Soil carbon inventories and $\delta^{13}C$ along a moisture gradient in Botswana

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Abstract

We present a study of soil organic carbon (SOC) inventories and $\delta^{13}C$ values for 625 soil cores collected from well-drained, coarse-textured soils in eight areas along a 1000 km moisture gradient from Southern Botswana, north into southern Zambia. The spatial distribution of trees and grass in the desert, savannah and woodland ecosystems along the transect control large systematic local variations in both SOC inventories and $\delta^{13}C$ values. A stratified sampling approach was used to smooth this variability and obtain robust weighted-mean estimates for both parameters.

Weighted SOC inventories in the 0–5 cm interval of the soils range from 7 mg cm^{-2} in the driest area (mean annual precipitation, MAP = 225 mm) to 41 $\pm$ 12 mg cm^{-2} in the wettest area (MAP = 910 mm). For the 0–30 cm interval, the inventories are 37.8 mg cm^{-2} for the driest region and 157 $\pm$ 33 mg cm^{-2} for the wettest region. SOC inventories at intermediate sites increase as MAP increases to approximately 400–500 mm, but remain approximately constant thereafter. This plateau may be the result of feedbacks between MAP, fuel load and fire frequency.

Weighted $\delta^{13}C$ values decrease linearly in both the 0–5 and 0–30 cm depth intervals as MAP increases. A value of –17.5 $\pm$ 1.0‰ characterizes the driest areas, while a value of -25 ± 0.7‰ characterizes the wettest area. The decrease in $\delta^{13}C$ value with increasing MAP reflects an increasing dominance of C_3 vegetation as MAP increases. SOC in the deeper soil (5–30 cm depth) is, on average, 0.4 $\pm$ 0.3‰ enriched in ^{13}C relative to SOC in the 0–5 cm interval.

Keywords: C-13, carbon cycle, carbon isotopes, savannahs, organic carbon, soil

Introduction

One of the major terrestrial reservoirs of carbon is the soil organic carbon (SOC) pool, amounting to approximately 1500 Pg of carbon. This is between one-half (e.g. Townsend *et al.*, 1995) and two-thirds (e.g. Trumbore *et al.*, 1996) of the total terrestrial carbon pool and therefore the SOC pool plays an important role in modulating anthropogenic changes to the global carbon cycle.

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The inventory of SOC in any soil profile is determined by the complex interplay of many factors including climate, soil texture, land use, fire frequency and topography (Bird *et al.*, 2001). In order to better understand these interactions, there is considerable need for observational studies of the SOC pool, conducted using techniques designed specifically to provide data at the large spatial scales appropriate to the modelling of global scale phenomena. This study uses a stratified sampling approach to examine the relationship between mean annual precipitation (MAP), SOC inventories and the $\delta^{13}C$ value of SOC on a moisture gradient through Botswana and into southern Zambia, through a range of desert, savannah and forest biomes.

The stable isotopes of carbon ($^{13}C/^{12}C$, expressed as a $\delta^{13}C$ value) represent one of the most direct tracers for the global cycling of carbon between the geological, terrestrial, marine and atmospheric reservoirs, and the many smaller reservoirs of carbon within each of these four broad subdivisions. Because the SOC pool integrates the isotopic signature of local vegetation over several to many years, it potentially provides the best integrated measure of the carbon isotope composition of regional biomass, if this signature can be adequately isolated from the isotopic effects associated with degradation (e.g. Agren *et al.*, 1996) and the terrestrial 'Seuss effect' (Bird *et al.*, 1996; Fung *et al.*, 1997). An improved knowledge of controls on the distribution of the isotopes of carbon within the SOC pool can be used to:

(i) provide tighter constraints on the magnitudes and sources of CO_2 released to the atmosphere and the fate of CO_2 sequestered from the atmosphere (Ciais *et al.*, 1995; Fung *et al.*, 1997; Bakwin *et al.*, 1998; Battle *et al.*, 2000).
(ii) assist in better understanding the environmental controls on the distribution and productivity of C_3 and C_4 biomass in the modern environment.
(iii) enable more reliable reconstructions of the past environment using the carbon isotope composition of modern soils, paleosols, phytoliths, soil carbonate, guano deposits, fossil material and so forth.

