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Carbon sequestration in forests and woodlands (savannas).

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Processes that affect net emissions

Historical accounts, photographic records and quantitative studies have demonstrated extensive invasion of grasslands by woody plants and increases in woody plant density in savannas over the past 200 years (see comprehensive bibliographies of Archer 1994, 1995, Idso 1995). A widespread increase in the biomass of surviving neotropical forest over recent decades has also been reported (Phillips *et al*. 1998) and tree invasions (Mast *et al.* 1997) as well as the potential for increased carbon storage in unreserved timberlands of the United States have been highlighted (Sohngen and Haynes 1997). In fact woody plant thickening in grazed rangelands (also known as bush encroachment, shrub encroachment, woody weed increase, woody weed invasion and woody regrowth) is an example of the more general phenomenon of vegetation recovery and succession that either follows episodic ecosystem disturbance events, or is associated with certain protracted disturbances in many woody ecosystems (Gifford and Howden 1999).

Traditional explanations offered to account for the historic displacement of grasses by woody plants have centred around changes in climate, livestock grazing and fire regimes. Idso (1995) claimed that the worldwide invasion of grassland by trees and shrubs that began c. 200 years ago has closely followed the upward trend in the air's CO_2 content. However Archer *et al.* (1995) examined this argument in detail and provide convincing evidence that the correlation between CO_2 and woody plant thickening is spurious.

Fensham (1998) has recently suggested that the observed woodland thickening in Northern Australia is part of a normal tree death - regrowth cycle in this region, primarily driven by climate variation. But $\delta^{13}C$ analyses of soil organic matter in thickening woodlands indicate that these woodlands had a more open structure in the past (Burrows *et al*. 1998) - not a more wooded one as Fensham's fluctuating climate model implies. Boutton *et al*. (1998) also employed the $\delta^{13}C$ technique and reached similar conclusions about the nature of *Prosopis* invasion into the desert grasslands of the South-West USA.

Growing experimental evidence suggests all mixtures of mature trees and grass are unstable in savanna environments. In the absence of disturbances such as repeated fires, clearing by humans or feeding by large herbivores the tree cover increases at the expense of grass production, until it is limited by tree - tree competition (Scholes and Archer 1997). The rarity of the latter situation provides credence to the suggestion that both in Australia and elsewhere in the tropics/sub-tropics the savannas (woodlands) were maintained as a fire mediated sub-climax prior to the "recent" introduction of domestic livestock (Burrows *et al*. 1998). The prime agent changing the structure of these communities has been the conversion of land use from hunter-gathering or nomadism to the raising of sheep, cattle or goats - a practice which has often been associated with increased grazing pressure, reduced fuel loads and the containment of fire. It is indisputably a change brought about by altered management practices (Noble 1997).

The conversion of an open savanna to a closed woodland structure can lead to a change in potential above ground biomass from 2-10 t/ha to 30-100 t/ha (Burrows *et al*. 1999). Changes of the same order but different magnitude can be expected in below ground biomass stocks. For much of the world's broad leaved savannas there is an inverse relationship between herbage production and tree-shrub basal area. Thus, as the woody plants thicken potential livestock (ruminant) carrying capacity declines, and this should contribute to concomitant declines in methane emissions from the latter source.

The actual outcome in carbon storage terms will very much depend on the location of the woody plant thickening. Where demands for fuel wood or agricultural products dictate, or population density is high (e.g. West Africa), the thickening process will most likely be kept in check by ongoing management. Yet in other situations the value of timber products or potential recognition of thickening trees and shrubs as 'carbon offsets' may provide financial benefits (incentives to store carbon) which exceed those available from livestock raising or marginal farming. By way of contrast, Scholes and van der Merwe (1996) concluded that for much of Africa it would be preferable to move to 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.

Estimates of the net source or sink of carbon in terrestrial ecosystems can be divided into two types: those based on changes in land use and those based on periodic forest inventories (Houghton 1995). Houghton further observed that inventory data are generally applicable to forests only - systematically ignoring about 70% of the terrestrial surface not covered by these ecosystems. Woody plant thickening in savannas and grazed woodlands has also been ignored in inventory data so far because most of the trees involved have limited commercial timber value and therefore have not been censused; while the IPCC[A] focus has been on "Land Use Change and Forestry". However the recent COP4 meeting of the FCCC[B] held in Buenos Aires (Nov 1998) changed this area of responsibility to "Land Use, Land Use Change and Forestry" (decision FCCC/CP/1998/L.5) presumably because the *change* wording was being interpreted too narrowly by inventory compilers. This altered emphasis suggests that man induced changes in carbon stocks, resulting from changes in vegetation structure (thickening) should be recognised for inventory purposes; even though the dominant land use under which it is occurring (e.g. livestock raising) remains in place to various degrees.

