

Commentary

The global carbon sink: a grassland perspective

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Abstract

The challenge to identify the biospheric sinks for about half the total carbon emissions from fossil fuels must include a consideration of below-ground ecosystem processes as well as those more easily measured above-ground. Recent studies suggest that tropical grasslands and savannas may contribute more to the 'missing sink' than was previously appreciated, perhaps as much as 0.5 Pg (= 0.5 Gt) carbon per annum. The rapid increase in availability of productivity data facilitated by the Internet will be important for future scaling-up of global change responses, to establish independent lines of evidence about the location and size of carbon sinks.

Keywords: below-ground, carbon sink, grasslands, net primary production, NPP, savannas

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Introduction

Global change research requires interdisciplinary collaboration, transcending the different scales at which ecosystem processes are observed and modelled, from the microbiological perspective through the physiological to the geographical level. Within the bounds of global change research, 'scale' has become a prominent feature of contact between different disciplines. Our own perspective of plant physiological ecology exists over a scale from square centimetres of leaf area, through square metres of quadrats to hectares of study sites. However, there are geographical processes within the landscape operating over tens, hundreds or thousands of hectares, and even the half-degree grid cells of a phytogeographical model are only just beginning to represent the 'thin green smear' of vegetation incorporated within Global Climate Models, which generally place more emphasis on 3D energy flux processes. Yet at the other end of the spectrum, there are soil microbiological processes operating over square millimetres of root–mycorrhiza–soil interfaces which our ecological models of plant–soil systems can only represent crudely.

Earlier indications that a large carbon sink ('missing sink') in the global carbon budget may be located in the terrestrial regions of the Northern Hemisphere (Tans *et al.*

1990) have been reinforced by evidence from analysis of $^{13}\text{C}/^{12}\text{C}$ isotope ratios from a worldwide network of 43 carbon dioxide sampling stations during 1992–93, although the possible existence of a 'terrestrial sink in the southern tropics' is also discussed cautiously (Ciais *et al.* 1995). The challenge is now to identify the processes that would cause the terrestrial biosphere to absorb quantities of carbon dioxide amounting to about one-third the total emissions from fossil fuels. Some of this substantial new carbon store may indeed comprise the above-ground biomass (wood) of northern temperate and boreal forests, but below-ground allocation of considerable amounts of additional carbon to roots and soil organic matter (SOM) is likely to account for a significant fraction of the carbon sink, and 'nonforest' biomes may play a more important role here (Hall & Scurlock 1991). Consistent and complete information is required on the net primary productivity (NPP) of all biomes, including above- and below-ground detrital inputs to SOM, since transient or long-term soil carbon turnover may provide a route for CO_2 sequestration (Trumbore *et al.* 1996; Bird *et al.* 1996; Batjes & Sombroek 1997). Understanding the fate of stored carbon and its potential for anthropogenic manipulation (e.g. government land-use and climate change policy) is critically important if we are to manage the foreseen global change (Tans & Bakwin 1995; Melillo *et al.* 1996).

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Carbon in grasslands

Tropical and temperate natural grasslands play a significant but poorly recognized role in the global carbon cycle (Hall & Scurlock 1991; Hall *et al.* 1995). Like many estimates of net primary productivity (NPP) for natural ecosystems, their carbon fluxes may have been previously underestimated, especially in the tropics (Long *et al.* 1989, 1992). Grasslands are one of the most widespread vegetation types worldwide, covering 15 million km² in the tropics (as much as tropical forests) and a further 9 million km² in temperate regions; together nearly one-fifth of the world's land surface (Lieth 1978). At the regional level, for example on the African continent, tropical grasslands and savannas may be more extensive than tropical forests. Grassland soil carbon stocks amount to at least 10% of the global total (Eswaran *et al.* 1993), but other sources estimate up to 30% of world soil carbon (Anderson 1991). Comparisons of SOM stocks between biomes and different studies are complicated by divergent definitions and procedures (Batjes & Sombroek 1997); the least that can be said is that grassland soils represent a significant carbon pool, of the order of 200–300 Pg. SOM may turn over on a long timescale by the standards of human history and policy (e.g. 50–5000 years); Batjes & Sombroek (1997) quote a global mean of 22 years (litter included), and a maximum of up to 5000 years. Even modest changes in inputs to grassland carbon storage may therefore result in significant and long-lived sequestration.

