

# Soil Carbon-13 Natural Abundance under Native and Managed Vegetation in Brazil

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## ABSTRACT

The conversion of native Cerrado vegetation (a mixed C<sub>3</sub> and C<sub>4</sub> vegetation) to *Pinus caribaea* Morelet plantations (a pure C<sub>3</sub> vegetation) and to *Brachiaria decumbens* Stapf pastures (a pure C<sub>4</sub> vegetation) likely affects the C cycle. We used the natural abundance of <sup>13</sup>C (δ<sup>13</sup>C) in vegetation and soil to: (i) quantify the contributions of C<sub>3</sub> and C<sub>4</sub> plants to the organic matter input into the soil under Cerrado vegetation and (ii) determine the degree of the replacement of original Cerrado-derived C by *Pinus* plantations and pastures. The mean δ<sup>13</sup>C value of the soils (Anionic Acrustoxes) under Cerrado vegetation ranged from -20.5 to -19.7‰, which was dissimilar to the mass-weighted mean δ<sup>13</sup>C signal of the aboveground biomass (-25.8‰). This was because grasses being C<sub>4</sub> plants contributed 11% to the aboveground biomass but about 50% of the organic matter input to the soil, which was estimated with a simple mixing model of the C<sub>3</sub> and C<sub>4</sub> <sup>13</sup>C signals. After 12 and 20 yr, only 30% of the original organic matter in the topsoil was replaced by new organic matter under pasture or *Pinus* plantation, respectively. This turnover took place without significantly changing the C storage of the top 2 m of the soil (17–19 kg m<sup>-2</sup>). The C replacement under *Pinus* affected only the top 0.15 m. Our results demonstrate that the C replacement in soils following land-use change in the Oxisols of this study takes several decades and is considerably slower under *Pinus* than under pasture.

THE NATIVE VEGETATION in the Brazilian savanna, the Cerrado, consists of a mixture of C<sub>3</sub> and C<sub>4</sub> plants. In the central Cerrado region, native species are dominated by C<sub>3</sub> plants with no substantial variation during the last 12 000 yr (Pessenda et al., 1996). Although C<sub>4</sub> grasses contribute little to the total aboveground biomass in native Cerrado vegetation (Lilienfein et al., 2001b), they may play an important role in C input to soil because the C from grasses has faster turnover rates than the C from trees. The C isotopic composition of organic matter derived from C<sub>3</sub> or C<sub>4</sub> plants can be used to determine their relative contributions to soil organic matter under mixed C<sub>3</sub>-C<sub>4</sub> vegetations like the Cerrado ecosystem (Balesdent and Mariotti, 1996).

In the Brazilian Cerrado region, pastures currently cover 0.35 to 0.40 million km<sup>2</sup>, representing the largest land-use practice of agriculture in this region (Resck et al., 2000). The agricultural land use also includes *Pinus* plantations. Thirty years ago, more than 2000 km<sup>2</sup> were transformed into *Pinus* plantations (IBDF, 1984; Espirito Santo, 1995). The current agricultural development of the Brazilian savanna is characterized by rapid changes and expansion of land-use practices (Resck et al., 2000).

Both, *Pinus* plantations and pastures would be ex-

pected to affect C isotopic composition of soil organic matter compared with that of the native Cerrado vegetation because *Pinus* trees have the C<sub>3</sub> photosynthetic pathway and pasture grasses such as *Brachiaria decumbens* Stapf have the C<sub>4</sub> pathway. Such land-use changes may be used to assess the organic matter turnover (Veldkamp, 1994; Balesdent and Mariotti, 1996; Roscoe et al., 2001). Veldkamp (1994) studied the C turnover by using the δ<sup>13</sup>C signal in different soils of a pasture chronosequence in Costa Rica and found that it takes about three decades for pastures to reach maximum, equilibrium C concentration in the soil.

The objectives of the study were to: (i) quantify the contributions of C<sub>3</sub> and C<sub>4</sub> plants of Cerrado vegetation to the organic matter input into the soil and (ii) determine the degree of C replacement in soils under productive pure-grass pastures or *Pinus* plantations relative to the native Cerrado ecosystem after 12 to 20 yr.

## MATERIALS AND METHODS

### Study Sites

The study was performed southeast of Uberlândia (State of Minas Gerais) about 400 km south of Brasília (19° 5' S Lat., 48° 7' W Long.). Mean annual temperature in Uberlândia between 1981 and 1990 was 22°C with only small variations between the coldest (June, July: 19°C) and the warmest months (February: 24°C). Mean annual precipitation during this period was 1550 mm with 130 mm during the dry season between May and September and 1420 mm during the rainy season between October and April (Rosa et al., 1991).