In the tropics and sub-tropics, precipitation exerts a major control on both the inventory of SOC and its $\delta^{13}C$ value, by controlling type and amount organic carbon input to the soil from standing biomass. Where precipitation is low, carbon inventories are low, and C_4 plants, mostly grasses, are favoured ($\delta^{13}C$ of bulk C_4 plant matter = – 11‰ to – 13‰). As precipitation rises, carbon inventories rise, while the $\delta^{13}C$ value of SOC decreases as a result of increasing carbon inputs to the soil from trees and shrubs that utilize the C_3 photosynthetic pathway ($\delta^{13}C$ of bulk C_3 plant matter = – 25‰ to –27‰).

A major consideration in any study of mixed C_3/C_4 ecosystems must therefore be that the distribution of SOC and its $\delta^{13}C$ value is determined by the usually heterogeneous distribution of C_3 and C_4 vegetation in the landscape (e.g. Bird & Pousai, 1997; Bird *et al.*, 2000). In order to overcome the difficulty of spatial heterogeneity, this study utilizes a stratified sampling approach that divides the landscape into areas currently dominated by C_3 or C_4 vegetation, and separately samples these areas. Analyses of these separate samples are then weighted according to the proportion of C_3 and C_4 vegetation cover present in the area to provide a weighted inventory and $\delta^{13}C$ value for SOC (see Bird *et al.*, 2001 for discussion).

Study area and samples

This study was conducted at sites spread over approximately 1000 km, from the south-western corner of Botswana, to the northernmost corner of Botswana, and on into southern Zambia at Mongu (Fig. 1). There is a modest increase in mean annual temperature (MAT) from 20.0 °C in the south to 23.2 °C in the north, but a strong gradient in MAP from 225 mm in the south to 920 mm in the north. As a result of this gradient in precipitation, vegetation changes from arid shrub savannah in the driest areas to dry deciduous forest (miombo) in the wettest northern areas (Fig. 1; Weare & Yalala, 1971).

The transect passed through the Okavango delta (OKA). This area, although experiencing a MAP of 450 mm, is inundated by floodwaters derived from Angola, and flooding occurs in the local dry season. Thus, there is abundant water available for uptake by vegetation year-round, complicating the otherwise simple moisture gradient from south to north.

Soil texture exerts considerable control on both the inventory of SOC in a soil and the $\delta^{13}C$ value of SOC, mainly through interactions between fine soil particles

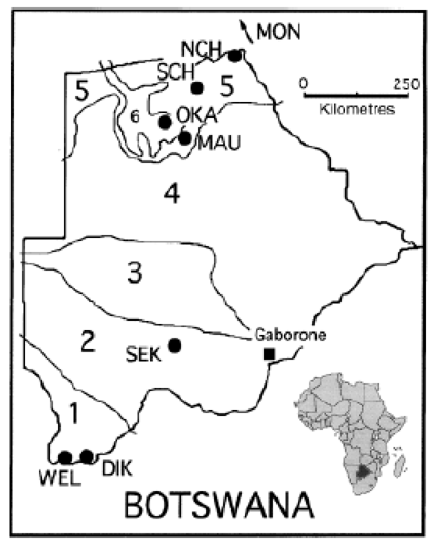

Fig. 1 Location of regions sampled for this study, and vegetation along the transect simplified from Weare & Yalala (1971): (1) arid shrub savannah, (2) southern Kalahari bush savannah, (3) central Kalahari bush savannah, (4) northern Kalahari tree and bush savannah, (5) tree and tree/bush savannah (various types), (6) Okavango delta swamp grassland. Sample sites: WEL = Welverdein; DIK = Dikbos; SEK = Sekoma; MAU = Maun; OKA = Okavango; SCH = South Chobe; NCH = North Chobe; MON = Mongu.

and degrading SOC (e.g. Parton *et al*., 1987). In order to minimize the effects of soil texture, sampling was limited to topographically high locations on the sand plains and sand ridges that are widespread throughout the region (Joshua, 1981; Soil Survey Advisory Services Project, 1991). The sands range from medium to coarse-grained, loose to compacted. They are usually grey-brown to red-brown in colour with little or no differentiation of horizons over the 30 cm interval sampled. A litter layer was usually very sparse or absent. Areas of apparently intense land-use (mostly grazing) were avoided during sampling.