Magnitude

Scholes and van der Merwe (1996) estimated the rate of accumulation of woody biomass in South African savannas at 250-2500 kg DM/ha/yr. This is comparable with a mean above ground dry matter accumulation rate for 47 grazed savanna sites in North Eastern Australia of 922 kg DM/ha/yr (based on an average 9 year observation period in which rainfall was below normal) (Burrows *et al.* 1998).

Scholes and Hall (1996) suggest increased tree cover in savannas could be contributing a worldwide sink of ≈ 2 Pg C/yr. However this potential could be limited in parts of Africa and South America because of population pressures on land use. In Australia, Burrows *et al.* (1998) calculate that vegetation thickening in the state of Queensland currently provides a sink in excess of 27 Tg C/yr[C] above ground. This approximates the C source currently attributable to land clearing in Australia (NGGI 1997). If below ground growth was also accounted for a further 9

[A] IPCC = Intergovernmental Panel on Climate Change
[B] COP4/FCCC = Fourth conference of the Parties to the Framework Convention on Climate Change
[C] P = Peta = 10^{15}; T = Tera = 10^{12}

Tg C/yr might be added to this sink, based on calculated root: shoot ratios - (see Burrows *et al*. 1999).

Savannas cover c. 9M km^2 of Africa or c.55% of the non-desert land area and are one of the major global biomes accounting for c. 16 M km^2 or 11% of the world's terrestrial vegetated surface (Scholes and van der Merwe 1996). Not all this area is undergoing thickening and some is being actively cleared for fuel wood or agriculture. Earlier Donaldson (1969) quoted van der Schijff (1964) as estimating that at least 13 M ha of savanna were in various stages of bush encroachment in South Africa. Contemporary reports (e.g. Milton and Dean 1995, Jeltsch *et al*. 1997, Moleele and Perkins 1998) suggest this encroachment remains widespread and could even be increasing. The data of Burrows *et al*. (1998) are based on an area of 60 M ha of grazed woodland in north east Australia which is in various stages of thickening in response to changed management practices (introduction of livestock grazing, reduced fire incidence).

Phillips *et al*. (1998) claim to have detected significant annual C sinks (0.62 ± 0.37 t C/ha/yr) in humid neotropical forests of Central and South America over a total area of c.8.7 M km^2. No statistically detectable change in biomass was found for the intact paleotropic (African, Asian, Australian) forests but these areas were only sparsely censused. The effect of fire exclusion in promoting forest expansion and thickening in the wet tropics of Australia and Central Africa is outlined by Hopkins *et al*. (1996) and King *et al*. (1997) respectively. Savannas are also thickening in North and South America (Buffington and Herbel 1965, Adamoli *et al*. 1990, Montana *et al*. 1995) but C sequestration rates and areas involved are inadequately detailed. However Archer (1995) found the mean area of closed-canopy woodland increased by 38% over the period 1941-1990 at his *Prosopis* study site in southern Texas. Basal area growth rates for *Prosopis* (Archer 1989, 1990) are in line with those reported for eucalypt woodlands in Australia (Burrows *et al*. 1998) and for woody species in savannas generally i.e. 2-5% of stand basal area/yr (Scholes and van der Merwe 1996).

The data cited by Archer (1989) suggest that *Prosopis* expansion could continue for at least another 100 years - assuming the maintenance of existing management and climatic regimes. Burrows *et al*.(1998) calculated it would take c. 50 years to arrive at a new equilibrium status for the grazed woodlands of north east Australia (based on a current mean tree live basal area of 9.6 m^2/ha, a mean site potential of 23m^2/ha and a current growth rate of 0.24 m^2/ha/yr). These estimates are in accord with those of Scholes and van der Merwe (1996) for African savannas. The latter authors further stated that, since published biomass distributions were approximately normal, transforming current forest, woodland and open savannas from their current median state to a carbon density attained by the top 10% of stands would involve approximately doubling the stored carbon.

[As noted earlier where woody biomass thickening is occurring on grazing lands it would bring about a reduction in livestock carrying capacity. This would reduce methane emissions from this source but its affects on other Greenhouse gases (except CO_2) are not known?]