Previous studies based upon the International Biological Programme (IBP) of the late 1960s and early 1970s suggested the NPP of tropical savanna grasslands is 13.5 Pg dry matter, or 6.75 Pg C per annum (Lieth 1978), about 9% of total global terrestrial production. However, this would rise to more than a quarter of the world total (i.e. about 15 Pg C per annum) if the IBP underestimation of NPP found for certain tropical grassland sites is generally applicable (Long *et al.* 1989, 1992). Independently, Scholes & Hall (1996) conservatively estimated the combined NPP for tropical grasslands, savannas and savanna woodlands at between 3.2 and 10.8 Pg C per annum, or about half the net carbon fixation attributed to tropical forests. Below-ground biomass turnover times for root biomass of a year or less appear to be widespread – findings which have wide implications for the prediction of global carbon cycling and grassland responses to global change. Similarly, temperate grassland productivity and turnover was also conservatively estimated under the IBP. Less than 10% of the grassland studies made direct measurements of below-ground biomass, and losses such as root exudation were generally ignored. Overall, therefore, natural grass ecosystems may be responsible for a substantial proportion (as much as 20% or more) of total terrestrial production.

Grassland ecosystems are far from uniform, ranging from the natural savannas of Africa to the prairies and steppes of North America and Russia, from the derived savannas found on many continents to the sown pastures of Europe and Latin America. Overall, grasslands are likely to remain roughly constant in area, as the future conversion of forest to humid pastures matches the loss of the apparently less productive marginal grasslands to semidesert; but if either humid or semiarid grasslands are a possible carbon sink, then information is urgently required on both the extent of land-use change and the characteristics of the different grassland types.

Interactions between climate change and grassland biogeochemistry have received much less attention compared with forests (Hall & Scurlock 1991). The effects of changes such as temperature, water and nutrients are relatively well understood, but only recently have the interactions with long-term CO₂ fertilization become sufficiently well-known to evaluate or model the consequences for global carbon fluxes (Schimel *et al.* 1990, 1991; Long 1991; Thornley *et al.* 1991). Owensby *et al.* (1993) have shown that production is stimulated in native C4 grasslands due to increases in water use efficiency, despite the lack of a direct CO₂ fertilization effect, and evidence for a possible C3 grassland carbon sink (albeit sensitive to N feedbacks and soil moisture) has also been presented (Lutz & Gifford 1995).

Grasslands NPP data

Consistent and comparable data on NPP (the most widely available carbon flux parameter) are essential for modelling the terrestrial carbon cycle and its response to climate change and CO₂ fertilization, regardless of the scale of the model and its mechanistic, empirical or diagnostic properties. One approach to synthesizing data on carbon fluxes uses a combination of satellite remote sensing data together with ground-based biome-specific measurements, in order to estimate light energy interception by the vegetation canopy and its utilization for carbon fixation and storage (Prince 1991). The alternative is to combine existing ground-based field measurements of vegetation biomass and productivity within models driven by local environmental variables such as climate, soil type and N inputs (e.g. Parton *et al.* 1993).

Our own field measurements of tropical grassland net primary productivity (NPP) used a common methodology which took into account simultaneous growth and death, both above and below-ground (Long *et al.* 1989, 1992). NPP was defined as the sum of net monthly increases in live biomass plus losses due to death (measured directly) and decomposition (estimated using litter bags), i.e. attempting to account for most of the components of NPP. NPP at three of these grassland sites was

up to five times higher than that obtained using the standard IBP procedure, which measures positive increments in above-ground live biomass only.