A previous study has examined SOC abundances along a transect through similar locations in Botswana (Ringrose *et al*., 1998). These authors defined an erratic increase in carbon abundance in both surface soil and 'deep' soil ($\sim$10 cm depth) from $<0.1\%$ C in the south to and average of $\sim 0.35\%$ C in the north. Unfortunately, this study presented only carbon abundances, and without information on soil densities, it is not possible to convert the results to inventories. There was also no attempt to constrain soil type, or sampling locations with respect to the local distribution of trees and grass, making comparison with the results of the current study difficult.

Experimental methods

Field methods

Sampling was conducted over several short periods between April 1999 and 2000. A complete set of samples from two depths were collected, the 0–5 cm interval and the 0–30 cm interval. In some cases, the deeper samples were collected from 5 to 30 cm, but in such cases the results have been recast to a uniform data set for 0–30 cm.

Separate samples were collected from beneath trees (designated –T; tree) and away from trees (designated –G; grass). The –T samples were collected at half-crown-distance from local trees, while the –G samples were collected from localities approximately equidistant from the trees in the area and between tussocks of grass. In areas where the crowns of the trees overlapped, the –G samples were collected at the centrepoint relative to the surrounding tree trunks and the –T samples were collected halfway between this centrepoint and the tree, but never closer to the tree than one metre. The purpose of the –T and –G samples is to encompass the likely maximum and minimum carbon contents and δ^{13}C values at each sample locality (see Bird *et al*., 2001 for further discussion).

For the 0–5 cm –T and –G samples, three cores for each sample were taken to smooth out local heterogeneity. Single –T and –G cores were taken from the 0 to 30 cm interval at each locality. All bags were sealed after collection to prevent moisture loss. A visual estimate of crown cover was made at each location to allow weighted carbon densities and δ^{13}C values to be calculated from the carbon densities of the –G and –T samples.

A single sample *locality* is thus represented by six cores from the 0 to 5 cm interval and two cores from the 0 to 30 cm interval, generally collected within a 50 m radius of each other. A single *transect* comprises five such locations over a horizontal distance of kilometres to tens of kilometres. In some cases, only a single transect was collected from a climate region (WEL, DIK, NCH). In cases where up to five transects were collected from a single climate *region*, a measure of variability is possible from standard deviation of results from the transects. In total, 625 individual soil cores were collected from 25 transects along the climate gradient from WEL in the south to MON in the north (Table 1).

Laboratory methods

The samples were first weighed in their sealed bags, opened, clumps broken up by hand and then dried at

Table 1 Summary of site information (for locations see Fig. 1)

Site	Location	MAP (mm)	MAT (°C)	Veg	Woody cover	Transects	Sampled
WEL	Welverdien, Botswana	225	20.0	ASS	1	1	April
DIK	Dikbos, Botswana	300	20.0	SKBS	7.5	1	April
SEK	Sekoma, Botswana	330	20.1	SKBS	19 ± 5	5	August
MAU	Maun, Botswana	410	21.7	MTBS	30 ± 4	5	August
OKA	Okavango delta, Botswana	410	21.7	MTBS	25 ± 5	3	April
SCH	South Chobe N. P., Botswana	525	22.0	MTBS	16 ± 10	5	August
NCH	North Chobe N. P., Botswana	650	22.0	DDF	30	1	May
MON	Mongu, Zambia	920	23.2	DDF	45 ± 5	4	April

MAP = mean annual precipitation, MAT = mean annual temperature, veg = vegetation type (ASS = arid shrub savannah; SKBS = south Kalahari Bush savannah; MTBS = Mopane tree and bush savannah; DDF = dry deciduous forest).

60 °C for 3 days. The dry weights were used to calculate soil dry bulk density. Samples from each of the five localities in a transect were then split in half and half of each sample added to each of four 'bulk' samples representative of the transect (0–5T, 0–5G, 0–30T, 0–30G). The half of each individual sample not added to the bulk sample was retained, and in the case of transects SEK-1 and MAU-1, the individual samples were analysed separately to provide an estimate of how closely the bulking procedure reproduces the value derived from the averaging of results from individual samples.

