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SPECIAL ISSUE

Productivity and carbon fluxes of tropical savannas

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ABSTRACT

Aim (1) To estimate the local and global magnitude of carbon fluxes between savanna and the atmosphere, and to suggest the significance of savannas in the global carbon cycle. (2) To suggest the extent to which protection of savannas could contribute to a global carbon sequestration initiative.

Location Tropical savanna ecosystems in Africa, Australia, India and South America.

Methods A literature search was carried out using the ISI Web of Knowledge, and a compilation of extra data was obtained from other literature, including national reports accessed through the personal collections of the authors. Savanna is here defined as any tropical ecosystem containing grasses, including woodland and grassland types. From these data it was possible to estimate the fluxes of carbon dioxide between the entire savanna biome on a global scale.

Results Tropical savannas can be remarkably productive, with a net primary productivity that ranges from 1 to 12 t C ha^{-1} $year^{-1}$. The lower values are found in the arid and semi-arid savannas occurring in extensive regions of Africa, Australia and South America. The global average of the cases reviewed here was 7.2 t C ha^{-1} $year^{-1}$. The carbon sequestration rate (net ecosystem productivity) may average 0.14 t C ha^{-1} $year^{-1}$ or 0.39 Gt C $year^{-1}$. If savannas were to be protected from fire and grazing, most of them would accumulate substantial carbon and the sink would be larger. Savannas are under anthropogenic pressure, but this has been much less publicized than deforestation in the rain forest biome. The rate of loss is not well established, but may exceed 1% per year, approximately twice as fast as that of rain forests. Globally, this is likely to constitute a flux to the atmosphere that is at least as large as that arising from deforestation of the rain forest.

Main conclusions The current rate of loss impacts appreciably on the global carbon balance. There is considerable scope for using many of the savannas as sites for carbon sequestration, by simply protecting them from burning and grazing, and permitting them to increase in stature and carbon content over periods of several decades.

Keywords

Carbon cycle, carbon sequestration, cerrado, fire ecology, forest protection, Kyoto, llanos, miombo.

INTRODUCTION

Savannas are a major component of the world's vegetation, covering one-sixth of the land surface and accounting for *c.* 30% of the primary production of all terrestrial vegetation. Africa contains by far the largest area of savanna, with as much as 15.1 million km^2, or 50% of African territory (Menaut, 1983; Campbell, 1996). In South America the savanna covers over 2.1 million km^2, most of it being in Brazil, Colombia, Venezuela and Bolivia (Cochrane *et al.*, 1985). Substantial

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areas of savanna also occur in India, Australia, southeast Asia, Central America and Pacific islands (Whyte, 1974; Gadgil & Meher-Homji, 1985; Werner *et al.*, 1991; McKeon *et al.*, 1991; Scholes & Walker, 1993).

As a result of the large areas savannas occupy, and because they are frequently burned, their management may influence the regional and possibly global energy, water and carbon balances (Santos *et al.*, 2003, 2004), and the products of their combustion may profoundly influence atmospheric chemistry (Delmas *et al.*, 1995; Hall *et al.*, 1995; Andreae *et al.*, 1998). Savanna burning results in an efflux of carbon to the atmosphere that Seiler & Crutzen (1980) estimated to be as high as 5–8 Gt C year^{-1}, although this is made up of an unknown proportion of 'natural flux' associated with natural fires, and 'anthropogenic influences' including management for grazing, and land-use change. The magnitude of land-use change is not well known, but there is no doubt that these lands are under great pressure. For example, they provide cattle grazing, wood extraction, charcoal for smelting and land for agriculture. Increasingly, savanna lands are being brought into intensive use, and there are consequent environmental risks. Burning of tropical grazing ecosystems for agricultural and grazing uses is estimated to have released an annual gross flux of carbon in the range of 2.4–4.2 Gt C year^{-1} or 42% of global burned phytomass (Hall & Scurlock, 1991). Burning may increase greatly over the next century as a result of climate change, particularly as a result of warming and drying causing savanna to replace rain forest (Cox *et al.*, 2000). Some savannas are remarkably biodiverse, and they contain a high degree of endemism with a wide range of life forms. For example, the Brazilian cerrados contain *c.* 800 species of large trees and shrubs with a large proportion of endemic species, and a correspondingly rich fauna (Eiten, 1972; Silberbauer-Gottsberger & Eiten, 1983; Silberbauer-Gottsberger & Gottsberger, 1984; Furley *et al.*, 1992; Ratter *et al.*, 1997). In this Brazilian case, there is widespread concern about the loss of biodiversity, and the difficulty of managing the resource on a sustainable basis (Dias, 1990; Felfili *et al.*, 1993; Myers *et al.*, 2000). In other cases, savannas are lacking in such a high degree of endemism: for example in the Orinoco savanna 706 species of vascular plants have been recorded with a range of life forms (Montes & San José, 1995) but 75% of these were found in surrounding ecosystems and only nine were endemic (San José *et al.*, 1998a,b).

In this paper we estimate the magnitude of carbon fluxes between savanna and the atmosphere, and suggest the significance of savannas in the global carbon cycle. We also suggest the extent to which protection of savannas could contribute to a global carbon sequestration initiative.