Assuming woodland and forest thickening is encouraged the net carbon sequestered could remain at these raised levels for centuries. All mixtures of mature trees and grass are unstable in savanna environments (Walker and Noy-Meir 1982, Scholes and Archer 1997) especially when grazed by domestic livestock (Burrows 1980). Once a system has 'flipped' to the tree dominant state it is unlikely to revert to an open woodland structure without considerable energy inputs. In the absence of human intervention catastrophic fire is the major threat to carbon storage in 'closed' savannas. This may be impossible to prevent in the long term (50-100 years - Scholes and van der Merwe 1996) but since this vegetation type evolved under a regular burning regime, recovery post fire to the pre fire structure is usually rapid.

The greatest risk to ongoing vegetation thickening in forests and savannas is the need to use the land for fuel wood and agricultural products, especially in areas such as West Africa with expanding human populations. However the most widespread woody plant thickening in the world's savannas has occurred where Europeans occupied these lands and converted traditional land use to domestic livestock raising. This has invariably been associated with reduced fire incidence and the suppression of those fires which do occur. In the absence of governmental regulations or incentives not to clear, the livestock raiser will eventually seek to control tree densities in thickening savannas because in most instances (Burrows *et al.* 1990, Scanlan 1992) this is associated with reduced pasture production and lowered livestock carrying capacities.

So a critical greenhouse accounting conundrum arises as tree cover increases on agricultural land. If there is no economic incentive to retain trees landholders will embark on land clearing activities to "restore" agricultural production. Thickening can therefore be a significant catalyst for land clearing, but because there is a lag in the landholder's response, the biomass contained in the area cleared is greater than would have been present in the absence of thickening. Thus by ignoring thickening a large sink is not being included in National Greenhouse Gas Inventories, while the land clearing it provokes means an even larger CO_2 source is being released to the atmosphere.

Prevention of tree clearing could lead to compensation claims from owners of freehold land designated for agricultural production. However an incentive to further encourage tree thickening and maintain the stands generated is potentially available via proposed carbon trading or offset schemes. At an offset price of, say, $US 10/t of C fixed it would be very attractive, for example, for graziers to favour tree thickening with resultant reduced income from cattle in north east Australia; rather than concentrating on maximising cattle production alone (Rolfe and Campobassi 1997).

Projected climate changes under various greenhouse scenarios are still subject to debate (McKeon *et al*. 1998), although increasing temperatures associated with rising CO_2 levels are now generally agreed upon. While higher temperatures should favour C_4 cf. C_3 plants (including trees) this will be counter - balanced by improved water use efficiency of the latter under elevated CO_2 (Scholes and van Breeman 1997). Above average rainfall can play a major role in aiding the successful establishment of invading woody plants (Brown and Carter 1998), but imposed management still remains the proximate cause for woody plant thickening in savannas (Scholes and Archer 1997). The major risk to this increasing carbon sink is therefore likely to remain from management reacting to prevent it, rather than changing environmental variables.

Data needs, verification and accounting

Scholes and van der Merwe (1996), Burrows *et al*. (1997, 1998) and Phillips *et al*. (1998) detail similar procedures, based on forestry mensuration practice, for documenting fluxes in above ground woody plant biomass stocks. These involve determining allometric relationships for dominant tree species and using 'mean tree' approaches to calculate the biomass of minor components of the vegetation. These relationships are then applied to successive readings of the independent variable, usually stem circumference or diameter at breast height, measured on all the tree stems located in permanent monitoring plots or transect lines. Allometric methods are well established (Attiwill 1996, Kira and Shidei 1967, Whittaker and Woodwell 1968) although for large trees there is increased focus on random branch sampling (Valentine *et al.* 1984, Gregoire *et al.* 1995).

Monitoring focuses on the need to detect change and, because it is dependent on repeated observations, these must always be made at fixed locations to provide data which is comparable between visits (Critchley and Poulton 1998). The method of locating these monitoring sites therefore becomes critical to their accuracy in determining actual trends in population structure and biomass. The nexus lies between selection of field locations that are judged to be representative in some subjective sense, but which are not representative in a statistical sense (Gregoire *et al*. 1995).

This problem arises more in stating regional or country wide trends rather than trends occurring within individual forest plots or on specific landholdings. At the regional or country scale one needs only to sample areas with trees and not, for example, open grassland or cultivation if the prime purpose is to detect thickening effects. The 'treed' area is easily defined to-day with the aid of remotely sensed imagery.