Within an area of about 100 km<sup>2</sup>, three plots (replications) of each ecosystem were selected. The three systems were (i) native savanna (Cerrado), (ii) *Pinus* plantations, and (iii) productive pure-grass pastures. The study sites are located in Fazenda Pinusplan, the largest commercial farm of the study area and its surroundings, east of the main road linking Uberlândia and Uberaba. To enable a valid statistical ANOVA, independent, and randomly distributed plots of all replicates of the same native or land-use system were separated from each other by a distance of at least 300 m (Lilienfein et al., 1999). Furthermore, there was an area between replicates of a given system with different land use except in the *Pinus* plantation where all replicates were located in a large forested area.

On the native Cerrado vegetation sites, the vegetation was a typical Cerrado as defined by Sarmiento (1984). These sites are characterized as open grassland with a 15 to 40% cover of 3- to 5-m high trees. Tree density was 6487 ha<sup>-1</sup> with only 602 trees ha<sup>-1</sup> taller than 2 m. Tree species that dominate in the canopy layer >2 m were *Pouteria torta* (Mart.) Radlk., *Ouratea spectabilis* (Mart.) Engl., *Roupala montana* Aubl., *Byrsonima coccolobifolia* H.B. et K., *Dalbergia miscolobium* Benth., *Kielmeyera coriacea* Mart., and *Caryocar brasiliense* Cambess., which together represented 70% of the biomass of the >2-m canopy layer. In the 0.5- to 2-m tall tree canopy layer, many different species were found of which *Ouratea hexasperma* (St.-Hil.) Baill. representing 33% of the biomass in the 0.5- to 2-m layer was most abundant. The dominant shrub species were *Miconia holosericea* DC., *Hortia brasiliana*

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Vand. ex DC., *Myrcia rostrata* DC., *Parinari obtusifolia* Hook. f., and *Campomanesia velutina* Blume, which contributed 93% of the total shrub biomass. Among the grass species we most frequently found *Andropogon minarum* Kunth, *Axonopus barbigerus* (Kunth) Hitchc., *Tristachya chrysothrix* Nees, and *Echinolaena inflexa* (Poir.) Chase of the family Poaceae, which comprised the highest number of species; among the herbaceous species, members of the families Asteraceae, Rubiaceae, Fabaceae, and Mimosaceae were most abundant.

To establish the *Pinus caribaea* Morelet plantations, natural savanna vegetation was cleared by harvesting the trees including their large roots. *Pinus caribaea* trees were planted in 1977 into holes and fertilized with about 33 kg Ca, 13 kg P, and 20 kg S ha<sup>-1</sup> (80 g of superphosphate per tree was applied to 1670 planted trees ha<sup>-1</sup>) at the time of plantation. The soils were not plowed, weeds were not controlled and there were no further fertilizer applications. At the time of our study (1997–1999), there were about 950 trees ha<sup>-1</sup> with an average height of 21 m. The average diameter at breast height on the three plots was 234 to 261 mm.

The most important criteria for the selection of the pasture plots were based on visual qualitative assessment and the likelihood that the pasture establishment followed directly after clearing native vegetation. The selected plots were pure grass pastures of *Brachiaria decumbens* Stapf with a closed vegetation cover. Although there was no written historical documentation about the pastures, landowners were interviewed and a reasonable management record was made. Only the pastures with the best-known history were selected. All pastures under study were established in about 1985 by harvesting the native Cerrado vegetation including the large roots. The most common procedure was to plant upland rice (*Oryza sativa* L.), which was fertilized with approximately 40 kg P, 65 kg K, 32 kg N, and 1 Mg of dolomitic limestone ha<sup>-1</sup>. The fertilizer was mixed with seeds of *Brachiaria decumbens*, an imported grass species from Africa. After the harvest of the rice the *Brachiaria* was already stabilized and grazing began. In 1996–1997, we fertilized all pasture replicates with 17 kg P and 33 kg K ha<sup>-1</sup>. One of the three replicates of the pastures was an experimental pasture where the fertilizing rates are well known. The experimental pasture received 17 kg P and 33 kg K ha<sup>-1</sup> at 4-yr intervals (i.e., in 1988, 1992, and 1996). The other pasture replicates received maintenance fertilizer applications at similar but unknown rates and application dates.