An aliquot of each bulked sample was dry sieved at 2000 μm with the weight of both fractions recorded. The <2000 μm material was crushed to a powder in a ring mill prior to further analysis. An aliquot of each bulked sample was also sieved at 500 and 63 μm to provide information on particle size distributions in the samples.

Carbon contents and $\delta^{13}C$ values were determined in duplicate using an elemental analyser coupled to a Prism III mass spectrometer operated in a continuous flow mode. The reproducibility of carbon abundance measurements averaged ±2% and $\delta^{13}C$ values are reported as per mil (parts per thousand; ‰) deviations from the V-PDB standard, with an uncertainty of ±0.1‰. For the purposes of this study, SOC is defined as organic carbon present on the soil surface or at depth in a soil profile, with a particle size of <2000 μm.

Results and discussion

Soil characteristics

Particle size analysis confirmed the sandy nature of all soils analysed with a strong peak in abundance in the 63–500 μm fraction in all samples. Less than 2% of the total sediment was present in the >2000 μm fraction, <5% in the 500–2000 μm fraction and always <15% (generally <10%) in the fine <63 μm fraction of all samples.

The pH values (1 : 1 water/soil) of all samples were in the range 5.05–7.15 for the 0–5 cm interval and 5.0–7.5 in the 0–30 cm interval. There were no discernible trends between –T and –G samples or along the transect. Soil bulk densities ranged from 1.20 to 1.61 for the 0–5 cm interval, with –T samples generally having a lower bulk density than the paired –G value. Over the 0–30 cm interval, bulk densities ranged from 1.32 to 1.84, with a less marked, but discernible tendency towards lower bulk densities in the –T samples.

Variation in the samples

SOC contents ranged from 0.12% to 1.61% in the 0–5 cm interval, with a marked tendency for –T samples to contain more carbon than –G samples. The same tendency is present in the 0–30 cm samples, where SOC contents ranged from 0.08% to 1.45%. The lower carbon contents in the 0–30 cm interval reflect the general tendency for SOC abundance to decrease with increasing depth in most well-drained soil profiles.

The bulk density and carbon abundance measurement were used to calculate SOC inventories for all samples. These ranged from 2 to 237 mg cm^{-2} for the 0–5 cm interval and 31–513 mg cm^{-2} for the 0–30 cm interval, with inventories in the –T samples being generally higher than in the –G samples. Weighted inventories of SOC (calculated using the % crown cover to weight the –T and –G results) increase as rainfall increases. For the 0–5 cm interval, the weighted inventories increased from 7 mg cm^{2} in the driest area (MAP = 225 mm) to 41 ± 12 mg cm^{-2} in the wettest area (MAP = 910 mm). For the 0–30 cm interval, the weighted inventories were 37.8 mg cm^{-2} for the driest region and 157 ± 33 mg cm^{-2} for the wettest region. This effect of changing precipitation is eclipsed in the OKA, where plants have year-round access to groundwater and hence the highest SOC inventory of any area sampled, approximately double that found even in the wettest (MON) site.

$\delta^{13}C$ values ranged from –16.0‰ to –25.4‰ for the 0–5 cm interval and –16.3‰ to –25.4‰ for the 0–30 cm interval. In both intervals, the –T samples had lower $\delta^{13}C$ values than their paired –G samples. Weighted $\delta^{13}C$ values along the transect decreased with increasing rainfall, although again the overall trend is complicated by the local availability of groundwater, most noticeably for the OKA samples.

Comparison of 'individual' with 'bulk' samples

Figure 2 allows comparison of the results for 20 individual samples (five each for 0–5T, 0–5G, 0–30T and 0–30G) collected on transect SEK-1 with the results obtained from the four bulk samples made from the individual samples. The figure also shows a comparison between the results for the SEK-1 transect and the other four SEK transects taken in the same climatic region (see Fig. 1 for location).

