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Carbon storage by introduced deep-rooted grasses in the South American savannas

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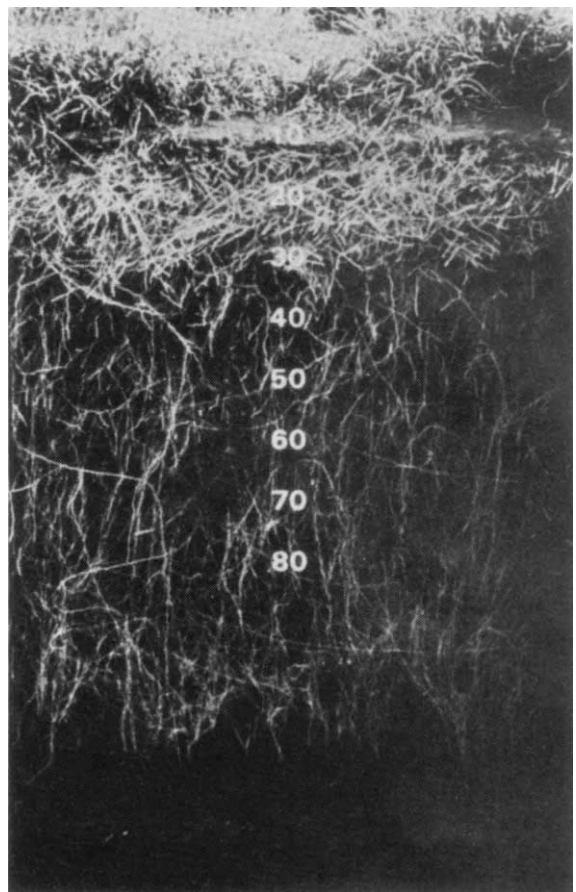
FIG. 1 *Andropogon gayanus* has the capacity to penetrate deep into oxisol soils of the savannas of tropical South America (from Spain and Couto[17]). The numbers indicate the soil depth in cm.

ESTIMATES of the global carbon dioxide balance have identified a substantial 'missing sink' of 0.4–4.3 Gt per year[1]. It has been suggested that much of this may reside in the terrestrial biosphere[2]. Here we present an analysis of the carbon stored by pastures based on deep-rooted grasses which have been introduced in the South American savannas. Although the deep-rooted grasses were chosen principally for agricultural reasons[3], we find that they also sequester significant amounts of organic carbon deep in the soil. If our study sites are representative of similar pastures throughout South America, this process could account for the sequestration of 100–507 Mt carbon per year—a substantial part of the 'missing sink'. Thus, although some land-use changes[4] (such as burning tropical rainforests) contribute to the atmospheric CO_2 burden, we conclude that the introduced pastures studied here help to offset the effect of anthropogenic CO_2 emissions.

Savannas occupy some 250 million hectares (Mha) of South America, mainly in Brazil (200 Mha), Colombia (20 Mha) and Venezuela (12 Mha). They are used for extensive cattle ranching on the native forage, although in Brazil cropping with maize and soybeans (now 12 Mha) and introduced pastures (35 Mha) have become important during the past 30 years (ref. 5). The soils of the savannas are mainly oxisols and ultisols, characterized by low pH (4.0–4.8), aluminium saturation up to 90% and low levels of phosphorus and calcium. Rainfall is 1,500–3,000 mm with a unimodal seasonal distribution[6].

The perennial grasses *Andropogon gayanus* and *Brachiaria humidicola* are of African origin[7,8]; the former is tall-growing with a tussock habit, whereas the latter forms swards. The legumes *Arachis pintoi* and *Stylosanthes capitata* are from South America[9,10]; *A. pintoi* is a vigorous, stoloniferous perennial and *S. capitata* is a free-seeding biannual. Grass–legume associations

of these forages produce cattle liveweight gains up to 500 kg ha^{-1} yr^{-1} (refs 11, 12), compared with 7–20 kg ha^{-1} on well-managed savanna[13,14]. They produce green forage for several months into the dry season, and regrow vigorously soon after the first rains of the wet season. Since 1980, all four have been released as cultivars (cv.) in one or more countries in South America[15].