These measurements and others assembled for a worldwide grasslands modelling study (Parton *et al.* 1993, 1995) have now been incorporated into an Internet database on net primary productivity. Data are available on-line through a World-Wide Web site maintained by the U.S. Oak Ridge National Laboratory (ORNL) Distributed Active Archive Centre (http://www-eosdis.ornl.gov/npp/npp_home.html). This activity, a component of the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) Global Primary Production Data Initiative, is addressing both the availability of data sets for modelling and the scaling issue (Olson & Prince 1996; Cramer *et al.* 1997, forthcoming). Internet access represents an important advance in availability of field data which were otherwise archived only in published tables and text — previously, most data users had to 're-invent the wheel' by searching through the literature.

Grasslands and savannas as carbon sinks

Despite earlier studies based on historical data (e.g. Jenkinson *et al.* 1991), there is presently little reason to suppose that soils have a low carbon storage potential under both present-day and future climate change conditions (Amthor 1995). Tate *et al.* (1995) suggest that some grasslands and forest soils in New Zealand may already be sequestering carbon.

The grassland NPP data described above have already been used in a synthesis of temperate and tropical grassland studies for the purpose of modelling projected ecosystem responses to global change (Breymer *et al.* 1996). Long-term data from 11 tropical and temperate grassland sites were used to validate the CENTURY model of plant-soil ecosystems (Parton *et al.* 1993); climate change and CO₂ effects were then modelled for 31 temperate and tropical grassland sites, representing 7 'ecoregions' of the world (Parton *et al.* 1995).

Climate change alone caused a moderate loss of soil carbon (4 Pg after 50 years), substantially lower than earlier estimates which did not consider the feedback between soil processes and global change effects on NPP (Jenkinson *et al.* 1991). As was also suggested for temperate grasslands using the CCGRASS model (Vandasselaar & Lantinga 1995), elevated CO₂ tended to ameliorate climate-driven carbon losses worldwide, but Parton *et al.* (1995) found that tropical savannas actually became a modest carbon sink. However, it is precisely these regions which are subject to management pressures from over-grazing, too-frequent burning or conversion to marginal agriculture. Degradation and reduction of

productivity by poor management may reverse this potential, leading to carbon losses by erosion and oxidation instead of the desirable carbon sequestration.

About 80% of the total ecosystem organic carbon in savannas and tropical woodlands is in the soil (Scholes & Hall 1996). However, the spatial distribution of carbon is patchy, with increased levels under trees. Removal of tree cover from savannas can actually lead to a decline in soil carbon over a period of years; conversely, encouraging the trees to grow larger and more densely (e.g. by excluding fire) will store carbon both in biomass and soil. It has been estimated that such an increase from current average savanna carbon levels (6700 g m⁻²) to levels more typical of tropical woodlands (14 900 g m⁻²), if achieved over the total area of nonwoody savannas (11.5 million km²), would theoretically account for a carbon sink of 94.3 Pg C (Scholes & Hall 1996). Through intensive land-use management of savannas, such carbon sequestration might be achieved over a period of 50 years (about 2 Pg per annum, or about a quarter of current anthropogenic carbon emissions). Although this demonstrates the carbon storage potential of the world's large areas of tropical savannas, it may not be a recommended policy option (Scholes & van der Merwe 1996). The significant alteration of savanna ecology may have unforeseen consequences, and recent experience with fire suppression in California and Australia shows the danger of uncontrolled fires in seasonally dry climates.

Soil carbon storage has increased in Colombian pasture following the introduction of deep-rooted African pasture grasses and legumes into native savannas (Fisher *et al.* 1994, 1995). Given the large areas of 'improved' pastures established throughout Latin America (0.35–0.70 million km², notably in Brazil), these grasslands may be storing an additional 0.1–0.5 Pg carbon per annum. Further research is urgently required to evaluate the significance of this discovery, its true extent, and whether it is a temporary or long-term effect. The replacement of native savanna grasslands by improved pastures is not advocated for the purpose of carbon sequestration, but the management of existing improved pastures to optimize carbon storage may be an option. Furthermore, Neill *et al.* (1995) have shown that pasture soils of the Western Amazon have equal or higher total carbon content (and total N), compared with the soils of adjacent intact tropical moist forests. Recent eddy covariance measurements over Brazilian *cerrado* suggests that even the native savannas may seasonally sequester carbon (Miranda *et al.* 1997).