METHODS

Data on carbon flows and stocks involving tropical savanna ecosystems were accessed using the ISI Web of Knowledge, and through library catalogues and personal collections at the authors' institutions. A broad definition of savanna was adopted following Eiten (1972). He pointed out the approximate parallels between the terms used for Brazilian savanna, and those in wider usage for savannas of Africa, India and Australia, as follows: (1) grassland type savanna, savanna grassland, or campo limpo is tropical grassland with no trees; the grasses are predominantly C_4 species; (2) shrub type savanna, low tree and shrub savanna, or campo sujo (in Brazil) is herbaceous vegetation with scattered small trees, height 3 m, trees less than 1000 ha^{-1} and basal area 3 m^2 ha^{-1}; (3) woodland type savanna, savanna woodland or campo cerrado (in Brazil) is orchard-like vegetation, height 4–6 m, trees 1400–2000 ha^{-1} and basal area 7–17 m^2 ha^{-1}; (4) forest type savanna, savanna woodland or cerradão is substantial woodland with a canopy of nearly 50%, height 9 m, trees 3000 ha^{-1} and basal area exceeding 30 m^2 ha^{-1}. The distinction between forest-type savanna and forest itself is not always clear. Many of the world's seasonally dry tropical forests resemble forest-type savannas but are floristically quite distinct, lacking a significant grass component, and so are excluded from the definition of savanna.

Carbon stocks and productivity

In savannas world-wide, as might be expected, the above-ground carbon stocks vary widely, according to the extent of tree cover, from 1.8 t C ha^{-1} where trees are absent, to over 30 t C ha^{-1} where there is substantial tree cover (Table 1). In the few studies where roots have been thoroughly excavated (Jackson *et al.*, 1996), it is clear that roots of many trees are deep and that the below-ground component may exceed that of the above ground (Table 1). There seems to be a marked difference between regions in the allocation to below-ground biomass. The Brazilian cerrado has a root : shoot ratio that greatly exceeds 1.0, whereas the Venezuelan savanna does not (Table 1). As for grasses, the capacity of tropical grasses to accumulate below-ground carbon has often been emphasized (Scurlock & Hall, 1998). Moreover, many of the woody species found in the savanna have ligno-tubers and deep roots, enhancing the root : shoot ratio to well beyond what is found in tropical forests (Eiten, 1972; Furley *et al.*, 1992). The soil carbon pool for the savanna biome is 200–300 Gt C (Scurlock & Hall, 1998) or 10–30% of the world soil carbon (Anderson, 1991; Eswaran *et al.*, 1993). Furthermore, as a global average, native savanna soils contain at least as much carbon as that stored in above- and below-ground biomass (Anderson, 1991; Eswaran *et al.*, 1993; Scholes & Hall, 1996).

Savanna carbon fluxes are highly seasonal, and are characterized by high interannular variability caused by fire. As savannas contain C_4 grasses, they may be expected to be highly productive but the data suggest they are only moderately productive (Table 2). Long *et al.* (1989) pointed to the likely under-estimation of productivity resulting from the failure of most authors to estimate components of below-ground productivity, such as fine root turnover and exudation. Taking this into account, it seems likely that many of the published data based on classical harvesting techniques are

Table 1 Carbon stocks in savanna ecosystems of the world, expressed as above ground biomass–carbon per area of land (t C ha^{-1}), obtained from published data by assuming that biomass is 50% carbon (Schlesinger, 1997). See Methods for further details

	Leaf	Wood	Total above-ground biomass	Litter	Total below-ground biomass	Soil carbon	Authors
Brazil, campo limpo	1.8		1.8		7.6	246	Castro (1996)
Brazil, campo sujo	2.7		2.7	1	15.1	211	Castro (1996)
Brazil, cerrado *sensu stricto*	3	6.6	9.6	2.6	23	257	Castro (1996)
Brazil, cerrado denso	2.6	8.4	11	1.8	25.5	255	Castro (1996)
Brazil, campo cerrado			3.7				Valeriano & Bitencourt-Pereira (1988)
Brazil, cerrado recently burnt			3.4				Santos (1988)
Brazil, unburnt cerrado			4.4				Santos (1988)
Brazil, campo limpo			3.56	0.2			Kauffman *et al.* (1994)
Brazil, campo sujo			3.48				Kauffman *et al.* (1994)
Brazil, campo cerrado			2.96	1.32			Kauffman *et al.* (1994)
Brazil, cerrado *sensu stricto*			2.22	2.74			Kauffman *et al.* (1994)
Brazil, cerrado *sensu stricto*	3.6	12.3	15.9	2.6	20.6	373	Abdala *et al.* (1998)
Brazil, cerrado *sensu stricto*	3.2	11.3	14.5				Santos (1988)
Northern Australia	0.9	29.9	33.6	1.0	19.3	151	Chen *et al.* (2003)
Canas, Costa Rica, derived savanna, grazing, annual burning (April)	6.3	12.7	19				Daubenmire (1972)
Calabozo, Venezuela, closed bush island savanna, grazing/burning	2	6.2	8.2	4.2	12.7		San José (1995)
Lamto, Cote d'Ivoire, humid savanna annual burning (February)	6.8	13.6	20.4	1.5	52	18	Menaut & Cesar (1979)
Lamto, Cote d'Ivoire, open humid savanna			17.7	16	17.7		Mordelet & Menaut (1995)
Lamto, Cote d'Ivoire, under tree clumps humid savanna			12	22.5	12		Mordelet & Menaut (1995)
Entire savanna area, South Africa, all land use types			6.1		4.9		Rutherford (1993)
Entire savanna area, South Africa, natural system			6.7		5.4		Rutherford (1993)
Nylsvley, South Africa, broad-leaved savanna	1.4	8.1	9.5	6.6	7	23.3	Tothill & Mott (1985)
Nylsvley, South Africa, broad-leaved savanna, fire every 3 years	2.6	5.1	7.7	12		33.9	Scholes & Walker (1993)
Klong Hoi Khong, Thailand, savanna woodland	11.3	22.7	34	1.3	50		Kamnalrut & Evenson (1992)
Mean (where appropriate)			9.4		19.0	174	

