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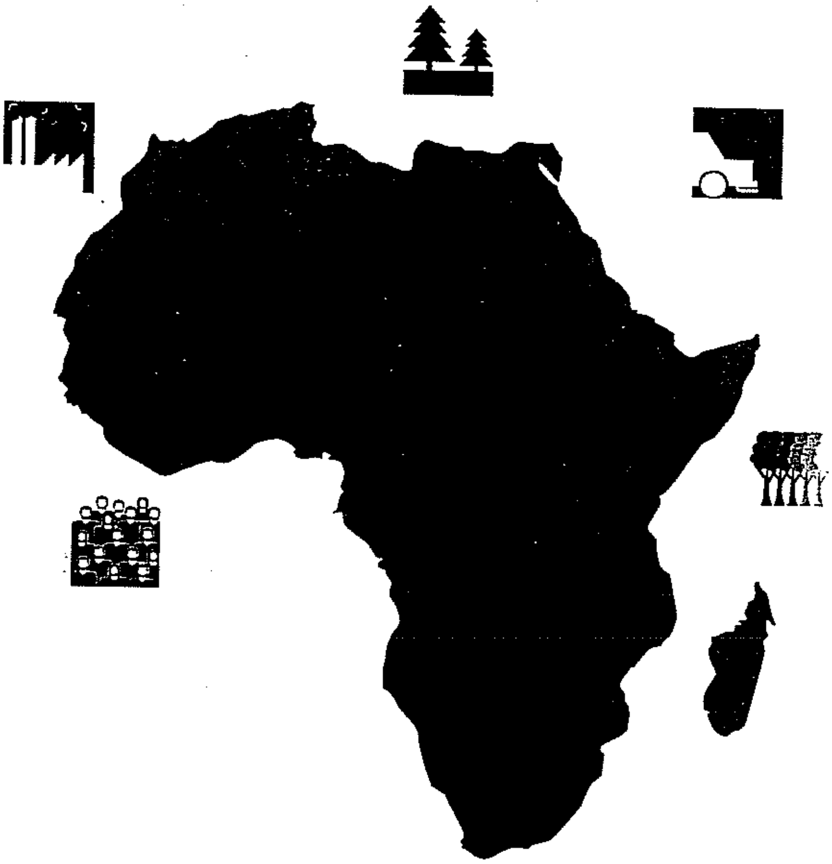

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AIMS AND SCOPE OF THE JOURNAL

The Environmental Professional is the official journal of the National Association of Environmental Professionals (NAEP). The central purpose of the journal is to provide an open forum to NAEP members and other concerned individuals for the discussion and analysis of significant environmental issues.

Professionals in different fields, such as government, consulting, research, industry, and education are faced with developing imaginative approaches to the resolution of environmental problems which often cut across disciplinary boundaries. In recent years, numerous theoretical concepts, methodologies for application, and specific case studies for the analysis of interdisciplinary environmental issues have been presented in diverse publications. *The Environmental Professional* provides a timely and single comprehensive outlet for the publication of such interdisciplinary findings.

Due to the very nature of contemporary environmental concerns and the diversity of NAEP membership, articles that have substantial interdisciplinary content are given priority for publication. Normally, reports of findings that go beyond a laboratory analysis, a field experiment, or a theoretical derivation and further discuss the ramifications of implementation in public, governmental, industrial, or educational situations are considered appropriate for the journal. In particular, studies linking scientific, technologic, and socioeconomic systems to effective impact assessment, regulation, and environmental protection are most welcome. In general, articles in *The Environmental Professional* will include those that attempt to capture and analyze the issues that occur at the interface of environmental science, technology, education, economics, sociology, administration, management, planning, law, and policy.

For the NAEP membership and the public, the journal will carry association news, chapter news, and brief sketches of representative professional activities of members. It will encourage timely discussion of the needs of the profession together with those of the programs of the NAEP. Periodically, the journal will devote its pages to selected topics of special concern to a significant segment of NAEP membership.