### Soil Sampling

Soils at all sites were very fine isohyperthermic Anionic Acrustoxes (Soil Survey Staff, 1997) or Latossolos vermelhos escuros and Latossolos vermelhos-amarelos according to the Brazilian soil classification (EMBRAPA, 1999) and had similar chemical and physical properties before the beginning of land use (Lilienfein et al., 1999). All soils were developed from the same geological parent material, fine limnic sediments of the lower Tertiary. The clay content of the soils ranged between 615 and 885 g kg<sup>-1</sup>. In the topsoil (0–0.15 m), the pH (water) ranged from 4.7 to 5.4, and the effective cation-exchange capacity between 4 and 15 mmol<sub>c</sub> kg<sup>-1</sup>. Properties, which are typically not influenced by land use such as soil classification, particle-size distribution, and the concentrations of dithionite-soluble Fe (Holmgren, 1967) and oxalate-soluble Al (Schwertmann, 1964) were not significantly different among the studied soils (Lilienfein et al., 1999).

Within each of the nine plots, one composite soil sample from the 0- to 0.15-, 0.15- to 0.3-, 0.3- to 0.8-, 0.8- to 1.2-, 1.2- to 2-m layers was taken in January 1998. For the 0- to 0.15- and 0.15- to 0.3-m layers, samples were taken from five locations and combined, while those of the deeper layers were

taken from one soil pit on each plot. Additionally, we sampled the organic horizons on the Cerrado and *Pinus* soils. All mineral samples were dried at 40°C and sieved to <2 mm. Fine roots that passed the 2-mm sieve were not removed. The organic horizon samples were ground to fine powder in a ball mill for analysis.

## Biomass Sampling

### Aboveground

It can be assumed that the old-growth Cerrado vegetation was in steady state and that the storage of C and nutrients in its biomass changes very slowly and does not fluctuate significantly on a seasonal basis. This roughly was true for the *Pinus* stands. In contrast, the pastures have significant seasonal variations. We measured biomass at the time of the year when it was largest.

The Cerrado biomass was determined in a 0.1 km<sup>2</sup> area of native Cerrado vegetation around one of the three Cerrado plots in February and March 1998 and 1999 described by Lilienfein et al. (2001b). Briefly, the biomass of the native Cerrado vegetation was estimated on three plant replicates of the dominant tree and shrub species. This was done on the seven dominant tree species of the upper canopy (>2 m height), the one dominant tree species of the lower canopy (<2 m height); and the five dominant shrub species, which were harvested and separated into stems, barks, twigs, leaves, and dead wood, and analyzed. The biomass of the grass-herb layer was determined by harvesting five replicate 1-m<sup>2</sup> plots.

According to the records of the largest commercial farm in the study area, the Fazenda Pinusplan, total biomass for stems with a diameter at breast height (1.3 m) >5 cm after 20 yr was 140 000 kg ha<sup>-1</sup> (dry weight). The biomass of the remaining slash (needles, branches, stems <5 cm) was 7000 kg ha<sup>-1</sup>.

The standing biomass of the pastures was determined by harvesting the total aboveground biomass of three 0.5-m<sup>2</sup> large subplots on six dates between October 1997 and April 1999 at all pastures plots.

### Litterfall

On each Cerrado site and *Pinus* plantation plot, we installed five litter collectors with a surface of 0.25 m<sup>2</sup>. Three litter collectors were placed at distances of 1.5 m from the stems and two at distances of 0.5 m from the stems. The content of the five collectors was combined as a representative sample on each collection day. Litter was collected in 1- to 3-wk intervals between 25 Apr. 1997 and 28 Apr. 1999.

### Belowground

The biomass of coarse (>2 mm) and fine roots (<2 mm) was determined separately. Coarse root biomass was determined by digging out the entire root system of trees to the depth where the root diameter decreased to <2 mm. In the Cerrado vegetation, we sampled one individual of each dominant tree and shrub species and in the *Pinus* stands a total of three trees were sampled. To determine the fine root biomass and distribution, five soil samples were taken from 2 m-long soil trenches per plot with a root auger (diameter 7 cm, height 10 cm) from the 0- to 0.15-, 0.15- to 0.3-, 0.3- to 0.8-, 0.8- to 1.2-, and 1.2- to 2-m soil depth layers in January 1999, during the high rainy season when the fine root system of all studied ecosystems should be maximum. The soil fraction <0.5 mm was separated by washing the sample through a sieve. Roots were then collected from the remaining sample with a pair of tweezers.

All biomass samples were air-dried, weighed, and ground to a fine powder in a ball mill.

### Chemical Analyses

Total concentrations of C were determined by dry combustion and gas chromatographic separation with a CNS analyzer (Elementar Vario EL, Elementar Analysensysteme GmbH, Hanau, Germany).