Table 2 Net primary productivity of savannas (t C ha^{-1} year^{-1}), assuming that biomass is 50% carbon (Schlesinger, 1997)

Forest type	Method	Location	Net production (t C ha^{-1} year^{-1})	Authors
Savanna derived from semi-deciduous forest	Harvesting	Canas, Costa Rica	6.9	Daubenmire (1972)
Closed bush island savanna, unburned	Harvesting	Calabozo, Venezuela	3.4	San José (1995)
Closed bush island savanna, burned	Harvesting	Calabozo, Venezuela	3.8	San José (1995)
Open shrub savanna	Harvesting	Lamto, Cote d'Ivoire	6.4	Mordelet & Menaut (1995)
Dense shrub savanna	Harvesting	Lamto, Cote d'Ivoire	8.1	Mordelet & Menaut (1995)
Cenchrus ciliaris	Harvesting	Jodhpur, India	3.7	Singh *et al.* (1985)
Sehima nervosum, plains, ungrazed	Harvesting	Khirasara, India	1.8	Singh *et al.* (1985)
Dry grassland	Harvesting	Khirasara, India	1.7	Singh *et al.* (1985)
Mixed grass savanna	Harvesting	Pilani, India	1.4	Singh *et al.* (1985)
Mixed grass savanna	Harvesting	Udaipur, India	2.2	Singh *et al.* (1985)
Mixed grass and forbs, tropical grassland	Harvesting	Kurukshetra, India	13.4	Singh *et al.* (1985)
Savanna woodland	Harvesting	Varanasi, lowland, India	22.8	Singh *et al.* (1985)
Savanna woodland	Harvesting	Varanasi, upland, India	18	Singh *et al.* (1985)
Shrub/grass savanna	Harvesting	Jhansi, India	7.6	Singh *et al.* (1985)
Grass savanna	Harvesting	Ujjam, India	4.9	Singh *et al.* (1985)
Shrub/grass savanna	Harvesting	Berhampur, India	9.7	Singh *et al.* (1985)
Grass savanna	Harvesting	Ratlam, India	4.2	Singh *et al.* (1985)
Shrub/grass savanna	Harvesting	Sagar, India	9.3	Singh *et al.* (1985)
Savanna woodland	Harvesting	Sambalpur, India	12.2	Singh *et al.* (1985)
Grass savanna	Harvesting	Nairobi, Kenya	6.1	Kinyamario & Macharia (1992)
Shrubs and grasses	HAPEX-Sahel flux measurements	Niger, West Africa	2.2	Hanan (1998)
Grass savanna	Harvesting	Nairobi National Park, Kenya	6.2	Long *et al.* (1989)
Humid savanna woodland	Harvesting	Klong Hoi Khong, Thailand	9.5	Kamnalrut & Evenson (1992)
Herbaceous savannas	Harvesting	Orinoco Lanos, Venezuela	3.9	San José & Montes (2001)
Tree savannas	Harvesting	Orinoco Lanos, Venezuela	7.0	San José & Montes (2001)
Woodlands	Harvesting	Orinoco Lanos, Venezuela	7.6	San José & Montes (2001)
Eucalyptus scrub	Harvesting	Northern Australia	11.0	Chen *et al.* (2003)
Mean ± 95% confidence interval			7.2 ± 2.0	

under-estimates (Table 2). Nevertheless, it is clear that productivity varies widely. The mean and 95% confidence interval of the published values in Table 2 are 7.2 ± 2.0 t C ha^{-1}yr^{-1}. Many of the higher values are from India, at sites where the savanna is largely a degraded form of sub-humid rain forest (Singh *et al.*, 1985). The mean value in Table 2 is a significantly higher figure than published estimates in the ecological literature: Whittaker & Likens (1975) quote 4.5 t C ha^{-1} year^{-1} and House & Hall (2001) 5.4 t C ha^{-1} year^{-1}. However, House & Hall's Table 16.1 shows considerable variation depending upon the type of savanna system, and if we disregard all their figures except for 'tropical savanna and woodland' they have a value of 7.1 t C ha^{-1} year^{-1}, essentially the same as the one presented here in Table 2.

It is useful to compare these new, higher estimates of savanna productivity with those from rain forests. In a recent literature review based on ten studies, the mean and standard deviation of the net productivity of rain forests was found to be 11.2 ± 4.2 t C ha^{-1}yr^{-1} (Grace *et al.*, 2001). Savannas are less productive, despite having C_4 grasses. When well-managed, as in derived pastures, C_4 grasses in savanna environments can be very productive (Santos *et al.*, 2004). But in the natural state, they sometimes have a remarkably low foliar nitrogen concentration, which limits the rate of photosynthesis (Miranda *et al.*, 1997). The productivity of savannas is, however, normally attributed to the generally lower precipitation, the occurrence of a pronounced and prolonged dry season, or in some cases the result of soil characteristics in relation to water-holding capacity. In savannas, linear relationships have been found between biomass and precipitation (Scholes *et al.*, 2002), and productivity and days of water stress (House & Hall, 2001), although from place to place productivity will be strongly affected by biomass burning (Frost, 1996), which reduces the duration of leaf area and thus limits productivity.