SEQUESTRATION OF CARBON IN SAVANNAS AND WOODLANDS

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Abstract. Over half of the vegetated surface of Africa is covered with savanna, a vegetation type in which trees and grasses co-dominate. Th proportions of woody to grassy biomass are highly variable and subject to management within broad climatic and edaphic constraints. Whe a savanna is converted from a grassy form to a more densely wooded form (through control of wood harvesting and/or fire suppression) substantial increase in carbon storage occurs (in the order of hundreds to thousands gC/m^2), over a period of thirty to fifty years. This carbo is distributed between the soil and the woody biomass. Retaining the carbon in sequestered form depends on being able to maintain th management regime, but catastrophic release is unlikely. In the worst case (conversion to crop agriculture) the release takes place over a perio of about a decade). Another approach to carbon storage is the replacement of shallow-rooted grasses (usually on highly acidic soils) with dee rooted acid tolerant grasses. Large amounts of carbon are sequestered deep in the soil as dead roots. The stability of this option is unknow The most stable form of carbon is elemental carbon, a component of the soot formed by fires. The most beneficial and secure option with respe to the global carbon cycle is to use the savannas to grow biomass fuels to replace fossil fuels.

1. Introduction

The amount of carbon dioxide emitted annually by anthropogenic activities (about 6 Gt) is small relative to the annual exchange between the atmosphere and biosphere (about 150 Gt) (Schimel, 1995). A small change in the balance between ecosystem carbon assimilation and respiration would therefore be sufficient to cancel a large part of the anthropogenic inputs, at least for a few decades while less carbon-intensive energy options and lifestyles were developed. There is some evidence that this is happening already — about 1.5 Gt of the global carbon cycle is unaccounted for. One of the many places it could be disappearing is into increased growth in temperate (LaMarche *et al.* 1984) and tropical trees (Phillips & Gentry, 1994). Much of the focus on carbon storage in the past has been on forest ecosystems and plantation trees (Dixon *et al.* 1994). In this paper we present evidence that the savanna woodlands, specifically in Africa, have substantial potential for carbon storage if managed appropriately.

Savannas are tropical ecosystems which are co-dominated by woody plants and grasses (Scholes & Walker, 1993). They include a wide variety of structural formations ranging from almost-closed canopy deciduous woodlands at the moist extreme to sparsely-treed grasslands at the arid extreme. Together they comprise the major biome in Africa (55% of the non-desert land area: see Table 1) and one of the major global biomes (about 16 million km^2, or 11% of the global vegetated surface (Scholes & Hall, in press). In Africa, a convenient high-level ecological classification separates the broad-leaved savannas typical of the subhumid interior plateau, where they occupy old, highly-weathered, infertile soils, and the fine-leaved savannas of the lower-lying, semi-arid regions where the soils are typically younger and more fertile (Scholes & Walker, 1993). Both have a potential fo carbon storage, but the potential is probably higher in th broad-leaved savannas than the fine-leaved savannas, due t the larger area and higher rainfall.

2. Storage of Carbon in Savanna Trees

The total ecosystem carbon in a typical broad-leaved savann is divided approximately in the ratio 4:1 between the soil an the biomass (Scholes & Walker, 1993; Scholes & Hall, i press). Within the biomass fraction, woody plants contai almost all the carbon, despite the fact that the net primar production may be almost equally divided between trees an grasses. Therefore, should the tree cover in a savanna chang significantly, the ecosystem carbon density (gC/m^2) will als change.

The woody cover and biomass in savannas is inherentl variable, both in time and space. A large part of this variabili can be accounted for by differences in climate and soil. I general, humid areas have a higher woody cover and bioma than dry areas, and deeper, more porous soils have more tre cover than shallow or clayey soils (Nadelhoffer *et al.* 1995 The variation which remains once these broad trends hav been accounted for is large, and is mainly related to lan management history - particularly the fire regime and woo cutting. Thus for a given climate and soil, the variation i possible tree biomass can be wide, and is under the influenc of management. For instance, in *miombo* woodlands, whic are one of the most extensive savanna types in Africa, th linear relationship between mean annual precipitation an tree aboveground biomass has a S_{xy} of 0.441 Mg/ha (n= (Walker, 1985). In other words, at a given rainfall, the rang of tree biomass which includes 95% of the stands is appro

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Table 1. The area of savannas in Africa relative to other vegetated surfaces (thousands of km^2).
Source: (White, 1983).