The results for the individual samples from SEK-1 scatter over a wide range and in the worst case, the inventories calculated for the five individual 0–30T samples vary by almost 50%, from 73 to 130 mg cm^{-2}. This spread reflects the large, real spatial heterogeneity of SOC in the landscape. Nevertheless, the inventories calculated from averaging the results for the individual 20 samples agree with the inventories calculated from bulking the samples and analysing only four bulk samples to better than ±4% in all cases.

The weighted inventories calculated from the individual samples from the SEK-1 transect (collected over

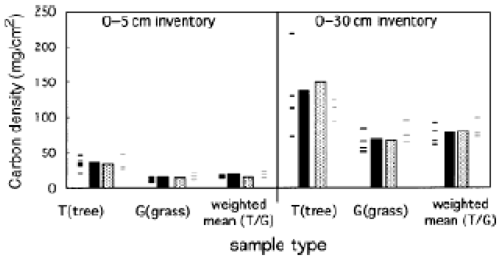

Fig. 2 Comparison of 'individual' sample with 'bulked' sample results for the SEK-1 transect, and with the results obtained from transects SEK-2 to SEK-5, for –T, –G and weighted total T/G inventories for 0–5 and 0–30 cm (dark horizontal bars = individual sample results (SEK-1); black boxes = arithmetic mean of individual results (SEK-1); stippled boxes = results for 'bulked' samples (SEK-1); light horizontal bars = results for bulked samples from transects SEK-2 to SEK-5). Inventories expressed as mg cm^{-2}.

1 km) are 15.6 ± 1.4 and 72 ± 13 mg cm^{-2} for the 0–5 and 0–30 cm interval, respectively. The weighted inventories for the region calculated from the bulked samples from the five SEK transects (collected over ~70 km) are 18.3 ± 4.1 and 85 ± 13 mg cm^{-2} for the 0–5 and 0–30 cm intervals, respectively. The observation that the errors for the individual samples collected over 1 km are similar to the errors for bulked samples collected over 70 km suggests that collecting many samples and 'bulking' them to reduce the cost of analysis is an effective technique for smoothing local heterogeneity and arriving at robust regional estimates of SOC inventories.

The results in Fig. 2 also highlight the consistent differences between the –T and –G samples over both the 0–5 and 0–30 cm intervals. The inventories of SOC under trees are consistently higher than away from trees. In the case of the SEK transects (with 19 ± 5% crown cover), the SOC inventory of the –T samples is about twice that of the –G samples, underscoring the need to consider the distribution and proportion of trees in the landscape explicitly, particularly in savannah ecosystems (Kellman, 1979).

The relationship between SOC inventory and $\delta^{13}C$ values for the individual samples from transects SEK-1 and MAU-1 for both 0–5 and 0–30 cm is shown in Fig. 3. The tendency for –T samples to contain higher SOC inventories and lower $\delta^{13}C$ values than –G samples from the same transect is confirmed by both transects. The differences are not as large in the MAU-1 transect because of the higher proportion of tree cover on the transect, which means a greater influence of local tree cover on the –G samples.

Both transects fall on much the same trend, particularly in the 0–5 cm interval, despite the differences in

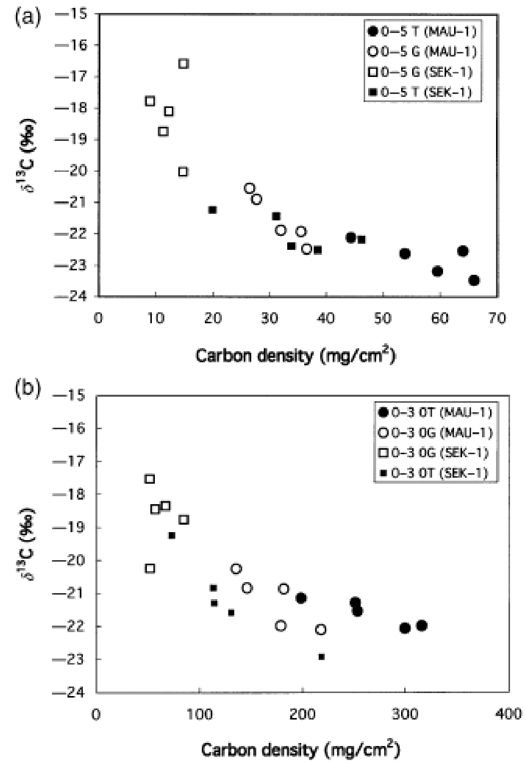

Fig. 3 Relationship between SOC inventory and $\delta^{13}C$ value for individual –T and –G samples for the SEK-1 and MAU-1 transects. (a) 0–5 cm and (b) 0–30 cm.