CO_2 and water vapour fluxes

In recent years, it has become possible to measure directly the fluxes of carbon dioxide over vegetation using micrometeorological techniques, especially eddy covariance. From the tropics, data are available from rain forest (e.g. Grace *et al.*, 1995), C_4 pasture (Grace *et al.*, 1998) and savannas. Savanna data are available from the Orinoco Llanos (San José *et al.*, 1991), African Sahel (Verhoef *et al.*, 1996) and Brazilian cerrado (Miranda *et al.*, 1997; Silva, 1999; Santos, 1999; Santos *et al.*, 2003; Veenendaal *et al.*, 2004). In the wet season the maximum net uptake rates in bright sunlight are typically 10–15 μmol C m^{-2} s^{-1}, which is about two-thirds of the maximum typically observed for rain forests (Grace *et al.*, 1995; Malhi *et al.*, 1998; Saleska *et al.*, 2003). In the wet season the savanna is a strong carbon sink, absorbing between 0.1 and 0.2 mol C m^{-2} day^{-1}, but in the dry season the overall activity declines and the vegetation may even become a weak source of carbon to the atmosphere (Miranda *et al.*, 1997; Santos *et al.*, 2003; Veenendaal *et al.*, 2004). The seasonal decline in the rate of photosynthesis is partly the result of stomatal closure, evident especially in the afternoon, and partly the result of seasonal leaf abscission for woody and herbaceous species and marcescence in grasses and sedges. There are strong seasonal changes and in both wet and dry seasons, the gas exchange appears to be limited by stomatal closure in the afternoon (Miranda *et al.*, 1997; Eamus *et al.*, 1999; Meinzer *et al.*, 1999; Chen *et al.*, 2003).

Miranda *et al.* (1997) present the annual course of net ecosystem flux of CO_2 for a cerrado ecosystem near Brasilia. By interpolation of Fig. 8 of Miranda *et al.* (1997), we may obtain an estimate of year-round net ecosystem productivity of 6.7 t C ha^{-1} $year^{-1}$, and a gross primary productivity of 14.4 t C ha^{-1} $year^{-1}$. The total respiratory efflux from the system (autotrophic and heterotrophic) was 7.7 t C ha^{-1} - $year^{-1}$. If we assume that autotrophic and heterotrophic respiration contribute equally to this efflux, we may estimate net primary productivity as 10.6 t C ha^{-1} $year^{-1}$. Miranda *et al.* (1997) used the isotopic signature of the respiratory CO_2 from the soil to estimate that some 40% of the net primary productivity may have been of C_4 origin, even though the C_4 plants had a leaf area index of only 0.4 and 0.2 in the wet and dry seasons respectively.

The behaviour of soil carbon is not well understood, especially in savannas and dry forests where there have been few detailed studies. In general, it is probably true to say that soil organic matter is as much controlled by moisture as it is by temperature, with the expected behaviour being akin to Mediterranean ecosystems, for which there are more data (Rey *et al.*, 2004).

Carbon emission from burning native savanna

For the tropics, recent estimates of net annual flux of carbon between terrestrial ecosystems and the atmosphere, including burning, photosynthesis and respiration, indicate a carbon source ranging from 0.6 to 2.0 Gt C $year^{-1}$ (Read *et al.*, 2001) and an observed tropical deforestation rate which varies from 0.5% and 0.9% per year (FAO, 1999; De Fries *et al.*, 2002), whereas the mean loss for grassland areas in tropical regions between 1850 and 1980 is 0.12% per year (Houghton & Hackler, 1995). There is a fundamental difference between most rain forest and *most* savannas, in that the latter are naturally subjected to frequent fires and so are dynamic aggrading systems (*sensu* Likens & Bormann, 1995). Nevertheless, not all savannas will respond to fire exclusion. In those known as pedologic savannas, forest never develops, even when the system is protected from fire (see cases in South America reported by San José *et al.*, 1985, and those in West Africa reported by Schnell, 1976). Often, it is unclear which these are unless experimental studies are undertaken.

Quantitative estimates of the extent of burning have been made from satellite images. For example, over Central Africa, Eva & Lambin (1998) found that 52% of pixels in Guinean savanna and 28% of pixels in Sahelian savanna had been affected by fire in the period from mid-October 1994 to early March 1995. Burning of tropical grazing lands involving clearing of savannas and deciduous forest has been estimated to release an annual gross flux of carbon in the range of 0.5–4.2 Gt C $year^{-1}$ (Seiler & Crutzen, 1980; Crutzen & Andreae, 1990; Delmas *et al.*, 1991; Hall & Scurlock, 1991; Menaut *et al.*, 1991; Scholes & Hall, 1996). Burning of biomass also causes emissions to the atmosphere of a huge range of volatile organic material and particulates. Overall, phytomass burning of savannas is estimated to emit 1.80 Gt C as CO_2; 0.31 Gt C as CO; 0.038 Gt as methane; 0.240 Gt C as non-methane hydrocarbons; 0.080 Gt nitrogen as nitrogen oxide and smaller amounts of other gases such as methyl chloride and 0.10 Gt C particulate matters (Levine *et al.*, 1995). Hao *et al.* (1996) have reported that the amount of CO, ethane, ethyne, propene, propane and benzene emitted per year from Zambia and South African savannas fires was 20–95% of the amount released from global industrial activities. Andreae *et al.* (1998) report the emissions of aerosols from savanna burning in southern Africa: the smoke aerosols were 10–30% black carbon, whilst K^+ and NH_4^+ were the dominant cations and Cl^- and SO_4^{--}were the most important anions.