Biome	Vegetation units defined by White (1983)	Area	Subtotal
Savanna			9171
Broad-leaved, moist-infertile savanna:	Drier Zambezian miombo woodland (Brachystegia and Julbernardia)	742	5413
	Sudanian woodland with abundant Isoberlinia	1054	
	Mosaic of Brachystegia bakerana thicket and edaphic grassland	144	
	Undifferentiated woodland. Sudanian	1469	
	Undifferentiated woodland. Ethiopian	126	
	Undifferentiated woodland. North Zambezian	247	
	Undifferentiated woodland. South Zambezian	204	
	Wetter Zambezian miombo woodland (Brachystegia, Julbernardia and Isoberlinia)	135	
	Mosaic of wetter Zambezian woodland and secondary grassland	60	
	Jos plateau mosaic	10	
	Mandara plateau mosaic	7	
Fine-leaved, arid-fertile savanna:	Transition from undifferentiated woodland to Acacia deciduous bushland and wooded grassland. Zambezian.	306	3165
	Transition from undifferentiated woodland to Acacia deciduous bushland and wooded grassland. Ethiopian.	92	
	Transition from undifferentiated woodland to Acacia deciduous bushland and wooded grassland. Windhoek.	19	
	Sahel Acacia wooded grassland	917	
	Acacia polyacantha secondary wooded grassland	11	
	Mosaic of East African evergreen bushland and secondary Acacia wooded grassland	132	
	Somalia-Masai Acacia-Commiphora deciduous bushland and thicket	1216	
	Tugela basin wooded bushland	8	
	Kalahari Acacia wooded grassland	464	
Mopane savanna: subtotal:	Transition from Colophospermum mopane woodland to karoo shrubland	54	593
	Colophospermum mopane woodland	539	
Rest of vegetation			7375
Forest		3031	
Fynbos		96	
Grassland		1508	
Afro-alpine		35	
Mosaics		2705	
Desert			10994
GRAND TOTAL			27540

mately 4$S_{x,y}$, or 1.76 Mg/ha. A similar relationship between rainfall and stand basal area has $S_{x,y}$ of 0.243 (n=15). Given that the mean basal area of miombo woodlands is around 10 m^2/ha, the scope for modification *within natural limits* can be seen to be about 10% of the mean.

An analysis of published aboveground biomass data from three drought-deciduous tropical forests, five woodlands and 15 open savannas worldwide (Scholes & Hall, in press) gave a mean aboveground woody biomass (and standard deviation) of 114.4 (54.6), 61.6 (28.5) and 18.6 (9.6) MgDM/ha respectively (Scholes & Hall, in press). The biomass distributions, as nearly as can be estimated from such a limited sample, are approximately normal. Therefore, in each case, transforming the vegetation from its median state to a carbon density attained by the top 10% of the stands would involve approximately doubling the stored carbon.

Another way to consider the role of woody plants in carbon storage is in terms of the relationship between the carbon and nutrients: nitrogen in particular but also phosphorus and other nutrients. There is much evidence to suggest that natural ecosystems in general are nutrient-limited; in other words, the rate at which they can accumulate carbon depends on the availability of other elements, such as N and P, which are essential components of the organic molecules which make up biomass and must be present in certain fairly fixed ratios to carbon (Frost & Chidumayo, submitted). The bulk of the tree biomass has a C:N ratio of around 200:1, whereas the bulk of grass biomass has a C:N ratio of 20-50, and soil has a ratio of 10-20. Thus a single atom of nitrogen can immobilise 200 atoms of carbon in the form of wood, but only 10 in the form of soil organic matter.