Although deep-rootedness is considered a major factor in adaptation to low-fertility soils, especially in *A. gayanus*[16,17] (Fig. 1), the role of the roots in the dynamics of soil C has largely been ignored. We measured soil C, including fine roots, in an *A. gayanus* pasture, and in two *B. humidicola* pastures at two sites on the eastern plains (Llanos orientales) of Colombia, some 200 km apart (Table 1). In each case we obtained corresponding measurements from immediately adjacent native savanna with the same soil texture.

The pastures had differing histories (Table 1), but all had carried grass-based pastures for 3–9 years. The pasture at Matazul farm was not fertilized after the rice that was used as a pioneer crop to establish it, whereas at Carimagua fertilizer was applied at pasture establishment and each second year thereafter. They were all grazed by cattle at normal stocking rates for improved pastures in the region.

All the grass-based pastures made a striking contribution to soil C compared to the native savanna, especially when grown with a legume (Table 2). Data for other pastures based on another grass of African origin, *Brachiaria dictyoneura* cv. Llanero at Matazul farm, show lower, but still significant, sequestration of ~30 tons of carbon per hectare (t C ha^{-1}) in 3.5 years (data not presented). If these data are representative

TABLE 1 Location and characteristics of the two sites on the savannas of the eastern plains of Colombia

Site	Matazul farm	Carlmagua research station
Location	Eastern plains (Llanos), Puerto Lopez, Colombia	Eastern plains (Llanos), 200 km ENE of Puerto Lopez, Colombia
Latitude, longitude	4° 9′ N, 72° 39′ W	4° 37′ N, 71° 19′ W
Altitude (m)	160	175
Mean annual rainfall (mm yr^{-1})	2,700	2,240
Soil	Oxisol	Oxisol
Texture	Clay loam	Clay loam
pH (1:1 water)	4.4	4.1
P (0–20 cm), Bray II (p.p.m.)	1.8	1.5
Pasture details	1989. Cropped from savanna with upland rice undersown with mixed A. gayanus cv. Carimagua 1 and S. capitata cv. Capica pasture. 1989–93. Rotationally grazed with cattle at 2 head per hectare.	1984. Sown to B. humidicola cv. Humidicola from savanna, with the legume Desmodium ovalifolium, which failed. 1987. Resown to B. humidicola cv. Humidicola alone or with A. pintoi cv. Mani Forrajero. 1988-93. Rotationally grazed with cattle at 3 head per hectare.
Date soil sampled	December 1992	April 1993

of the area sown to pastures of A. gayanus and Brachiaria species in South America, conservatively estimated at 35 Mha (ref. 5), then from 100 to as much as 507 Mt C is being sequestered each year.

The contribution of the legume in the 6 years since its establishment at Carimagua may be estimated by taking the difference between the grass alone and the association. This difference is 44.7 t C ha^{-1}, so that although legumes contribute only ~20% to root biomass[18], the association with A. pintoi increased carbon sequestration by 7.8 t ha^{-1} yr^{-1} compared with the pure grass.

Compared with the savanna, the grass-based pastures sequester most of the C in the deeper part of the soil profile, well below the plough layer (normally 10–15 cm). This C should therefore be less prone to oxidation, and hence loss, during any cropping phase that might be undertaken in integrated crop and pasture systems. Indeed, such systems should be able to accommodate rotations with annual crops and still contribute to C sequestration. Jones et al.[19] drew attention to the role of fire in determining the balance between the vegetation of native savannas as either a net sink or source of carbon in the tropics. Introduced pastures are rarely burned, except by accident, in contrast to the native savannas, which are usually burned as often as each year.

There is little information about soil C below a depth of 15–20 cm in the tropics, although there are occasional measurements down to 40 cm. Long et al.[20] carried out careful studies on native tropical grasslands to document total primary productivity, including roots in the surface 15 cm. They showed that productivity of tropical grasslands, above ground and below ground to 15 cm depth, was up to five times higher than previously reported, mainly because losses due to senescence were ignored. On the basis of our data even they may have substantially underestimated root production. They did not present information on soil C.