The  $^{13}\text{C}$  natural abundances in all samples were determined by dry combustion on a Carlo Erba NA 2500 analyzer (Carlo Erba, Milan, Italy) coupled with a Delta<sup>plus</sup> continuous-flow isotope ratio mass spectrometer (Thermo Finnigan, Bremen, Germany) in the soil scientific laboratory of the University of Bayreuth. Sucrose ANU (IAEA, Vienna, Austria) and  $\text{CaCO}_3$  (NBS 19, National Institute of Standards and Technology, Gaithersburg, MD) were used as calibration standards. Natural abundances of  $^{13}\text{C}$  were expressed as  $\delta^{13}\text{C}$  representing the enrichment of  $^{13}\text{C}$  (in ‰) compared with  $\text{CO}_2$  prepared from a calcareous belemnite of the Cretaceous Peedee formation in South Carolina according to Eq. [1]:

$$\delta^{13}\text{C} = \frac{{}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}}{{}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}} \times 1000 \quad [1]$$

The analytical precision of the measurements was 0.15‰.

### Data Evaluation

The replacement of native Cerrado vegetation-derived C by *Pinus* plantations and pastures in different soil layers was calculated by:

$$X = \frac{(\delta^{13}\text{C}_{\text{soil}} - \delta^{13}\text{C}_{\text{Cerrado}})}{(\delta^{13}\text{C}_{\text{Pinus/pasture}} - \delta^{13}\text{C}_{\text{Cerrado}})} \times 100 \quad [2]$$

where  $X$  is the percentage of new C,  $\delta^{13}\text{C}_{\text{soil}}$  is the  $\delta^{13}\text{C}$  value in the soil layer,  $\delta^{13}\text{C}_{\text{Cerrado}}$  is the  $\delta^{13}\text{C}$  value of the same soil layer under native Cerrado vegetation, and  $\delta^{13}\text{C}_{\text{Pinus/pasture}}$  is the mean  $\delta^{13}\text{C}$  signal of the organic matter input into the soil under *Pinus* plantation or pasture.

To enable data evaluation using ANOVA, the following three prerequisites must be met. The first prerequisite is that all study sites had homogeneous soil properties before land use that we have shown previously (Lilienfein et al., 1999). The second prerequisite is that the study sites are independent, which should be the case because all study sites are separated from each other by areas under other land uses (except *Pinus* plots) with distances of several 100 m between the plots being larger than geostatistical ranges of soil properties. The third prerequisite is random spatial distribution within a homogeneous study area. This prerequisite was most difficult to meet because we had to use pre-existing land-use locations that were established by land managers. Although we may not rule out site-specific reasons for the establishment of a given land use, the homogeneity of the soil suggests that random ownership was more important than soil quality. Therefore, we concluded that the assumptions for applying ANOVA tests were met.

Mean values of the soil parameters were tested for differences between plots under native Cerrado vegetation, *Pinus* plantations, and pastures by using Tukey's honest significant difference (HSD) means separation test (Hartung and Elpelt, 1989). Correlation analyses were performed using the Least Squares method (Hartung, 1989). Statistical analyses were performed with STATISTICA for Windows 5.1 (StatSoft, 1995, Loll and Nielsen, Hamburg, Germany). Significance was set at  $p < 0.05$ .

## RESULTS AND DISCUSSION

### Biomass and Organic Matter Turnover in the Cerrado Ecosystem

The mass-weighted mean  $\delta^{13}\text{C}$  signal of the above-ground biomass was  $-25.8\text{‰}$  based on the biomass data of Lilienfein et al. (2001b). The mass-weighted mean  $\delta^{13}\text{C}$  signals of the individual tree and shrub species ranged from  $-29.6$  to  $-26.0\text{‰}$  reflecting that all woody plants have the  $\text{C}_3$  photosynthetic pathway. In contrast, the grasses had a mass-weighted mean  $\delta^{13}\text{C}$  value of  $-13.1\text{‰}$  indicating that they belonged to the  $\text{C}_4$  photosynthetic group. The herbs (mass-weighted mean  $\delta^{13}\text{C}$ :  $-28.7\text{‰}$ ) and the trees and shrubs of the grass/herbs layer ( $-30.7\text{‰}$ ) belonged to the  $\text{C}_3$  photosynthetic group. The aboveground biomass of green and brown grasses was  $0.24 \text{ kg m}^{-2}$  contributing 11% to the total biomass of  $2.3 \text{ kg m}^{-2}$  (Lilienfein et al., 2001b).