rainfall (330 vs. 450 mm), suggesting some equivalence in the relative inputs or degradation rates per unit biomass of C_3- and C_4-derived carbon between the two areas. Linear relationships between SOC inventories and $\delta^{13}C$ values in the 0–5 cm interval have been noted previously (Bird *et al.*, 2000, 2001). A linear relationship also seems to pertain in these transects, although not at the lowest carbon inventories derived from the SEK-1 0–5G samples. As the tree cover was low on this transect, the 0–5G samples may be little influenced by local trees and the $\delta^{13}C$ values of the samples controlled by local differences in the proportion of small C_3 plants and grasses. Hence, there may be no relationship between SOC inventory and $\delta^{13}C$ value for 0–5G samples where trees are widely spaced.

Weighted inventories and $\delta^{13}C$ values of SOC along the moisture gradient

The discussion in the previous section has demonstrated that it is possible to obtain reliable estimates of

SOC inventories and $\delta^{13}C$ values from bulking individual samples from a transect into samples representative of the transect (0–5T, 0–5G, 0–30T and 0–30G). It is then possible to weight the results for the separate –T and –G samples according to the proportion of tree cover and arrive at representative values for each transect. Where only one transect was collected in a region, no estimate of error is possible. Where several transects are collected, the error is taken to be the standard deviation of the results from all transects in a region.

The weighted inventories and $\delta^{13}C$ values for all transects are presented in Fig. 4 as a function of MAP. Between 225 and ~400–500 mm MAP, SOC inventories increase by a factor of 4–5 in both the 0–5 and 0–30 cm intervals (excluding OKA; see discussion below). After this point, they remain approximately constant (at ~40 mg cm^{-2}, 0–5 cm; and 160 mg cm^{-2}, 0–30 cm) up to the wettest site at Mongu (MON; 910 mm). $\delta^{13}C$ values decrease in an approximately linear manner (again excluding OKA) as precipitation increases, reflecting the increasing proportion trees from the arid shrub savannahs in the south to the dry deciduous forest in the north.

The apparent plateau in SOC inventories between 400–500 and 900 mm may be related to feedbacks between biomass and fire frequency. Bird *et al.* (2000), for example, have demonstrated that fire reduced SOC inventories by 40–50% in comparison with fire-protected soils at Matopos in Zimbabwe. Below 400 mm MAP, there may be insufficient standing biomass, hence fuel loads, to carry frequent fires that can remove a substantial proportion of accumulated litter (Swaine, 1992). Between ~500 and 910 mm, a proportionately greater amount of litter may be recycled directly to the atmosphere as CO_2 by frequent fires without entering the SOC pool, thus depressing SOC stocks below levels that would be expected on the basis of climate alone.

The OKA, and to a lesser extent MAU transects, appear to be anomalous with respect to other transects. Both have high SOC inventories and low $\delta^{13}C$ values in comparison with both drier and wetter sites (Fig. 4). In the case of the OKA transects, where SOC inventories are more than double those observed in the other areas, this is clearly related to the year-round availability of groundwater from the seasonal flooding. The effect of increased water availability from groundwater may also be augmented by the fact that microbial SOC decay rates will not be similarly increased. Microbes in the 0–30 cm interval sampled cannot access such groundwater and must rely solely on moisture available from precipitation. During the dry season, the vegetation can continue to assimilate carbon and deliver it to the soil, but soil conditions may be too dry to allow commensurate increases in the rate of microbial degradation. It is also possible that the position of the transects, on sand islands in the delta, provides a measure of fire protection for local vegetation. This protection would further increase SOC inventories relative to the surrounding areas.