Random selection of permanent sampling plots within wooded areas is still the ideal, but is generally precluded at regional or country wide scales by the inability to access all the randomly chosen sites; and by cost constraints. This problem has been addressed by Austin and Meyers (1996) and Phillips *et al.* (1998). Indeed Austin and Heyligers (1989, 1991) argue that for most ecological purposes representative sampling is more important than an unbiased stratified survey. With this approach the range of variation in vegetation is sampled, rather than trying to obtain accurate estimates of the mean value of basal area for species in the region.

Austin and Meyers (1996) propose examining the distribution of study plots in both environmental space (defined by temperature, rainfall and lithology) and geographical space to look for evidence of spatial bias in sampling. Once identified such gaps can be addressed, where practical to do so, while clearly the greater the number of plots monitored, the more confident one can be that responses are well defined. At a continental scale it would also be very important to identify and stratify regions or countries with different land management practices in place.

Burrows *et al*. (1997) addressed the issue of representativeness of their sampling plots in determining the rate of thickening in Queensland's 60 M ha of grazed woodlands. They initially classified the various sites sampled as being either in "regrowth", "growth" or "mature" states, approximating identifiable stages in the sigmoid growth curve, by taking into account measured (basal area increment) growth rates. A sensitivity analysis showed that varying the area of vegetation in each state (within reasonable bounds) around the proportions of the total grazed woodland estate estimated to be under regrowth, growth and mature condition, did not make much difference to the total calculated thickening rate for the area as a whole i.e. mean growth rate for all plots times the total area affected. [14.35 M m^2/yr total basal area increment cf. sensitivity analysis range of 12.99 - 15.07 Mm^2/yr]. Scholes and van der Merwe (1996) used an analogous approach to determine the carbon sequestration potential for the total savanna region in Africa.

Another uncertainty is the representativeness of the weather during the monitoring period. Savannas are noted for their pronounced seasonality and, at least for the sub-tropics, the unreliability of their rainfall. To avoid misleading trends it would therefore be desirable to report carbon sequestration rates averaged over a minimum of three and preferably five year periods.

At the individual plot level the combination of allometry plus measured stem growth increment is a very powerful and accurate predictor of above ground biomass flux. Various plot sizes and shapes are adopted in forest mensuration. In Australia, the transect recording and processing system (TRAPS) and associated software package for field data capture, storage and synthesis of tree/shrub growth parameters (Back *et al*. 1997) is now widely adopted for savanna monitoring. Permanently positioned monitoring sites (located with the aid of satellite imagery and placed within a larger buffer zone) are identified by steel pickets aligned 100 m apart along a north-south axis and relocatable using GPS. A length of galvanized pipe buried at the datum picket can be pinpointed with a metal detector if this 'key' picket is removed between recordings. The position of all woody plants is determined within a 10 cm x 10 cm grid defined by a tape measure placed on the transect line and by a graduated 2m rod advanced along this line and to the right and left of it.

This system thus provides repeatable and accurate recordings of tree and shrub location, establishment, growth (stem circumference at 30 cm above ground) and death within fixed transect bands. Sets of parallel lines (transects) are usually located at each site, with the distance between lines exceeding average intertree space. The length of the lines is adjusted so that at least 30 individuals of each species and size class of interest are located within the transect bands. Edge effects are less a problem in savannas cf. rainforest, for example, while the length of the transect lines minimises potential bias in plot placement - given that the datum picket is the only one subjectively positioned once the site is chosen.

Growth models are now available which accurately predict the growth of trees in plantations (Weinstein *et al.* 1991, Landsberg and Waring 1997, Coops *et al.* 1998). However the utility of such models in predicting the growth of 'natural' vegetation responding to variable climatic and management inputs has yet to be proven. Likewise the capacity to determine forest and woodland biomass using remote sensing techniques is rapidly evolving (Richards *et al.* 1987, McDonald and Ulaby 1993, Sun and Ranson 1995). However it will be some time before these approaches offer the accuracy and reliability necessary to account for sequestration fluxes in 'natural' vegetation, over the short time scales required for Inventory or Carbon Offset crediting purposes.

The measurements detailed here are similar to those necessary to determine above ground biomass and its flux under, for example, the commercial forestry component of the IPCC (1996) methodology. The IPCC Land Use Change and Forestry Reference Manual (1996) is replete with recommendations for the inclusion of all fluxes of carbon, which result from human activities, as sources or sinks in national greenhouse gas inventories. In this regard fluxes resulting from land clearing and woody weed invasion are readily apparent, but those due to regrowth, secondary forests (Fearnside and Guimares 1996) and thickening of savannas (bush encroachment) are less obvious. The reason for the latter situation is that changes occurring are often subtle, and their connection with human activity is not necessarily clear to observers not trained in range science or the community ecology of vegetation.