The mass-weighted mean  $\delta^{13}\text{C}$  values of the coarse roots of the upper tree layer ( $-27.5\text{‰}$ ) were similar to that of the aboveground biomass ( $-27.1\text{‰}$ ). The mass-weighted mean  $\delta^{13}\text{C}$  values of the coarse roots of the lower tree layer ( $-26.7\text{‰}$ ) and the shrub layer ( $-27.2\text{‰}$ ) were consistently higher by 0.8 to 1.2‰ than those of the aboveground biomass ( $-27.9$  and  $-28.0\text{‰}$ , respectively). Higher  $\delta^{13}\text{C}$  values in roots than in other plant tissues are generally found (Boutton, 1996).

The mean  $\delta^{13}\text{C}$  values of the fine roots decreased from  $-22.5$  to  $-26.9\text{‰}$  with increasing soil depth indicating that the contribution of fine roots of the  $\text{C}_4$  plants decreased with increasing soil depth as a result of differential rooting strategies of woody plants, herbs, and grasses. To calculate the contribution of the  $\text{C}_4$  grasses to the total fine-root biomass we assumed that the fine roots of the grasses had the same  $\delta^{13}\text{C}$  as their aboveground biomass ( $-13.1\text{‰}$ , Table 1) and that the fine roots of the trees and shrubs had the same  $\delta^{13}\text{C}$  as the mass-weighted mean of their coarse roots ( $-27.2\text{‰}$ ). In the topsoil, between 16 and 45% of the fine-root biomass originated from the grasses that contributed  $<2\%$  to the fine-root biomass at soil depths  $>0.8 \text{ m}$ . In total,  $\text{C}_4$  grasses contributed 24% to the fine-root biomass down to the 2-m soil depth of  $1.8 \text{ kg m}^{-2}$  (Lilienfein et al., 2001b). As the roots frequently have greater  $\delta^{13}\text{C}$  values than the shoots (Boutton, 1996), our assumption of the same  $\delta^{13}\text{C}$  signal of grass roots and shoots may have overestimated the contribution of  $\text{C}_4$  grasses. However, if the  $\delta^{13}\text{C}$  of the roots was set to  $-12\text{‰}$ , the estimated mean total contribution of  $\text{C}_4$  grasses to total fine root biomass was only slightly reduced to 23%.

To assess the  $\delta^{13}\text{C}$  signal of the organic matter input into the soil, we determined the  $\delta^{13}\text{C}$  values of the fine litterfall in bulked samples for two dry and two rainy seasons (Fig. 1). The  $\delta^{13}\text{C}$  values of the fine litterfall showed a seasonal variation with greater values during the dry period, which agrees with findings that water stress results in greater  $\delta^{13}\text{C}$  values of leaves of  $\text{C}_3$  plants (Boutton, 1996). The  $\delta^{13}\text{C}$  value of the fine litterfall during the rainy seasons was close to that found on average in the leaves of the upper and the lower tree and the shrub stories ( $-28.7$ ,  $-29.1$ , and  $-29.7\text{‰}$ , re-

**Table 1. Biomass and  $\delta^{13}\text{C}$  of fine roots and percentage of contribution of  $\text{C}_4$  grasses to the fine-root biomass at various soil depths under native Cerrado vegetation.**

Sampling depth	Cerrado 1			Cerrado 2			Cerrado 3		
	Biomass	$\delta^{13}\text{C}$	$\text{C}_4$	Biomass	$\delta^{13}\text{C}$	$\text{C}_4$	Biomass	$\delta^{13}\text{C}$	$\text{C}_4$
m	$\text{kg m}^{-2}$	‰	%	$\text{kg m}^{-2}$	‰	%	$\text{kg m}^{-2}$	‰	%
0–0.15	1.0	–20.8	45	0.78	–25.0	16	0.95	–21.9	38
0.15–0.30	0.47	–24.0	23	0.23	–24.6	18	0.44	–23.6	25
0.30–0.80	0.26	–27.6	0.0	0.26	–25.4	13	0.34	–25.5	12
0.80–1.2	0.05	n.a.†	–	0.17	–27.4	0.0	0.05	n.a.	–
1.2–2.0	0.10	n.a.	–	0.06	n.a.	–	0.09	–26.9	2.1
Total	1.9			1.5			1.9		