The storage of carbon in trees is a transient phenomenon. In other words, carbon will only be accumulated for the duration of the period over which the biomass is increasing. At some stage the biomass will have increased to the level where respiration once again exactly equals assimilation and the ecosystem will be in net zero flux with respect to carbon. Of course, this 'steady-state' equilibrium is more conceptual than actual, since it only applies to long-term and large-scale averages. At the scale of individual trees there is no equilibrium: trees grow, and then die and decompose.

A key question is the duration of the accumulation period, or alternatively, how fast can savanna woodlands accumulate biomass? The upper limit of the carbon accumulation rate is determined by the vegetation net primary productivity (NPP), which is mainly a function of climate. Semi-arid savannas have a total (above- and belowground, tree and grass) NPP of around 500 gDM/m^2/y (about 225 gC/m^2/y), while very moist savannas (300 days of unlimited evaporation per year) have an NPP of around 3000 gDM/m^2/y (about 1350 gC/m^2/y). The relationship in between these limits is approximately linear (Scholes & Hall, in press). A large part of the NPP is allocated to short-lived structures, such as leaves, fine roots and twigs, which have little impact on C storage. The proportion allocated to large woody structures (the bole and coarse roots) varies with the stature of the vegetation, from less than 5% in a very open wooded grassland to perhaps 60% in a closed woodland. Very little reliable empirical data exists to support these estimates; they are considered conservative.

There is a small amount of data on stem increment in savannas. 'Increment' is the annual increase in stem radius (or equivalently, the diameter, circumference or stem cross-sectional area). Since the aboveground woody biomass is directly related to the stem dimensions (Tietema, 1993), and it is inferred that the belowground woody biomass bears some predictable relationship to the aboveground biomass, stem increment can be used as a surrogate for woody biomass growth rate. Stem increment in savannas varies from 2-5% of the basal area of the stand, with a weak suggestion that the percentage increment declines as the basal area of the plot increases (both within one plot over time, and comparing plots in different locations). Combining this information with the type of relationship mentioned above between climate and mean stand basal area, and further relationships between stand basal area and aboveground biomass, the rate of accumulation of woody biomass in South African savannas is estimated to range from 25 gDM/m^2/y at the arid extreme (200 mm annual rainfall) to 250 gDM/m^2/y at the moist extreme (900 mm annual rainfall) (Von Maltitz & Scholes, submitted).

A third rough way to estimate the potential rate of carbon accumulation in savanna trees is to estimate the time required by an individual tree to reach maturity. For most savanna trees this is of the order of 30 - 100 years. This is the minimum duration of the period for which the savannas could act as carbon sinks.

The above estimates assume that the growth rate of savanna trees will remain constant in the future. The effects of a rising atmospheric carbon dioxide content on the growth rate of savanna trees is unknown, but probably positive. The increase in growth rates of trees under doubled CO_2 is generally 15 to 35% (Dahlman, 1993). It may be lower under highly nutrient-constrained conditions, but tends to be higher under water constraint, which is typical in savannas.

3. Storage of Carbon in Savanna Soils

Although savanna soils are typically low in carbon (Montgomery & Askew, 1980), most of the ecosystem carbon store is nevertheless located there. There are three main reasons for relatively low organic mater content of savanna soils: on average they are sandy and dominated by low-activity clays, resulting in a low potential for stabilising carbon; the soil temperatures are high, which promotes respiration; and a significant fraction of the assimilated carbon is lost to fires.