The impact of burning on element stocks has been studied by several authors (Batmanian & Haridasan, 1985; Kauffman *et al.*, 1994; Poth *et al.*, 1995; Castro, 1996; Lilienfein *et al.*, 2001). In the sparser forms of cerrado ('*campo limp*' and '*campo sujo*') the carbon contents were reduced from over 3.0 to *c.* 0.2 t ha^{-1}, but in the more woody forms ('*campo cerrado*' and cerrado *sensu stricto*) the fire had much less impact (Table 3). Generally, trees and shrubs are well protected by thick bark, and the fire merely scorches them, allowing sprouting from the stems to occur after a few months. There is of course some variation in the intensity of the fire, depending on fuel load, moisture content and meteorological conditions. Volatilization of the lighter elements, nitrogen and sulphur, follows a pattern similar to carbon, but the heavier elements, phosphorus, potassium and calcium form ash, much of which is deposited on the soil surface (Kauffman *et al.*, 1994; Kuhlbusch *et al.*, 1996). The soil emissions of NO and N_2O may continue for months after the fire (Poth *et al.*, 1995). On the other hand, the burning releases a flush of nutrients which stimulates physiological activity and produces rapid growth with relatively high

Table 3 Above-ground elemental pools (kg ha^{-1}) in Brazilian cerrado before and after burning (abstracted from Fig. 2 of Kauffman *et al.*, 1994). The figures in parentheses represent the values obtained within 1 month after burning

Vegetation	Carbon	Nitrogen	Sulphur	Phosphorus	Potassium	Calcium
Campo limpo	3300 (150)	23 (2)	3.7 (0.6)	1.75 (0.8)	19 (12)	12.5 (7.5)
Campo sujo	3500 (250)	25 (4)	3.4 (0.6)	1.7 (0.5)	16 (8)	11 (4.7)
Campo cerrado	4350 (1650)	28 (18)	5.2 (1.8)	2.4 (1.4)	15 (8.5)	23 (16)
Cerrado *sensu stricto*	4200 (1900)	54 (30)	6.3 (2.2)	3.5 (2.0)	13.5 (7.0)	30 (18.5)

nutritional value to cattle (Holt & Coventry, 1991; Cook, 1994; Van de Vijver *et al.*, 1999).

The vast cover of savanna vegetation may significantly contribute to the global carbon budget and related gaseous fluxes (Hall, 1989; Delmas *et al.*, 1995; Hall *et al.*, 1995). Thus, Scurlock & Hall (1998) have estimated that globally, savannas might account for a carbon sink of as much as 0.5 Gt C in response to rising CO_2 concentrations.

Where there is no loss of savanna area, most of the CO_2 lost in the annual burn is assumed to be reassimilated during regrowth. A small fraction of the biomass is converted to black carbon, which is the product of incomplete combustion, and is generated during fire as aerosols and charcoal. The former are dispersed over great distances, and the latter remains as visible fragments in the soil profile. In southern Africa, Kuhlbusch *et al.* (1996) found that 0.6–1.5% of the exposed biomass-carbon was converted to black carbon. The formation of black carbon is potentially a long-term global carbon sink, as black carbon is not known to be easily oxidized to CO_2 by micro-organisms. Thus, assuming a typical net primary productivity (Table 2) of 7 t C ha^{-1} $year^{-1}$ to be burnt annually, we might expect an average rate of C accumulation as black carbon of *c.* 0.07 t C ha^{-1} $year^{-1}$. Over a century, this would be expected to accumulate in the soil as a carbon stock which ought to be included in global carbon estimates. However, Bird *et al.* (1999) have provided evidence that black carbon is not as stable as has been previously supposed. Moreover, one supposes that the black carbon remaining after the burn in 1 year will be oxidized in subsequent burns.

Effects of changes in land uses on savanna stores of carbon

Half of the total area of land clearance since AD 1700 has occurred in savanna-like vegetation (Goldewijk, 2001; Malhi *et al.*, 2002). Currently, human pressure on savanna resources continues, through the effect of fire, cattle raising, agricultural activities and resource extraction (Houghton, 1995), associated with an overall population density in these regions of (typically) above 24 people km^{-2} (Werner *et al.*, 1991). We do not, however, have a firm figure for the current rate of loss. Savannas are not routinely censused either by ground-based inventory or by satellite imagery, and so it is not as easy to track the changes in area or biomass as for forest cover. Therefore, savannas have been somewhat ignored in relation to the global carbon cycle, and carbon inventories have more frequently been reported only for forests (Houghton, 1995). In South America the savanna is evidently declining in area or biomass, as more land is taken into agriculture. Figures for the Brazilian cerrado, for example, suggest that the native vegetation has been cleared at an average rate of at least 1% per year, and that currently over 40% of the cerrado has been altered by agriculture (Alho & De Souza Martins, 1995). The most important crops include beans, corn, rice, soybean and coffee. A recent inventory study was completed for the Venezuelan Llanos, a savanna region of some 390,000 km^2 (San José & Montes, 2001). This study provides a regional picture of land-use change over the decade 1982–92. In the Llanos it was found that all savanna types had declined, but the largest decline was in the grassland savanna. It had decreased by 2.3% per year, as a result of conversion to agricultural usage. The savanna areas grazed by cattle had also declined, from 231 to 184 km^2 over the decade, but the number of cattle had increased significantly.

Careless management can result in significant degradation of vegetation and soil, leading to net carbon losses from the savannas to the atmosphere. In the natural grasslands and forests, the carbon loss depends on several factors including management and soil features (Gregorich *et al.*, 1996; Fujisaka *et al.*, 1998). Thus, cultivation of savannas may rapidly lead to a reduction in carbon content, as pointed out by Nye & Greenland (1960). Scholes & Hall (1996) have pointed out that half of the organic matter in tropical woodlands and savannas is lost within 20 years after modification to croplands. However, these results may be most relevant in the short-term as long-term cultivation in savannas has been shown to result in an increase in the soil carbon stock, as found for the Carimagua savannas (Colombia) by Fisher *et al.* (1994, 1995), or hardly any change in the soil organic matter as shown in Brazilian cerrado by Roscoe *et al.* (2001). In the latter case, it seems that the organic matter pool is stabilized by the clay fraction of the soil (Roscoe *et al.*, 2001; Neufeldt *et al.*, 2002).