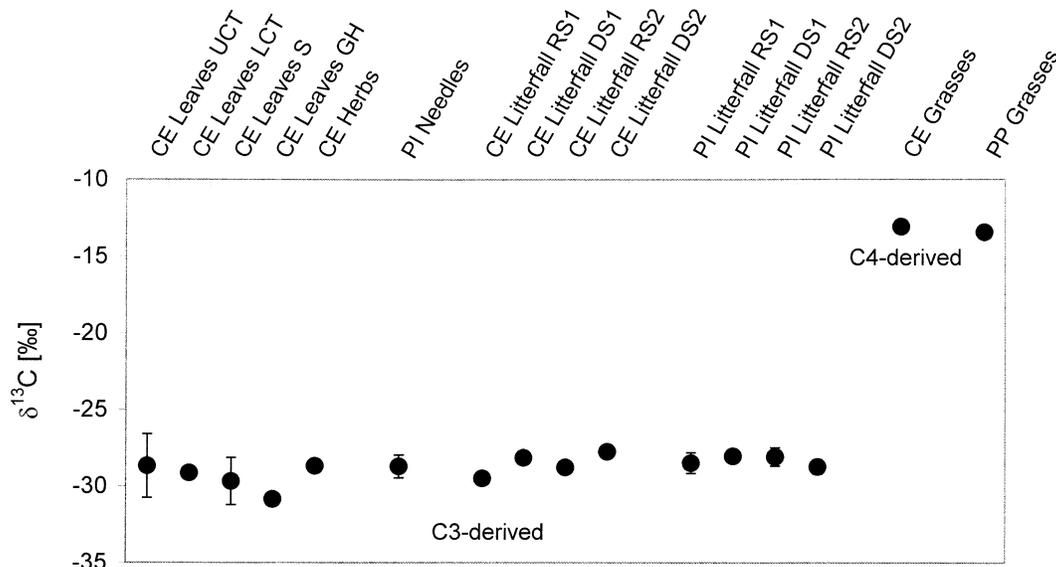
† Not analyzed because of a too small sample size.

spectively) indicating that the largest part of the fine litterfall consisted of leaves.

We estimated the  $\delta^{13}\text{C}$  value of the organic matter input by assuming that the whole aboveground grass and herb biomass turned over within 1 yr and by taking the value of 1.2 yr for the turnover time of the aboveground fine litter from Wilcke and Lilienfein (2002). This resulted in a mean  $\delta^{13}\text{C}$  value of  $-19.7\text{‰}$  for the annual organic matter input. Furthermore, if the leaves of the trees and shrubs in the grass/herbs layer were assumed to be turned over within 1 yr, the  $\delta^{13}\text{C}$  value would decrease to  $-20.3\text{‰}$ , which is close to that of the topsoil of  $-20.5\text{‰}$ . In the latter scenario, the  $\text{C}_4$  grasses would contribute 54% to the annual organic matter input and thus much more than to the standing aboveground biomass (11%). This assumption ignores that the fine roots may be turned over as frequently as eight times per year in savanna soils (Guillaume et al., 2001) and the small contribution of the coarse woody debris ( $\delta^{13}\text{C}$  of the tree stem wood:  $-25.8$  to  $-29.1\text{‰}$ ) with much longer turnover times, both shifting the  $\delta^{13}\text{C}$  of the organic matter input to the soil to more negative values. However, the latter may be compensated by the accumulation of  $^{13}\text{C}$  in soil organic matter because of

mineralization during the incorporation of the organic layer into the mineral soils shifting the  $\delta^{13}\text{C}$  value to heavier, less negative signals by 1 to 2‰ (Martin et al., 1990; Boutton, 1996).

In summary, we found that the  $\delta^{13}\text{C}$  signal in the soil was dissimilar to that in aboveground biomass because of differential contributions of the species belonging to different photosynthetic groups to organic matter input to the soil. The  $\text{C}_4$  grasses only contributed 11% to the total aboveground biomass but about 50% to the annual biomass input resulting in a high labeling of the soil with the  $\text{C}_4$  signature. A similar discrepancy between the mean  $\delta^{13}\text{C}$  value of the current vegetation and the soil was observed for the tiger bush savanna in Niger, which had a continuous succession of pioneer pure-grass followed by tree-grass communities (Guillaume et al., 2001). In the tiger bush, the  $\text{C}_4$  pioneer grasses saturated most binding sites for organic matter in soils before the  $\text{C}_3$ -dominated climax vegetation appeared. We conclude that for our typical Cerrado ecosystem, organic matter turnover is not dominated by  $\text{C}_3$  plants. In a mixed  $\text{C}_3$ – $\text{C}_4$  vegetation, even under steady state conditions the  $\delta^{13}\text{C}$  signal of the soil does not necessarily reflect the mean  $\delta^{13}\text{C}$  signal of the aboveground biomass.



**Fig. 1.** Mean  $\delta^{13}\text{C}$  values of leaves in the upper canopy trees (UCT), lower canopy trees (LCT), shrub (S), and grass/herb layer (GH) and in grasses and fine litterfall of a native Cerrado (CE), in needles and fine litterfall of *Pinus caribaea* Morelet stands (PI), and in grasses of pure-grass *Brachiaria decumbens* Stapf pastures (PP). Mean  $\delta^{13}\text{C}$  values are shown separately for two rainy (RS) and dry seasons (DS). The error bars show standard deviations of the three replicate plots of the native and land-use systems for needles and litterfall, of the various sampled tree and shrub species sampled at one Cerrado site for leaves, and of the six biomass harvests at the three replicate pasture plots for pasture grasses. (Those not showing bars have standard deviations smaller than the symbols.)