Soil carbon in any ecosystem occurs in several forms. A large proportion is as litter, both on the soil surface and within the profile (where it mostly consists of dead fine roots). Litter is defined as recently-dead organic material, mostly of plant origin. Although it is partly decomposed, the cellular structure is still microscopically discernable. The fragments larger than 2 mm are arbitrarily excluded from analyses of soil organic matter (SOM) as a result of the sieving procedure applied during sample preparation. A large proportion (40-70%) of the smaller than 2 mm SOM nevertheless consists of small particles of litter, sometimes called particulate organic mater (POM) (Cambardella & Elliott, 1992). It has a relatively low density (it can be partially extracted by floatation in water) and is therefore also known as the 'light fraction'. This material has a decay rate typical of litter, with a half-life of months to years. The decay rate is largely controlled by soil moisture and temperature, but also by the chemistry of the litter. A high content of lignin and phenolic compounds relative to nitrogen leads to a low decay rate. The second largest SOM fraction consists of humified substances, which are amorphous, high molecular weight organic compounds resynthesised from the litter. They are typically stuck to the mineral fraction of the soil and therefore have a high apparent density, and are thus called the 'heavy fraction'. Their complex structure and association with clays makes them extremely resistant to bacterial decay; they may therefore have half-lives of decades or centuries and are also referred to as the 'passive' soil carbon pool.

The most rapidly-changing SOM component is the microbial biomass, which typically makes up 2-5% of the total, and the low-molecular weight organic compounds such as sugars and proteins. The latter have a half-life in the soil of only hours. Stability of soil carbon storage in soils therefore depends on the passive pool and, to a lesser extent, the soil litter.

There is substantial potential for increasing the carbon stored in savanna soils and several mechanisms by which such storage could be achieved. Firstly, when the tree cover and biomass of a savanna increases, so does the soil carbon density. This can be observed within a savanna stand, where there is an approximately two-fold increase in carbon density between soils located below a tree canopy, and those between tree canopies (Scholes & Walker, 1993; Belsky *et al*. 1993). It is also apparent comparing the mean carbon density of woodlands (11180 gC/m^2) to that of open savannas (5650 gC/m^2) (Scholes & Hall, in press). Several causal factors are involved. Firstly, the combined tree and grass NPP of the microhabitat immediately below the tree canopy is higher than that of the intercanopy habitat (Belsky *et al*, 1993). Secondly, the soil moisture and temperature regime there are different. The relationships between water, temperature and litter decay rate are complex and non-linear, so the subcanopy microclimate could in some circumstances promote decay, while in others retard it (Scholes *et al*, 1994). Thirdly, the chemical composition of savanna tree leaf litter is different from that of grass litter, and in general more resistant to decay due to the presence of tannins and lignin (Scholes & Walker, 1993).

One method of increasing carbon storage in savannas is therefore to allow the tree biomass to increase. The rate at which soil carbon accumulates is less than the rate of accumulation of biomass, but can be expected to continue for many years after the aboveground carbon has reached a new equilibrium, due to the delays inherent in the formation of soil organic matter. Some data are presented in Table 2 which show the accumulation rates which have been measured during long-term fire-exclusion experiments, which are of the order 3-30 $gC/m^2/y$. Note that in some of the studies, the topsoil carbon decreased; this issue is discussed further below.

A second method of soil carbon accumulation in savannas is by encouraging the growth of deep-rooted grasses (Fisher *et al*, 1994). This mechanism has been reported for South American grasslands, where African savanna grasses have been introduced to replace shallow-rooted native grasses. Carbon accumulation rates of between 259 and 1267 $gC/m^2/y$ have been reported over 4 to 10 year periods (total increases of 2590 to 7040 gC/m^2 to a depth of 1 m). These high rates of accumulation over short periods of time must mean that most of the carbon is in the form of particulate organic matter: in other words, dead roots. A number of questions remain unanswered. Would these grasses perform in the same way in Africa, their native environment? Why do the South American grasses not root deeply, if resources are available there ? For how long can such accumulation rates be sustained? How stable is the carbon so stored ?

A third potential mechanism for soil carbon storage is by fertilising the soil. This both increases primary production, and thus organic matter inputs to the soil, and (following the ecosystem stoichiometry logic outlined above) allows stable SOM molecules to be built. This mechanism operates in temperate grasslands, but there are few data to test it in tropical situations. A 40-year factorial nitrogen and phosphorus trial in grasslands derived from savannas at Towoomba in South Africa showed no significant increase in soil carbon in the top 20 cm, despite a four-fold increase in grass production. In this case, the hay is cut and removed from the site, rather than decaying on site and adding to the SOM (Donaldson, 1984; R.J. Scholes, unpublished data).