Houghton & Hackler (1995) indicated that Latin American grasslands are releasing 0.169 Gt C $year^{-1}$. By contrast, Parton *et al.* (1995), Scholes & Hall (1996) and Scurlock & Hall (1998) have considered global savannas to be a substantial carbon sink of the range from 0.5 to 2.0 Gt C $year^{-1}$. This inconsistency could potentially be resolved by taking into account both deliberate and inadvertent changes in land use (Houghton, 1995). Fisher *et al.* (1994) have calculated a carbon sink for South American grazing lands (2.5×10^{12} m^2) ranging from 0.1 to 0.5 Gt C $year^{-1}$. In many savannas, protection from fire

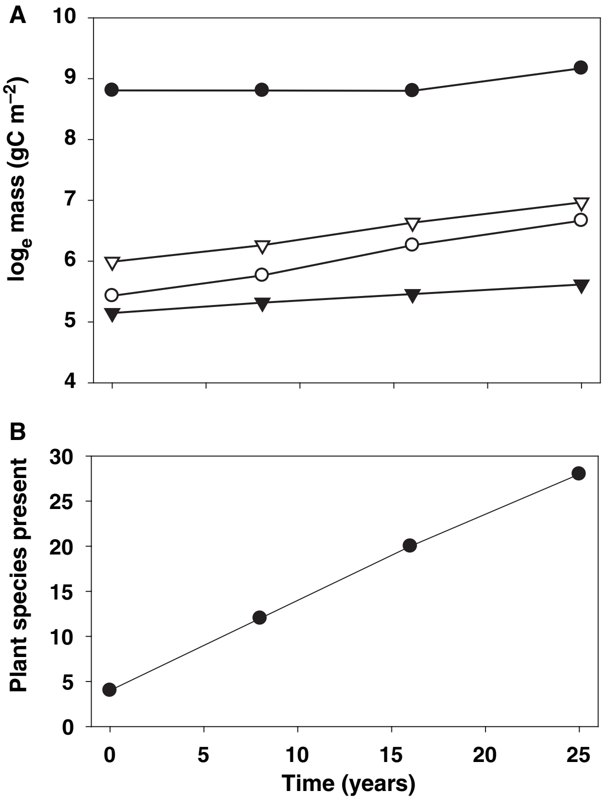

Figure 1 Increase in carbon stocks and species richness following protection of savanna against fire and grazing at a 3-ha permanent plot in the Orinoco Llanos (San José *et al.*, 1998a,b). The plot was recorded in 1961, 1977, 1969 and 1986. The initial stage of the plot was a frequently-burned savanna with grass-dominated cover and a few scattered trees. (A) soil carbon (●), total biomass (▽), above-ground biomass (○), and below-ground biomass (▼); (B) the increase in the number of tree species (including tree seedlings) in the plots.

and grazing would cause a build up of biomass, constituting a substantial carbon sink if carried out over a large area of the world's savannas. Data on the rate of increase in biomass of protected savannas are scarce. Data from the Orinoco llanos showed that protection from fire and grazing caused an invasion of woody plants and a rapid increase in plant biomass-C (Fig. 1). The carbon in the soil fell slightly at first, but increased sharply as the woody biomass became established. Overall, San José *et al.* (1998a,b) observed a sequestration rate of almost 1 t C ha^{-1} year^{-1} over 25 years (although the rate was much faster over the final harvest period). This is appreciably lower than the sequestration rates observed for re-growing rain forests (2–7 t C ha^{-1} year^{-1}, Brown & Lugo, 1990), but if repeated over the whole area of the Orinoco plains (0.39×10^8 ha) it would constitute a significant carbon sink over a 25-year period.

The aforementioned result indicates that it is important to develop methods of assessing carbon storage in vegetation and soil, and to identify management practices which reduce emissions from the soil surface as well as sequester carbon into biomass. Kern (1994) and Carter & Hall (1995) have proposed options for carbon sequestration. Management practices can be used to improve carbon sequestration through agroforestry and agro-silvopastoral systems (Sedjo, 1983; Belsky *et al.*, 1993; McPherson *et al.*, 1993). Thus increasing the area devoted to afforestation can improve carbon sequestration in savanna lands (Laarman & Sedjo, 1992). However, it is necessary to consider that a common trait in savanna soils is nutrient deficiency, especially of nitrogen and phosphorus (Lopez-Gutierrez *et al.*, 2004). Carbon sequestration should be achievable when the natural nutrient supply is sufficient, and artificial soil improvement may also be possible in an appropriate economic environment (San José, 1995). Even highly managed savanna systems can, in principle, be managed in a sustainable way through the use of fallow periods, the application of residues, and the use of N-fixing trees to augment the soil nitrogen during the fallow period (San José & Montes, 2003).