### Soil Carbon Replacement in *Pinus* Plantations or Pastures

In a previous work, we showed that the mean C storage in the 0- to 2-m soil layer was not significantly different among Cerrado ecosystems ( $18 \pm 0.68 \text{ kg m}^{-2}$ ), *Pinus* plantations ( $17 \pm 1.6$ ), or pastures ( $19 \pm 2.8$ , Lilienfein and Wilcke, 2003). However, in the 0- to 0.3-m soil layer, the *Pinus* plantations stored significantly less C ( $4.9 \pm 0.29 \text{ kg m}^{-2}$ ) than the Cerrado ecosystems ( $5.5 \pm 0.23$ ) or the pastures ( $6.4 \pm 0.81$ ), which was partly attributed to a lower bulk density of the 0- to 0.3-m soil layer compared with the other systems (Lilienfein and Wilcke, 2003).

The  $\delta^{13}\text{C}$  values of the Cerrado soil were higher than those reported for Cerrado soils near Salitre de Minas by Pessenda et al. (1996) of  $-24.7$  to  $-26.7\text{‰}$  and near Sete Lagoas by Roscoe et al. (2001,  $-24\text{‰}$ ) both in the State of Minas Gerais where our study took place. This reflected a larger contribution of  $\text{C}_4$  grass biomass to the organic matter input to the soil from our Cerrado vegetation. The mean  $\delta^{13}\text{C}$  values of the Cerrado soil increased greatly from the Oi horizon to the mineral soil but remained rather constant through all layers of the mineral soil (Table 2). In the *Pinus* stands, a similar increase in  $\delta^{13}\text{C}$  between the organic layer and the mineral soil was observed. However, in the top 0- to 0.15-m layer of the mineral soil the mean  $\delta^{13}\text{C}$  value tended to be lower under *Pinus* than under Cerrado vegetations, while at greater depths *Pinus* and Cerrado soils only differed slightly. In the pasture soils, the  $\delta^{13}\text{C}$  was higher than in the Cerrado and the *Pinus* soils at all depths. However, only the mean  $\delta^{13}\text{C}$  value of the topsoil between the pastures and the *Pinus* stands differed significantly.

To calculate the C replacement by the *Pinus* plantation after 20 yr and by the productive pure grass pasture after 12 yr, we used the mean  $\delta^{13}\text{C}$  values of the sampled Cerrado soil layers as a reference,  $-28.4\text{‰}$  for the *Pinus* organic matter input signal, and  $-13.0\text{‰}$  for the pasture input signal. The mass-weighted mean  $\delta^{13}\text{C}$  of the *Pinus* fine litterfall was  $-28.3\text{‰}$  and that of the *Pinus* fine roots was  $-28.4\text{‰}$ ; the mean  $\delta^{13}\text{C}$  of the aboveground pasture biomass was  $-13.4\text{‰}$  and that of the pasture fine roots was  $-12.4\text{‰}$ . We assumed a 50/50 contribution of

above- and belowground litter to the organic matter input into the mineral soil. This assumption is based on the finding that the root contribution to the organic matter input into the organic layer of temperate forests ranges between 23 and 80% (Vogt et al., 1986). For corn (*Zea mays* L.), Bolinder et al. (1999) found that about 17% of the root-derived C was retained as soil organic matter. The same authors collected data from the literature showing that a range of 7.7 to 20% with a mean of 12.2% of the shoot-derived C of corn remained as organic matter in the soil. Thus, the proportion of the C in belowground biomass retained in soil seems to be higher than that retained of the C in aboveground biomass. If this was also true for *Pinus* trees, a larger contribution of belowground than of aboveground litter to soil organic matter would compensate for the larger standing aboveground ( $15 \text{ kg m}^{-2}$ ) than belowground biomass ( $9.1 \text{ kg m}^{-2}$ ) of the *Pinus* stands (Lilienfein and Wilcke, 2003). This further supports our assumption that a 50/50 input of above- and belowground litter to organic matter in the mineral soil is reasonable. The uncertainty in the ratio of above- to belowground litter input, however, only introduces a small error in our estimate of the degree of C replacement because of the small differences in the  $\delta^{13}\text{C}$  signal among the above- and belowground plant compartments. We only calculated the C replacement using the mean  $\delta^{13}\text{C}$  values of the Cerrado, *Pinus*, and pasture soils to reduce the spatial variation.