4. Storage of Elemental Carbon

A forth mechanism of C storage is through converting a portion of the aboveground carbon to elemental carbon (soot or charcoal) through the use of fire. Elemental carbon is highly stable, since micro-organisms are unable to degrade it. It forms a portion of the 'passive' pool, from which it has usually not been differentiated in the past. It is speculated that some of it may occur in the soil either in crystalline form (such as graphite or micro-diamonds) or as complex soot polymers, such as fullerines ('bucky-balls'). A large part is probably in the form of fragments of charcoal, which is not completely elemental and therefore can be slowly decomposed. How-

Table 2. Changes in soil carbon density in African savannas as a result of fire exclusion and/or the cessation of cultivation. The bulk density was assumed to be 1.5 Mg/m³ in all cases.

Study	Depth (cm)	Soil carbon content (%)		Period (years)	Rate of change (gC/m2/y)
		Initial	Final		
Ndola fire trials, Zambia (Trapnell et al, 1976)	0-15	0.86	0.85	25	-0.9
	15-30	0.43			
	30-61	0.29			
	61-91	0.22			
	91-122	0.16			
Olokemeji fire trials, Nigeria (Moore,1960)	0-5	3.8	4.3-3.0	30	-32.5 to 32.5
	5-10	2.6	2.8-2.1		
	10-20	1.7	2.0-1.7		
Nwanetsi fire trials, South Africa (Jones et al. 1990)	0-15	2.0	2.5	34	32.5
West African fallows (Nye & Greenland, 1959)	Calculated on theoretical grounds. calibrated using West African savanna data: top 30 cm				2 to 18.5

ever, charcoal with ages exceeding one thousand years is regularly recovered from soils in archaeological sites in Africa.

Elemental carbon can make up 4 to 40% of the particle mass of smoke, depending on the degree of oxygenation of the fire (Lobert & Warnatz, 1993). Intense 'flaming' combustion, which is highly oxygenated and typical of savanna fires, produces black, sooty smoke, whereas the smouldering combustion typical of burning wood produces white, ashy smoke with little elemental carbon. The amount of smoke produced is also a function of the oxygenation conditions — flaming combustion produces far less than smouldering combustion (Ward & Radke, 1993). Taking both of these effects into account, savanna burning has been estimated to generate 357 GgC/y of elemental carbon in southern Africa, or 0.05gC/m²/y. This value is fairly constant between the frequently burned broad-leaved savannas and the infrequently burned fine-leaved savannas, due to the compensating effects of combustion oxygenation. An unknown fraction of this is blown out to sea, where it nevertheless remains sequestered; the rest settles to the ground and is incorporated in the soil. Given that this material must have a half-life of hundreds or thousands of years, this steady rain must mean that a portion of the organic matter in savanna soils must be elemental carbon. For instance, if it has a half-life of 5000 years, then 1.5% of the mean of 5600 gC/m²/y in savanna soils is predicted to be elemental.

5. Effects of Fire Regime on Savanna Carbon Density

Fire has two effects on carbon density: it is a major controller of the tree biomass; and it consumes carbon itself, preventing it from entering the soil. In theory, therefore, fire exclusion should lead to an increase in ecosystem carbon density. This seems to be true in all savannas with respect to the carbon in woody biomass, but is not necessarily true for carbon in the soil (Table 2). The failure to detect increases in SOM may partly be due to methodological issues - in most studies soil carbon is only measured in the top 15 cm, while it is possible that soil carbon may be accumulating at greater depths in the fire-protected plots. Trapnell et al (1976) suggest that the litter is being consumed by termites, in which case the SOM becomes concentrated in the termite mounds, and is underestimated by the typical sampling schemes.