Model-based estimates of the potential sink strength

Taylor & Lloyd (1992) developed an ingenious method of estimating the sink strength of a biome or an ecosystem in relation to the globally ameliorating conditions for plant growth. It applies to the undisturbed state (i.e. no fire and no land-use change), and so in some respects it is not so useful in relation to savannas, where 'the hand of man' is more important than climate change in determining the annual and decadal variations in carbon stocks. This method deals with presumed increases in net primary productivity (NPP). NPP is on the increase because of fertilization by CO_2 and deposition of active nitrogen, but heterotrophic respiration, which is related to temperature and therefore is also increasing, does not keep pace with NPP due to the residence time of carbon in the vegetation and soil. The sink occurs because heterotrophic respiration lags behind the breakdown of organic matter, especially in ecosystems where there are significant stores of carbon. Taylor & Lloyd (1992) assumed heterotrophic respiration at time t is equal to the NPP at time $t - t_r$ where t_r is the residence time (estimated as carbon in vegetation plus soil divided by NPP), that is

$$R_h = \mathrm{NPP}(t - t_r).$$

Assume that NPP is initially NPP_0 and increases linearly in response to rising CO_2 concentration, thus:

$$\mathrm{NPP}(t) = \mathrm{NPP}_0(1 + at).$$

Based on experiments on woody plants grown at twice-normal CO_2 it is reasonable to propose that a doubling of CO_2 would increase the NPP by 30% (Wullschleger *et al.*, 1995; Idso, 1999) and so the observed annual increase of CO_2 of 0.4% per year might cause an annual proportional increase in NPP of $a = 0.0012$ year^{-1}.

By definition, net ecosystem productivity, NEP = NPP − R_h. Thus,

$$\mathrm{NEP} = \mathrm{NPP}(t) - \mathrm{NPP}(t - t_r) = \mathrm{NPP}_0 a t_r.$$

Table 4 Carbon fixed by the Earth's vegetation, as net primary productivity (NPP) (Saugier *et al.*, 2001), and the average sink strength estimated by the Taylor & Lloyd (1992) method, which ignores land-use change. The total C pool includes vegetation and soil organic matter. NPP (column 1) has been rounded to the nearest 0.1 tC. This table shows a higher NPP than Saugier *et al.* (2001) because the mean NPP from Table 2 is higher than the 5.4 (t C ha^{-1} $year^{-1}$) assumed in the table given in Saugier *et al.* (2001). See text for the assumptions

Biome	NPP (t C ha^{-1} $year^{-1}$)	Area (million km^2)	Total carbon pool (Gt C)	Total NPP (Gt C $year^{-1}$)	Estimated sink (Gt C $year^{-1}$)	Average sink per ha (t C ha^{-1} $year^{-1}$)
Tropical forests	12.5	17.5	553	21.9	0.66	0.37
Temperate forests	7.7	10.4	292	8.1	0.35	0.34
Boreal forests	1.9	13.7	395	2.6	0.47	0.34
Arctic tundra	0.9	5.6	117	0.5	0.14	0.25
Mediterranean shrublands	5.0	2.8	88	1.4	0.11	0.38
Crops	3.1	13.5	15	4.1	0.02	0.01
Tropical savanna and grasslands	7.2	27.6	326	19.9	0.39	0.14
Temperate grasslands	3.8	15	182	5.6	0.21	0.14
Deserts	1.2	27.7	169	3.5	0.20	0.07
Ice		15.3				
Total		149.1	2137	67.6	2.55	

We can see from this analysis that environmental change causes an increase in sink strength that is proportional to the residence time of carbon in the plant-soil store. Applying the above equation to the global productivity data suggests that the sinks are predominantly in forests and savannas (Table 4). Using this method we have a global terrestrial sink of 2.55 Gt C $year^{-1}$, of which 0.39 Gt C% is attributable to tropical savannas.

The Kyoto Protocol and carbon projects

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) is the first step by the world's nations to limit the emissions of carbon dioxide and other greenhouse gases, in order to reduce global warming. The Protocol, came into force in February 2005, and if successful, will reduce the rate of increase in CO_2 emissions by the developed countries. One part of the Protocol is the Clean Development Mechanism (Article 12) whereby rich countries are meant to assist sustainable development of poorer countries by providing 'clean' projects that create sinks for greenhouse gases or reduce emissions. These 'certified emissions reductions' may include afforestation and reforestation, but protection of existing forests and woodlands is currently excluded (Grace *et al.*, 2003). The exclusion of 'protection projects' is unfortunate, as potentially the carbon 'savings' to be had from protection far exceed those which could in practice be obtained by afforestation and reforestation. There is considerable pressure from conservation bodies and others to allow such projects. In the meantime, there are many 'informal' forest and woodland protection projects that are now well documented (Orlando *et al.*, 2002; Swingland, 2003).

One example of how carbon may be sequestered at a local scale, in the tropics, is provided by a project of the Edinburgh Centre of Carbon Management. The management scheme is called *Plan Vivo*, and is currently being applied to a community in the savanna region of Mozambique. Farmers living on the edges of the Gorongosa National Park are producing working plans to increase the carbon content of their land by planting trees, including trees for fruit and pharmaceuticals, on land that is otherwise marginal. A summary of the dynamics of land use is given as Fig. 2. Payment for carbon sequestered is made according to a schedule (some up-front payment, payment on planting and payment when the trees have reached specific size). As a result, the requirements of the community for fuel wood and structural timber will be met on a sustainable basis, without the need to exploit further the native savanna vegetation. Clearly, one ought to be able to define the conditions for sustainable land use given the area of land available and the number of people in the community. Sustainability is here defined as the condition where it is no longer necessary to harvest pristine forest.