Figure 5a shows the SOC inventory and its partitioning between the 0–5 cm interval and the deeper 5–30 cm

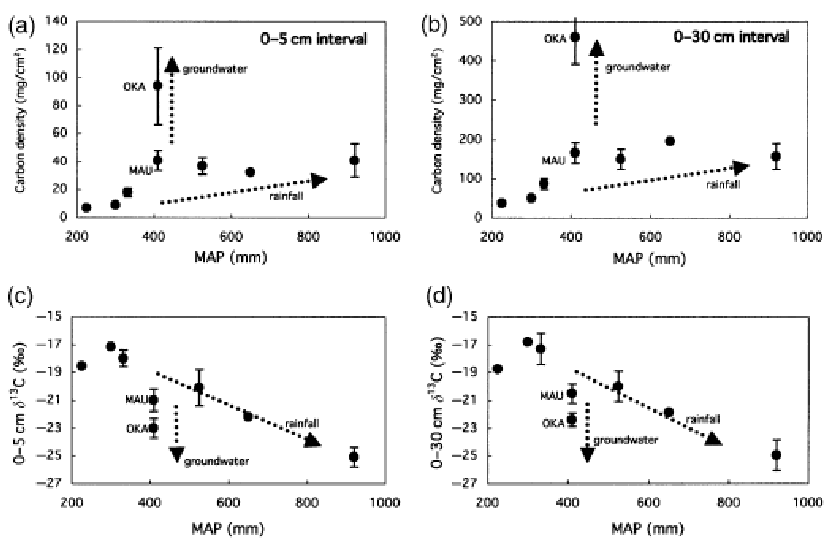

Fig. 4 Relationship between weighted SOC inventory and mean annual precipitation for all transects for the 0–5 cm (panel a) and 0–30 cm (panel b) intervals. Also shown is the relationship between weighted $\delta^{13}C$ value and mean annual precipitation for all transects for the 0–5 cm (panel c) and 0–30 cm (panel d) intervals. 'Rainfall' and 'groundwater' trends are indicated by dashed arrows.

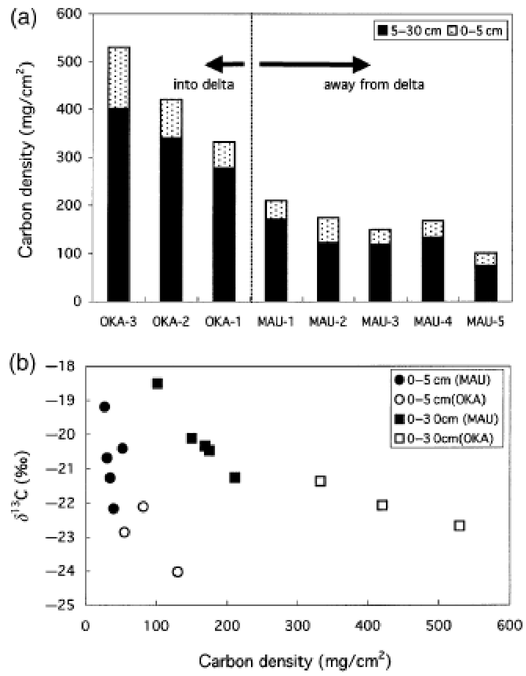

Fig. 5 (a) Weighted carbon inventories for the OKA and MAU transects for the 0–5 and 5–30 cm intervals (5–30 cm results calculated by mass balance from 0–5 and 0–30 cm results). (b) Relationship between weighted SOC inventory and weighted δ^{13}C value for OKA and MAU transects.

interval for transects from both the MAU and OKA regions. The elevated inventories in the OKA transects are apparent, but it is also evident that inventories in the MAU transects rise erratically from MAU-5 ($\sim$20 km from the delta) to MAU-1 ($\sim$10 km from the delta). This suggests that some of the MAU transects closest to the delta may also be affected by differential access to groundwater from the delta. Such a conclusion might explain why the MAU transects, with higher SOC inventories and lower δ^{13}C values, plot slightly off the trends defined by results from other regions.

Figure 5b confirms that the MAU and OKA transects form part of a continuum, with coherent trends between the SOC inventory and δ^{13}C value for both the 0–5 and 0–30 cm intervals. As the weighted SOC inventory increases, the weighted δ^{13}C value decreases, reflecting increasing inputs of tree-derived carbon, as observed with the individual samples and discussed in the previous section.