6. What is the Sequestration Potential in African Savannas?

Given the paucity of the data, it is not possible to estimate the carbon storage capacity of African savannas with a high degree of confidence. However, some approximate calculations can be made. Based on the review of mechanisms above, a storage rate in soils of around 30 $gC/m^2/y$ appears achievable in both arid and moist savannas by suppressing fires and allowing an increase in tree density. Control of harvest rates to below the rate of regrowth, coupled with fire suppression, would allow an aboveground biomass increase of at least the same rate, even in arid savannas. A conservative combined estimate would therefore be about 60 $gC/m^2/y$. If this is applied to the total extent of African savannas (9×10^{12} m^2:Table 1), the maximum storage potential is of the order of 540 Tg C/y, approximately 10% of the global anthropogenic carbon forcing of the atmosphere. Obviously, not all the savannas will be available for this purpose. This 'maximum potential rate of accumulation' could be sustained for somewhere in the order of the time taken for a sapling to reach maturity (30 years), after which it would decline substantially. The value of stored carbon, at a rate of $10/Mg, would be $6 billion/y, in the same order as (and perhaps a little larger than) the current market-economy agricultural output from savannas in Africa.

The purpose of the approximate calculation given in the previous paragraph is merely to establish that African savannas have sufficient C storage potential to be worth considering. Competing demands for the land make it unlikely that carbon storage will be the only land use practiced in savannas. A rigorous assessment of the realistic C storage targets would require a region-by-region analysis, which took agricultural expansion into account. As an example of a site-specific calculation, the broad-leaved savanna at Nylsvley in South Africa has been the subject of detailed study (Scholes & Walker, 1993). The soils are very sandy and about 1 m deep. The savanna ecosystem found there is functionally quite similar to the savannas on deep sandy soil throughout southern Africa, an area of about 2 million km^2. The mean annual rainfall is 630 mm, placing this savanna in the semi-arid range, and at the arid limit for broad-leaved savannas. The total system carbon density is 9357 gC/m^2, of which 6784 gC/m^2 is as particulate or humified SOM, 950 gC/m^2 is as above and belowground litter (the exact amount fluctuates between seasons), and 1122 gC/m^2 is as wood. The remaining 500 gC/m^2 is in a variety of small, shortlived and variable pools, such as fine roots, leaves and microbial biomass.

This savanna has been observed, through repeated measurements of all the trees in 6 large transects over a 16 year period, to be accumulating tree biomass at a rate of about 0.6 tDM/ha/yr (30 gC/m^2). The tree dimensions are converted to biomass via allometric relations developed for the site. The reasons for the increasing woodiness are probably related to the protection of the site from major disturbance or wood harvesting (it is a nature reserve used for research purposes) and reduction in the frequency and intensity of fire. A patch of floristically-similar savanna on a neighbouring farm, from which fire has been excluded for 35 years, has a woody plant basal area 57% higher than the average for Nylsvley, which translates into a wood increment of about 20 $gC/m^2/y$. The owner prior to 1974 was a cattle rancher opposed to the use of fire, but lacked the resources to reliably exclude fires from neighbouring properties - the area probably burned once every three years. The current conservators are able to manage fire, and aim to burn on average once every five years (in practice, a little less frequently). The fires are generally relatively cool.

If it is assumed that the area covered by tree canopy increases at the same rate as the tree basal area, then the associated increase in SOC in the subcanopy habitat (which is 20% higher in C than the between-canopy habitat, measured to a depth of 1 m) adds another 9 $gC/m^2/y$. This does not include unstable pools, such as leaves, twigs and surface litter. The evidence from the neighbouring fire-protected plot suggests that the canopy cover may stabilise at about 65% after about 50 years: in other words, the relatively open savanna (35% canopy cover) will be converted to a relatively closed woodland.

Thus, in this case a savanna with little potential for crop agriculture (the rainfall is marginal and the soil poor) has accumulated C for several decades at a rate conservatively estimated at 49 gC/m^2 for two decades (about 10% of annual NPP) and with potential to continue doing so for perhaps another three decades. The required conditions were curtailing wood harvesting, prevention of clearing for crops, and reducing (not eliminating) fire frequency. The land continues to be grazed (in this case, by wild ungulates, but on surrounding properties, by cattle). A sustainable harvest of fuelwood (i.e. at a rate less than or equal to the rate of wood production) which was then efficiently substituted for fossil fuel, would allow this system to continue saving carbon emissions at a rate of 45 $gC/m^2/y$ (the current wood production rate) indefinitely.