It may also be necessary to reconsider the common assumption that the terrestrial carbon sink is located primarily in the forests of the Northern Hemisphere. Ciais *et al.* (1995) expressed concern about the influence of C₄ and C₃ photosynthetic types (both grasses and trees) on the interpretation of ¹³C/¹²C isotopic signatures.

Table 1. Grassland and savanna soil carbon sinks, present and future – a range of estimates.

	Sink size (Pg C y ⁻¹)	Reference	See note
Present	0.74	Thornley <i>et al.</i> (1991)	1
	0.1–0.5	Fisher <i>et al.</i> (1994, 1995)	2
Future	(-1.0)–(-2.0)	Parton <i>et al.</i> (1995)	3
	1.5–1.6	Lutz & Gifford (1995)	4
	† 2.0	Scholes & Hall (1996)	5
Present best estimate	0.5	this paper	

1 We have multiplied modelled soil carbon increase over 130 years (4000 g m⁻²) by world grassland area (24 million km²) — see authors' discussion.

2 Latin American pastures only.

3 Sum of temperate sources and tropical sinks for modelled climate change and carbon fertilization.

4 Extrapolated from pot experiments.

5 Increasing tree cover in savannas — an unlikely future policy option.

Unlike C3 vegetation (i.e. most forests and temperate grasses), C4 vegetation (such as tropical grasslands) produces an isotopic fractionation barely discernible from that of marine systems. Thus the replacement of tropical forest by tropical grassland would appear as a loss of terrestrial sink in the ¹³C record, even if the grassland sequestered as much carbon as the forest that it replaced. It may even be argued that there is a terrestrial sink in the southern tropics, and that 'the ongoing net deforestation in SE Asia and the Amazon is currently over-estimated, or that it is offset by regrowth or fertilization of tropical forests' (Ciais *et al.* 1995). A carbon sink of C4 grasses is entirely plausible, despite the lack of a direct CO₂ effect in their photosynthetic pathway (Owensby *et al.* 1993). Some other method will be required to resolve whether oceans or grasslands in the tropics are rivalling the forests as a potential carbon sink.

Conclusions

The uncertainties associated with the estimation and detection of global carbon fluxes have been reviewed by Schimel (1995) and Melillo *et al.* (1996). It is considered that several processes, including forest regrowth and ecosystem response to elevated CO₂ and N deposition, may be responsible for the 'missing sink'. Various pieces of evidence support a Northern Hemisphere sink, but direct evidence is still lacking, and the processes responsible (either above or below-ground) have yet to be established. Lack of knowledge about positive and negative feedbacks from the biosphere is still a limiting factor; for example, feedback from enhanced N mineralization as soil carbon is lost may partly offset the overall efflux

of carbon. Reiterating our introductory remarks, Schimel (1995) identifies scaling-up of global change responses from the within-plant level to the regional-global level as a critical area for future research, if we are to develop a predictive understanding of these changes. Such work will be important in establishing 'several truly independent lines of evidence [to make] our knowledge of the carbon cycle very firm' (Tans & Bakwin 1995).

Grasslands and savannas – with their below-ground carbon storage, seasonal burning, regrowth and tree-grass dynamics – are major players in the global carbon cycle. Although carbon stocks, productivities and turnover times are subject to considerable uncertainty, we cautiously propose on the basis of present evidence that these biomes may already constitute an annual sink of about 0.5 Pg carbon (Table 1). The future sink under climate change is much less certain, given its dependence upon future management regimes, with extreme values suggested here of – 2 and + 2 Pg C per annum.

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