δ^{13}C relationships with depth

The weighted δ^{13}C value of the 0–5 and 5–30 cm intervals at each (the latter calculated by mass balance

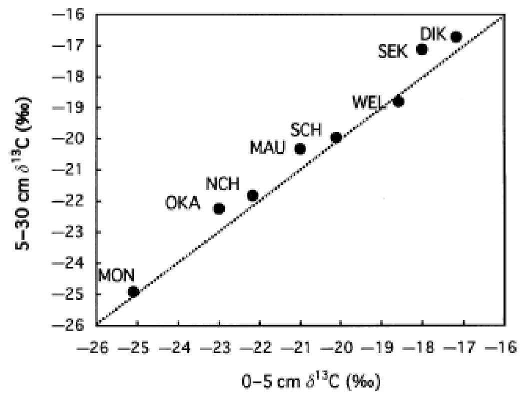

Fig. 6 Relationship between the weighted δ^{13}C value of the 0–5 and 5–30 cm interval of all samples from the eight regions sampled for this study (5–30 cm results calculated by mass balance from 0–5 to 0–30 cm results). 1 : 1 relationship is shown by dotted line.

from data for the 0–5 and 0–30 cm intervals) are closely related (Fig. 6). The δ^{13}C value for the 5–30 cm interval is 0.13–0.8‰ higher than the 0–5 cm interval for all bulked samples, except the single WEL transect, and an increase in δ^{13}C value with depth has been reported for many well-drained soil profiles (e.g. Desjardin *et al.*, 1994). The increase is due to the isotope effects associated with microbial degradation of SOC and to older carbon, deeper in the soil profile, having been fixed from atmospheric CO_2 having a higher-than-modern δ^{13}C value.

These effects in these samples (0.40 ± 0.3‰) are comparatively small because of very low fine particle abundances in the samples. This low abundance limits the capacity of these soils to protect 'old carbon' and stabilize the high-^{13}C products of microbial decay. The result from the WEL transect is excluded from this analysis, as the very low carbon abundances (as low as 0.08%) in samples from the transect made the accurate determination of δ^{13}C value difficult. The slightly negative difference (-0.22‰) between 0–5 and 5–30 cm intervals for the WEL samples is therefore likely to be the result of a slightly larger analytical uncertainty for samples from this transect.

Conclusions

The stratified sampling approach employed in this study has allowed the definition of coherent trends in both SOC inventories and the δ^{13}C value of SOC despite considerable spatial heterogeneity. The results confirm the need to consider the distribution of trees and grass in savannah regions explicitly when attempting to determine either SOC inventories or the average regional $\delta^{13}C$ value of SOC. This is because systematically higher SOC inventories (with systematically lower $\delta^{13}C$ values) characterize the areas under trees, in comparison with areas away from the influence of trees. This study further confirms the utility of 'bulking' many individual samples in order to smooth local heterogeneity and obtain a coherent picture of regional trends.

Weighted SOC inventories along the moisture gradient increase from the southern end of Botswana to the north as MAP increases, plateauing at 400–500 mm and remaining approximately constant to the northern end of the transect at 910 mm, in southern Zambia. The reason for the plateau may be feedbacks operating between fire frequency and fuel load, such that a progressively higher proportion of carbon delivered to the soil surface is returned directly to the atmosphere without being cycled through the SOC pool by progressively more intense or frequent fires. Weighted $\delta^{13}C$ values along the transect decrease with increasing MAP, reflecting the increasing dominance of C_3 over C_4 photosynthesis as MAP increases. $\delta^{13}C$ values in the uppermost soil layers directly reflect the inputs of carbon from local standing biomass, but systematic changes with depth in the soil reflect more complex processes of microbial degradation and the mixing of SOC of different ages.

Results for both weighted inventories and weighted $\delta^{13}C$ values for samples from the OKA and possibly for the nearby MAU transects do not accord with the regional trend described above. This appears to be the result of access by plants in these regions to year-round groundwater. Access to groundwater is reflected in considerably higher weighted SOC inventories and lower weighted $\delta^{13}C$ values than would be predicted on the basis of regional trends alone.

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