This example is extrapolatable to many broad-leaved savannas not located in highly populated areas: in other words, excluding West Africa, but including perhaps 80% of the broad-leaved savannas in southern Africa. The main core of broad-leaved savannas receive around 1000 mm of rainfall per annum, and would therefore have rates of NPP significantly higher than Nylsvley. Despite the constraints imposed by aridity, the fine-leaved savannas can achieve similar C storage rates (note the fire exclusion experiment at Nwanetsi, in Table 2, which accumulated 32 $gC/m^2/y$ in the topsoil alone for a period of 34 years, and probably another 30 gC/m^2 in woody biomass, although the latter has not been rigorously quantified). The higher clay content, and greater prevalence of high-activity clays, enhances the soil carbon storage potential in fine-leaved savannas: however, in general they are currently subject to greater human use pressures. This may change in the future as new agricultural technology makes the broad-leaved savannas agriculturally attractive.

7. How Secure is the Carbon Stored in Savannas?

Savannas are characterised by the annual occurrence of a prolonged dry period. This results in a high susceptibility to fire — in the long term, it is impossible to keep fire out of savannas, it is only possible to reduce the frequency. With suitable investment in fire prevention and suppression, the frequency could probably be reduced to (on average) once in 50 - 100 years, the typical rate for plantation forests in southern Africa. The fire susceptibility of savannas decreases if the woody cover increases, due to the suppressive effect of tree canopies on grass growth. Furthermore, a single fire is unlikely to cause the loss of more than a few percent of the aboveground woody biomass, except under unusual circumstances. Nevertheless, the aboveground carbon will always be susceptible to relatively rapid loss, either by land use change or by combustion. If not disturbed, it is secure until it decays at the end of the tree life cycle, which in the case of savanna trees is about a century.

The belowground carbon is much more secure, since it only affected by fire in the top few centimetres. The plough layer (0-30 cm) is susceptible to loss following conversion to cropland. Savanna soils, because they are generally sandy, have a large fraction of their SOM in the relatively-easily decomposable particulate form (Scholes *et al*, 1992). Coupled with the high soil temperatures, this means that about 50% of the SOM in the plough layer can be lost in 20 years (Nye & Greenland, 1960).

One of the most secure forms of carbon is as fossil fuel. It would make more sense to use the biomass production in savannas as a fuel source, at high efficiency, in place of fossil fuels, than to use the fossil fuels and try to recover the carbon from the atmosphere into an at-risk form such as biomass.

8. Conclusions

1. Carbon can be accumulated in savannas at a rate of 200-1000 gC/m^2/y for a period of about a decade by encouraging deep-rooted grasses. However, if this involves cutting down the trees and burning them or allowing them to decay, the carbon balance will probably be negative. The carbon is mostly in the particulate form, and could be lost again in a similar period.

2. Carbon can be stored in tree biomass at a rate of 10-100 gC/m^2/y over a period of around 30 years. The carbon is secure for a period of around a century unless burned.

3. Carbon can be stored in the soil in the form of litter and humified compounds at a rate of up to 30 gC/m^2/y, probably accumulating over a period of about a century. This material is relatively stable, since it is protected from fire, but could be lost over a period of 20-50 years if the soil were cultivated.

4. Carbon is stored in elemental form due to fires at a rate of about 0.05 gC/m^2/y. This carbon is extremely secure.

5. Assuming that the entire area of savannas in Africa were managed to maximise carbon storage, around 540 TgC/y could be stored over a period of 30 years. This carbon would be at risk from fire and discontinuance of the C storing management practices. It would be preferable to move to a sustained harvest management in which the carbon accumulated in wood was converted to long-lived articles, such as hardwood furniture, or burned in place of fossil fuels.

9. References

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