Although the emphasis on deep-rooted grasses by the Centro Internacional de Agricultura Tropical was for reasons other than sequestration of C, we have shown that some introduced grasses in the tropical South American savannas do sequester C deep in the soil. There must be a physiological cost in growing such a massive root system, but we do not see much evidence of it. Both A. gayanus and B. humidicola grow at least as vigorously as other promising introduced grasses, and much more vigorously than the savanna species.

We suggest that the sequestration of C in South American savanna soils is of global importance, in that deep-rootedness could be exploited from the point of view of both the individual farmer and the community at large for their mutual benefit. Can the ability of tropical grasses to sequester C at depth, especially when grown in mixtures with legumes, be used in selection and breeding? What are the implications for the generation of technolgies to recuperate degraded pastures in cleared areas of rainforests? The latter is an emotional issue, but there is considerable capacity for these soils to sequester C if they are managed correctly[21,22].

TABLE 2 Carbon in pastures compared to savanna

Site	Matazul farm			Carimagua research station				
Pasture	Savanna	A. gayanus/S. capitata		Savanna	B. humidicola alone		B. humidicola/A. pintol	
Depth (cm)	Carbon in layer (t ha^{-1})	Carbon in layer (t ha^{-1})	Difference from savanna (t ha^{-1})	Carbon in layer (t ha^{-1})	Carbon in layer (t ha^{-1})	Difference from savanna (t ha^{-1})*	Carbon in layer (t ha^{-1})	Difference from savanna (t ha^{-1})*
0–20	64.0	71.1	7.1 ± 2.0†	70.3	76.0	5.7 ± 4.3‡	88.1	17.8 ± 4.2†
20–40	42.7	51.9	9.3 ± 2.8†	52.4	57.6	5.3 ± 3.2‡	71.2	18.6 ± 6.0†
40–100¶	79.8	114.2	34.3 ± 9.3§	74.3	89.2	14.9 ± 6.2‖	108.4	34.0 ± 10.0†
Total	186.5	237.2	50.7 ± 11.4§	197.0	222.8	25.9 ± 7.7†	267.7	70.4 ± 15.5§

Each sample comprised eight cores at Matazul and four at Carimagua, taken at random by soil auger to the depths indicted. In the grazed A. gayanus/S. capitata pastures at Matazul farm, samples were taken from each quarter of each of three 1-ha plots in a randomized complete block experiment covering 9 ha. At the same time four samples were taken from the native savanna immediately adjacent to the experiment. At Carimagua, the grass-based pastures were 0.5-ha plots in a randomized complete block grazing experiment. Five samples were taken from each of two replicates of the plots and three from the immediately adjacent savanna. Analysis methods were as follows. The samples were dried and milled to pass a 1-mm sieve. Fine roots were not removed before milling. Subsamples were digested in sulphuric acid/potassium dichromate heated (150 °C) for 30 min on a temperature-controlled hotplate. Carbon concentration in the digest was determined colorimetrically against calibrated standards made up of carbon-free soil to which measured amounts of glucose were added. Soil bulk density, used to convert the gravimetric figures of soil C to volumetric data, was determined by standard methods[25]. The data for each depth of each pasture were treated as independent samples, and the standard error of each mean and the standard errors of the difference between the means were calculated. Differences between the means were tested for statistical significance with Student's t-test.

* Differences quoted are ±s.e., where s.e. is the standard error of difference between the means ($n = 14$ for Matazul farm, $n = 12$ for Carimagua). Levels of significance indicated by symbols as follows:-
† $P < 0.01$. ‡ $P > 0.05$. § $P < 0.001$. ‖ $P < 0.05$.
¶ At Carimagua research station the deeper layer was 40–80 cm.