Nevertheless the current (1996) IPCC Land use Change and Forestry Guidelines Reference Manual (p. 5.16) notes that "forests classified as natural, or abandoned/regrowing, can be excluded from the woody biomass stocks accounting only if there is no significant human interaction with these forests. If they are being used as a source of fuelwood, or are being affected in other ways by ongoing human activities they should be accounted for on an annual basis as part of changes in forest and other woody biomass stocks". Thickening of savannas and woodlands, as previously described, clearly meets the condition of "being affected by ongoing human activities". Indeed the Reference Manual further states (Section 5.2.2) that "woody shrubs in grassland should be included when they are a significant component of total changes in biomass stocks". The absence of this impact in national greenhouse inventories to date therefore reflects a lack of access to the necessary plot data (cf. commercially logged temperate forest, for example) rather than a lack of recognition of its appropriateness under IPCC (1996) definitions.

The cost of measurement is very much a function of the location and density of the vegetation being monitored. It is assumed that suitable allometric relationships are known or can be approximated for that vegetation whose carbon flux is being followed. This may not be as daunting as first appears e.g. Phillips *et al*. (1998) justified the use of a common allometric relationship to estimate the biomass of neotropical forests from permanent plots. Burrows *et al*. (1999) found there was no significant difference in the slopes of regression used to predict above ground biomass for three widespread Australian savanna eucalypts (*Eucalyptus crebra*, *E. melanophloia* and *E. populnea*).

The Queensland Government maintains a network of c. 125 permanent monitoring sites representative of c. 600,000 km^2 of grazed woodland (savanna) for a total cost of c. $Aust. 250,000 per year. This includes staff, travel costs and data processing and should be sufficient to permit accurate reporting of above ground biomass (carbon sequestration) fluxes on a three yearly cycle. However this does not include the cost of actually setting up the initial site network - which in this case was gradually implemented over a 15 year time frame.

The size of the carbon sink detected by this permanent monitoring site network (and not yet included in Australia's national greenhouse gas inventory) is c. 27 Tg C/yr (Burrows *et al*. 1998), more than warranting the cost of its determination. The sensitivity analysis referred to earlier (Burrows *et al*. 1997) suggests that, provided monitoring sites are selected so as to be truly representative of the vegetation being monitored, it may be sufficient to record c. 30-40 sites per region. Measurement accuracy is ensured by the TRAPS (Back *et al*. 1997) methodology. The tradeoffs between sampling effort, logistical constraints and power to detect trends can be assisted by statistical power analysis of an initial data set (Gibbs *et al.* 1998).

The preceding discussion refers to above ground fluxes in biomass and carbon sequestration. As a general rule it is usually accepted (by default?) that below ground biomass flux will be proportionate to that above ground, in line with community root: shoot ratios (e.g. Nihlgard 1972).

Verification and auditing of biomass flux in thickening woodlands should be comparatively simple and inexpensive in relative terms. For example, suppose the growth in Queensland's grazed woodlands was included in Australia's National Greenhouse Gas Inventory based on the information recorded on the 125 TRAPS sites previously detailed. An international audit team could:

(i) interrogate a satellite imagery data base, not necessarily kept in the target country, to ensure the integrity of all sites had been maintained (site Lats and Longs would be logged with the audit secretariat)
(ii) randomly select (say 25) of the sites for ground inspection in the audit year
(iii) on arrival at the site quickly verify site tree growth by reading dendrometers attached to a subset of selected trees/shrubs contained within the transect lines. Burrows, Back and

Anderson (unpublished) have confirmed that the percentage annual growth increment recorded in selected dendrometers accurately reflects that of the total plot. On this basis it would be possible to sample this subset of 25 permanent transects located over the 600,000 km^2 area within 7-10 days. Obviously the principle would remain constant but the logistics of such auditing would be very much country dependent.

Support for such an audit would require the complete re-recording of all individually censused trees/shrubs in each permanent plot on at least a five year frequency. This would allow accurate recalibration of site growth and the dendrometer subset. In practice dendrometers themselves need to have their springs readjusted on a 12-18 month basis to maintain appropriate tension around the trunk circumference. This 'regular' site maintenance visit also serves as a local check on site integrity etc.