In the topsoil under *Pinus* plantation and pasture, about 30% of the soil organic matter was derived from the present vegetation (Table 2). The contribution of organic matter derived from pasture grasses decreased continuously with depth. In contrast, in the *Pinus* soil there was almost no detection of *Pinus*-derived organic matter in 0.15- to 1.2-m depth. Thus, most of the *Pinus* litter accumulated in the organic layer and little was incorporated into the mineral soil probably because of a low bioturbation.

The change in  $\delta^{13}\text{C}$  at the 1.2- to 2-m soil depth under *Pinus* coincided with a significant increase in C concentration compared with the Cerrado soil (Table 2). Both results suggest that there has been a higher C input from *Pinus* roots at this depth than under Cerrado vegetation.

**Table 2.** Mean C concentrations and  $\delta^{13}\text{C}$  in Anionic Acrustoxes under native Cerrado, *Pinus caribaea* Morelet plantation, and *Brachiaria decumbens* Stapf pasture and percentage of Cerrado-C replacement after 20 and 12 yr of continuous *Pinus* or pasture vegetation, respectively. Standard deviations are in parentheses ( $n = 3$ ).

Soil horizon/depth	Cerrado		<i>Pinus</i>			Pasture		
	SOC†	$\delta^{13}\text{C}$	SOC	$\delta^{13}\text{C}$	C replacement‡	SOC	$\delta^{13}\text{C}$	C replacement
m	$\text{g kg}^{-1}$	‰	$\text{g kg}^{-1}$	‰	%	$\text{g kg}^{-1}$	‰	%
Oi horizon	496 (14)	-29.2 (0.27)	505 (6.6)	-29.3 (0.13)	100		not present	
Oe horizon	not present		500 (1.6)	-29.5 (0.12)	100		not present	
Oa horizon	not present		415 (43)	-29.5 (0.20)	100		not present	
0-0.15	22 (1.3)	-20.5 (0.65)	22 (1.4)	-22.8 (2.2)	29	27 (3.5)	-18.2 (1.3)	31
0.15-0.30	18 (1.2)	-20.0 (0.87)	16 (1.6)	-20.1 (1.7)	0.74	18 (2.8)	-18.1 (2.5)	27
0.30-0.80	11 (1.3)	-19.7 (0.81)	11 (0.61)	-19.7 (0.95)	0.0	12 (1.7)	-18.1 (2.7)	24
0.80-1.2	8.4 (0.75)	-20.4 (0.44)	8.3 (0.43)	-20.4 (0.99)	0.0	8.5 (0.94)	-19.0 (1.7)	20
1.2-2.0	6.4 (0.20)	-20.0 (0.58)	6.9 (0.18)	-21.0 (0.71)	12	6.8 (0.78)	-19.6 (0.67)	5.4

† Soil organic C.

‡ To reduce the influence of the spatial variation in  $\delta^{13}\text{C}$  of the soil, C replacement was only calculated with mean  $\delta^{13}\text{C}$  values for the three native and land-use systems.

This input must stem from *Pinus* roots that extend to greater depths than Cerrado vegetation. In a previous study we found that coarse roots of *Pinus* reach to more than 4 m (Lilienfein and Wilcke, 2003). Root growth and subsequent root litter input at the 1.2- to 2-m soil depth might be stimulated by the high nitrate concentration at this soil depth because of high anion adsorption of the subsoil (Lilienfein et al., 2001a).

Our estimate of the degree of C replacement may be biased because we did not consider the  $^{13}\text{C}$  discrimination during humus transformation with increasing soil depth. However, there were only small changes in the  $\delta^{13}\text{C}$  signal of the mineral soil under Cerrado vegetation in the upper 2 m of the soil indicating that the humus transformation did not result in considerable changes of the  $\delta^{13}\text{C}$  value of the bulk soil organic matter.

Our results demonstrate that there has been C turnover after the change in plant species; although the C storage did not change significantly. After 12 to 20 yr of continuous land use only about one third of the original Cerrado vegetation-derived organic matter has been replaced by organic matter derived from the current vegetation in the layer 0- to 0.15-m. The rate of C replacement in our study soils may have been reduced because the high clay content of these soils stabilized and protected the original organic matter. However, our results are in line with findings for other tropical soils where the C replacement following land-use changes lasts several decades (Veldkamp, 1994). The pastures replaced the original C faster and to greater depth than the *Pinus* plantation. This can be attributed to the differences in root architecture and amount of root litter. Furthermore, lime and fertilizer applications to the pastures increase the biomass production and thus the root litter input into the soil.

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