The combination of a deep-rooted grass with a nitrogen-fixing legume can increase nutrient cycling, greatly improve animal production and markedly increase soil biological activity[18,23]. These effects occur mainly at the soil surface while C storage takes place below the plough layer. Thus, far from being environmentally degrading, improved pastures can fulfill the restorative role in tropical systems that was recognized in pre-Roman times for Mediterranean systems[24], and may play a vital part in stabilizing the global carbon cycle and minimizing the greenhouse effect of atmospheric CO_2. ☐

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Fluid trapping in mid-crustal reservoirs by H₂O–CO₂ mixtures

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A THIN reservoir of free aqueous or carbonic fluids at mid-crustal levels, perhaps in the form of water sills[1], has been suggested as the source of fault-transmitted metasomatizing fluids[2–4], as the cause of observed deep crustal electrical conductivity and anomalous seismic reflectivity[5], and as a lubricated potential detachment zone for thin-skin tectonics[6]. A problem with this hypothesis is that estimated crustal permeabilities are too high to permit long-term retention of such fluids[7,8]. Most mechanisms suggested for achieving the required permeability reduction rely on maintaining unusually low porosity[2,6,9,10]. Because porosity creation, by tectonic deformation, fluid release or infiltration, is a ubiquitous process, permeability reductions achieved by these mechanisms are hard to sustain for long periods of time. A sealing (permeability reduction) mechanism that can operate in the presence of significant porosity is required. Here I propose that the required mechanism is capillary sealing by immiscible CO_2–H_2O mixtures derived from rising volatiles.

Several sources are possible for such rising volatiles. In or adjacent to tectonically active regions, prograde metamorphism at crustal depths can provide them. Another source of such volatiles is the upper mantle[11,12]. Fyfe[13] has noted that the entire contents of the oceans may be recycled by subduction in less than 10^9 years. Most of this fluid is likely to be released for upward migration in, or adjacent to, tectonically active regions. Continuous fluid streaming through stable lower crust is improbable, however, because of the petrological evidence for a normally dry lower crust[14]. To be consistent with known lower crustal petrology fluid sources for sustained mid-crustal reservoirs must either be episodic, so that lower crust normally returns to a dry state, or involve horizontal migration at mid-crustal levels from active regions into stable regions, so that the lower crust is not involved. Such lateral migration is possible if a mid-crustal sealing mechanism operates as suggested in this Letter. To illustrate the role of the proposed sealing mechanism,

I consider the former scenario of a 'pulse' of metamorphic fluid supplied from the deep crust, but the arguments for sealing apply equally to the case of subhorizontally migrating water.

Driven by buoyancy forces, a pulse of supplied fluids will migrate rapidly upwards through ductile lower crust[6], followed upward by prograding isograds, leaving the lower crust restored to its usual dry state[15]. On reaching the brittle–ductile transition, above which ductile porosity creation by pore inflation cannot occur, fluids may escape through fractures to the upper crust. But in a tectonically stable (or stabilizing) region, it seems unlikely that pre-existing fracture permeabilities will be important at depths just above the brittle–ductile transition; as their last tectonic experience, these rocks probably underwent the annealing associated with slow post-tectonic cooling at depth. Arrival of higher-pressure fluids from below would be expected to induce hydraulic fracturing. Such fracture planes would be subhorizontal in the normal stable continental stress regime of horizontal compression. The vertical extent of such a reservoir of hydraulically connected sills must be small; it cannot exceed the value over which the difference in hydrostatic and lithostatic gradients will produce a fluid overpressure sufficient to induce hydraulic fracturing. Secor and Pollard[16] have shown theoretically that open fluid-filled vertical fractures in granite cannot extend vertically over more than a few hundred metres without initiating fracture extension. One might reasonably expect the same order of magnitude for maximum vertical reservoir extent to apply to horizontally extending hydraulic fractures. For mid-crustal depths, this number is a significant overestimate; the analysis in ref. 16 was for cold upper-crustal rocks. Significantly smaller strengths for rocks just above the brittle–ductile transition might be expected, and reservoir heights which are therefore significantly less than a few hundred metres.

The main difficulty with this hypothesis is that, even in the absence of vertical fracture permeability, the permeability of the sill roof rocks is likely to permit loss of water upwards in a geologically short time. Magnetotelluric evidence suggests an integrated thickness of water as sills (2–40 m)[6]. This would be lost upwards in a geologically short time if rock permeabilities exceed $\sim 10^{-23}$ m^2. This value is at the lower limit of measured permeabilities of intact rock specimens, and very much lower than estimated bulk permeability of crystalline rocks[7]. As a solution to this difficulty, I propose that the formation of immiscible