Associated impacts

Increased tree cover could enhance the habitat of arboreal animals and browsers, reduce runoff and erosion from landscapes and contribute to cleaner water supplies. By corollary it may reduce the water yield of catchments and pasture availability for ranchers or pastoralists. Increased tree cover could also help ameliorate salinisation in areas susceptible to this problem.

The most dramatic relative change as a result of woody plant thickening or encroachment occurs in savannas. In these regions thickening is more likely to impact on livestock rather than crop production.

Managers of land assigned for 'agricultural' purposes will, in the absence of regulation or alternative incentives, attempt to maintain a tree-grass balance in savannas, in favour of grass production. Trees will also tend to be controlled under subsistence agriculture regimes, in regions with high population densities or where wood is needed for fuel and/or cooking. These processes will usually become more acute the further the tree-grass balance switches in favour of trees.

In view of the above, jobs and rural incomes would be expected to decline as thickening proceeds and in the absence of ameliorative programs. In those countries facing a large net emission problem under the FCCC there could be steps taken to restrain clearing of landscapes subject to tree/shrub thickening. Such a regulatory approach will initially impact on government leasehold land, but it could also flow on to freehold tenure.

Annex I countries experiencing significant vegetation thickening are most likely to be best placed to take part in Carbon Offset programs which effectively 'reward' landholders who foster increasing carbon sinks. In such countries agricultural production is less critical to the nation's GDP. Therefore some agricultural production might be forgone, provided the landholder could access another form of income e.g. C offsets. However if C sequestration is favoured in this manner it should be encouraged based on a global perspective of the greenhouse problem, irrespective of the country or location in which it occurs.

Costs and Barriers to Adoption

Thickening in savannas and woodlands is widespread under livestock grazing, which is also often associated with a change in traditional burning practices. If grazing has been the catalyst for a change in vegetation structure it also provides the motivation for landholders to attempt to slow down the thickening process or reduce this new woody plant density. Blainey (1982) notes that without Aboriginal fires the grassy woodlands that occupied much of the fertile crescent in south-eastern Australia would have been scrubland or forest at the time of European occupation. Yet a period of fifty years was sufficient to change the character of this savanna country when fires were suppressed by Europeans and their livestock. Blainey concludes that "the widespread ringbarking (girdling) that was carried out around the turn of the 20^{th} century occurred in the regrowth (increased tree density). The landholders were attempting to re-establish the original grazing capacity". This tension between livestock carrying capacity and increased tree/shrub density is widespread throughout the world's savannas subjected to this form of agricultural production. Since the 1950's it has led to a huge industry producing and marketing aboricides, as well as widespread use of bulldozer and chain to keep woody plants "in check".

Signatories to the FCCC have much to gain by recognising the man induced nature of savanna thickening and accepting its potential as a substantial carbon sink. Under these circumstances there is no doubt that landholders would welcome the opportunity to further encourage vegetation thickening on their land, in return for carbon offset payments from fossil fuel users such as industrial plants and power utilities. In Queensland, Australia land with a gross margin from cattle raising of < $Aust.8/ha is currently fixing c.400 kg C/ha/yr in thickening vegetation. This suggests that a modest carbon offset credit would be sufficient to encourage a landholder to maintain and further foster tree growth on his land. Monitoring and maintenance costs (e.g. fire prevention and control) would need to be factored in. There would be few opportunity costs involved because of the limited land use options in savannas. However some form of legal caveat would be required to assign rights over carbon sequestration credits to the relevant firm or industry.

Conclusion

- There is overwhelming evidence that observed changes in structure of grazed woodlands and savannas (bush encroachment, vegetation thickening, woody weed invasion) are a direct consequence of changed management, following the introduction of domestic livestock. The area involved and potential C sink associated with it is immense.
- To-day's land managers are responding to bush encroachment in rangelands by clearing or thinning out the encroaching woody plants with bulldozers and chemicals. This acts to negate carbon sequestration in this thickening vegetation and, paradoxically, contributes to greater emissions to the atmosphere than would have occurred in the absence of thickening.
- Modern techniques provide accurate, reliable, easily verifiable and inexpensive methodologies to document vegetation thickening and its contribution to carbon sinks - at least for the above ground component.
- Implementation of a carbon offset trading scheme for thickening woodlands would lead to promotion of thickening (increased C sinks) and reduced land clearing (lowered C sources) on private land, and probably on government landholdings as well. Such outcomes would significantly reduce net greenhouse gas emissions in many developed and developing countries. There would also be flow on benefits to sustainable land management and the maintenance of biodiversity.

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