brazil show substantial accumulation, the rate is at best half of that measured on the eastern plains of Colombia. There have been no studies to measure

NAPP on the Colombian eastern plains, so I can only speculate that climatic differences may be responsible. The eastern plains of Colombia have uniformly high temperatures throughout the year, but a strong 3-month dry season. In contrast, central coastal Brazil (Rezende *et al.* 1999) has a cool season (April – October) but has uniform precipitation throughout the year. It is possible that the cool season in Bahia reduces NPP compared with that recorded in the Colombian savannas.

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

It seems possible to rejuvenate degraded pastures simply by the application of fertiliser, although we do not yet know how widely useful this may be. There may be a requirement to rejuvenate pastures periodically, using some version of the ley-farming practices employed in some temperate systems. Research in the last decade suggests that these agro-pastoral systems may 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 it should be substantially positive, if pastures are returned to a vigorous state. Given that most C accumulates at depth in the soil, the C cost of such a rotation may be minimal, and with zero- or minimum-till, a rotation may even contribute to soil C.

Carbon trading

As mentioned above, the key issues in C accumulation are baseline, permanence and leakage. To have a saleable product in the international C market, the seller must be able to demonstrate permanence. This is an obvious problem with the US CRC mentioned above, where the accumulated C is mostly in the surface soil and vulnerable to loss if the soils are cultivated again. Where the C accumulation is at depth, as in the South American savannas, the C is much less vulnerable and it should be straight-forward to demonstrate permanence.

Leakage in agricultural systems is probably not the problem that it can be in forest systems,

where timber exploiters can simply move their activities elsewhere. It is difficult to imagine that an arable-crop farmer would sow his land to pasture to sell the environmental benefits that the pasture provides and take his cropping activities elsewhere to land that was not already being cropped. When most of the C in the soil accumulates at depth, as in the case of our original data (Fisher *et al.* 1994), the C in the soil below the plough layer should “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].”

Scientists’ notions of measuring soil C by taking soil samples, followed by soil analyses (McKenzie *et al.* 2000) make little economic sense in a C trading exercise. Lal *et al.* (2001) put the problems of measuring soil C in context, while various sampling protocols are discussed in detail by Kimble *et al.* (2001). Lal and Kimble (2001) discuss the importance of soil bulk density and the difficulties in measuring it, which also increase the cost of measurement. It is therefore technically difficult to quantify soil C accurately. Quite apart from the sampling methodology, which is costly, at present analysis of just one sample for soil C costs US \$15¹. For this reason, it is not economically practical to provide statistically significant data to support an environmental service, given that the spot price for C is currently only about US\$ 40/tonne on the European exchanges. A suitable proxy is needed, and preferably one that allows for aggregation across a number of holdings and that can give guarantees of permanence.

To negotiate C credits, the main challenges are how to measure the baseline, *i.e.*, the levels of C in the system now, and how to estimate the rates of accumulation. Proxies are needed for both these parameters. Ground cover might be good enough for an estimate of the baseline using methods like BOTANAL on the ground or perhaps from satellite images or low-cost aerial photography.

The gross rate of C accumulation in the system must be discounted by the C cost (carbon footprint) of whatever management is employed. Once satisfactory baselines are established as proposed by the AGO (see above), one such proxy might be liveweight turnoff, which reflects pasture growth and its management (and

hence NPP) remarkably well. Liveweight turnoff means the live weight produced on a given area, whether it is an individual farm, a group of several farms, or even a district or municipality. The advantage of the latter is that movements of livestock are usually monitored by the local authority and hence are easy to document. The baselines may need some adjustment for individual situations and some soil samples and soil analyses will be needed to support the protocol. The main task will be to arrive at a consensus with the purchasers. The notion of a proxy such as liveweight gain will need considerable research to support its feasibility. I am unaware of any current work to do this.

Conclusions

There are over 50 M ha of introduced pastures in the central lowlands of tropical South America. As the area is huge, every tonne of C that is accumulated under those pastures is significant in terms of global C balance. For comparison, Norway’s current C emissions are 55 M t/yr. Clearly, pastures have a massive role to play in providing ecosystem benefits. The challenge is to devise methodologies that will allow pasture managers to obtain a cash return for the ecological services that their pastures provide.

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Endnotes

- 1 Cornell Nutrient Analysis Laboratory, Ithaca NY, USA. <http://cna1.cals.cornell.edu/forms/documents/CNAL-Form-RS-Research-Soil-External.pdf>. Accessed July 27, 2009.
- 2 Kirby *et al.* (2009) is a series of 11 Working Papers of the CGIAR Challenge Program on Water and Food. The first paper in the series is the Concepts paper listed above, which is followed by separate papers for 10 basins: *Water-use accounts in CPWF Basins: Simple water-use accounting of the [Ganges, Indus, Karkheh, Limpopo, Mekong, Niger, Nile, São Francisco, Volta, Yellow River] Basin*.