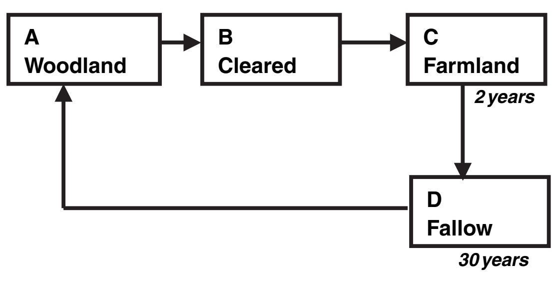

Figure 2 Traditional land use in miombo woodland in southern Africa. The high-carbon woodland ecosystem (A) produces forest products and is useful for ecotourism because of its high biodiversity. It is often cleared (B) by cutting and burning to produce agricultural fields (C), which can be cultivated for only a few years before the yields decline and they must be abandoned. After a fallow period (D) of 20–30 years the biomass and carbon stocks are replenished by natural processes. However, in that time, the farmer must cut new woodland to create new farmland. In an alternative system the regrowth at stage D is accelerated by the use of N-fixing crops and N-fixing trees. Hence, the requirement for new woodland areas is diminished.

Such projects in the tropics inevitably have a high failure rate (Grace *et al.*, 2003), and there may be 'project leakage'. The term project leakage refers to the tendency of people to continue to fell trees, but to do it outside the project area where it may not be detected (except by satellite surveillance). If 'carbon sequestration' projects can avoid pitfalls like the leakage issue, and were to become widespread, they would result in a flow of money from rich to poor countries, an alleviation of poverty in poor countries, and a shift towards a more sustainable form of land management, whilst a significant fraction of carbon emitted in rich countries would be absorbed in forest and savanna vegetation. E. O. Wilson has recently pointed out that conservation needs to be related to income generation for those who live near the reserves (Wilson, 2002). Earning carbon credits is one of the income streams he considers feasible, alongside ecotourism and bioprospecting. In this way, land can yield more income than logging or agriculture on the cleared land.

It is difficult to estimate the potential for a *managed* and *additional* global C sink in tropical savannas because of the varying effects of changed management practice as well as revegetation of cleared lands. However, calculating the potential for an additional global biogenic C sink from terrestrial ecosystems, Kauppi *et al.* (2001) have shown that 80–120 Gt C could be sequestered over the period 2000–2050, an average of 1.6–2.4 Gt C year^{-1} which is 24–40% of the current anthropogenic emissions from fossil fuel burning. There is of course great uncertainty in this figure, and a gap between what is theoretically possible and what could be achieved in practice. Read *et al.* (2001), addressing the same problem, considered that forest management oriented towards protecting and enhancing carbon stocks could lead to a strengthening of the biogenic carbon sink by up to 0.3 Gt C year^{-1}.

Estimates on the basis of data for savannas show the huge potential for harnessing these ecosystems for carbon sequestration. We may consider how much carbon might be sequestered if savannas were protected from burning and grazing so that an accumulation of carbon could occur. As we have seen, San José *et al.* (1998a,b) observed a sequestration rate of almost 1 t C ha^{-1} year^{-1} over 25 years. If we assume only half that rate, and apply it to all the 27.6 million square kilometres of savanna world-wide, we would expect a global carbon sink of 1.38 Gt C year^{-1}.

Global budget

Based on the data and discussion presented in the paragraphs above, it is possible to suggest a preliminary global budget for the current transfers of carbon between savannas and the atmosphere, expressed in billions of tonnes of carbon (Gt C) (Fig. 3). There are large uncertainties in the stocks and fluxes given, and especially in the flux attributable to biomass burning, which is given here as 4.5 Gt C year^{-1}. In the model represented in Fig. 3, the carbon lost by burning is approximately balanced by regrowth. Land-use change is a relatively small component, based upon the view that the conversion of savannas to agriculture on a world scale is 0.5–1.0% per year, and that the soil carbon remains intact during that processes, a contentious point which requires more research. If savannas were to be utilized as global carbon sinks it is evident that protection of the land from fire would be particularly useful, as the fire flux is as much as two-thirds the value of current fossil fuel burning.

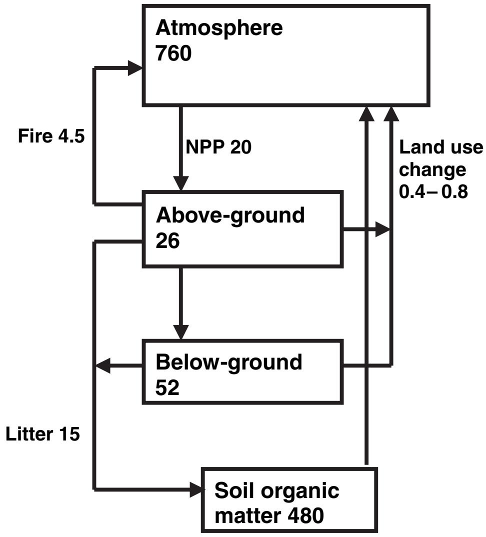

Figure 3 First estimates of the magnitudes of the major carbon fluxes between savannas and the atmosphere. Boxes give stocks in Gt C, arrows give fluxes in Gt C year^{-1}, all relating to the entire savanna area as defined in Table 4. 1 Gt = 10^9 tonnes = 10^{15} g. Abbreviation: NPP, net primary productivity which may be increasing at a rate of 0.39 Gt C year^{-1} as a result of environmental change. The stocks of carbon in above- and below-ground biomass and soil are based on data in Table 1 and are very uncertain. The annual combustion is estimated on the assumption that two thirds of above-ground carbon is lost following burning, and that burning occurs every 3.5 years. The flux representing land-use change is estimated from the assumption that savannas are being converted to low-carbon, agricultural systems at a rate of 0.5–1% per year. The flux from soil organic matter assumes an average decomposition rate of 3.1% per year: this value has not previously been estimated, and the chosen value is simply taken to be the value required to balance the model (i.e. to balance the overall gains and losses to the atmosphere).

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