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Low vertical transfer rates of carbon inferred from radiocarbon analysis in an Amazon podzol

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Abstract

Hydromorphic podzol soils in the Amazon Basin generally support low-stature forests with some of the lowest amounts of aboveground net primary production (NPP) in the region. However, they can also exhibit large values of belowground NPP that can contribute significantly to the total annual inputs of organic matter into the soil. These hydromorphic podzol soils also exhibit a horizon rich in organic matter at around 1 m depth, presumably as a result of elluviation of dissolved organic matter and sesquioxides of Fe and Al. Therefore, it is likely that these ecosystems store large quantities of carbon by (1) large amounts of C inputs to soils dominated by their high levels of fine-root production, (2) stabilization of organic matter in an illuviation horizon due to significant vertical transfers of C. To assess these ideas we studied soil carbon dynamics using radiocarbon in two adjacent Amazon forests growing on contrasting soils, a hydromorphic podzol and a well-drained alisol supporting a high-stature terra firme forest. Our measurements showed similar concentrations of C and radiocarbon in the litter layer and the first 5 cm of the mineral soil for both sites. This result is consistent with the idea that the hydromorphic podzol soil has similar soil C storage and cycling rates compared to the well-drained alisol that supports a more opulent vegetation. However, we found important differences in carbon dynamics and transfers along the vertical profile. At both soils, we found similar radiocarbon concentrations in the subsoil, but the carbon released after incubating soil samples presented radiocarbon concentrations of recent origin in the alisol, but not in the podzol. There were no indications of incorporation of C fixed after 1950 in the illuvial horizon of the podzol. With the aid of a simulation model, we predicted that only a minor fraction (1.7 %) of the labile carbon decomposed in the topsoil is transferred to the subsoil of the podzol, while this proportional transfer is about 90 % in the alisol. Furthermore, our estimates were 8 times lower than previous estimations of vertical C transfers in Amazon podzols, and question the validity of these previous estimations for all podzols within the Amazon Basin. Our results also challenge previous ideas about the genesis of these soils and

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suggest that either these soils are not true podzols or the podzolization processes had already stopped.

1 Introduction

It is well known that differences in soils have profound effects on the aboveground net primary productivity (NPP) of tropical forests (Cleveland et al., 2011; Quesada et al., 2012). Less clear however, is the role of soils controlling total NPP and total carbon storage in the tropics. Almost all soil orders are represented within the tropical biome, spanning along a wide range of soil morphology and genesis (Townsend et al., 2008; Quesada et al., 2010, 2011). These different soils represent a large heterogeneity in belowground characteristics, from nutrient depleted to organic-matter rich soils, and from hydromorphic to well-drained. These soils, in interaction with other variables such as climate, can control the patterns of carbon allocation between below and aboveground plant parts (Aragao et al., 2009; Malhi et al., 2011) as well as the speed of organic matter decomposition (Wieder et al., 2009; Cleveland et al., 2011), which together determine the capacity of forest ecosystems to store carbon (Chapin et al., 2006).

Particularly interesting in terms of their carbon dynamics and their carbon storage potential are the poorly-drained podzol soils of the Amazon Basin. These soils cover approximately $1.5 \times 10^6\,\mathrm{km}^2$, more than 18 % of the total basin area, and can potentially store 13.6 ± 1.1 Pg C in their illuviation (Bh) horizon (Montes et al., 2011; Lucas et al., 2012). This horizon contains large amounts of organic matter associated with sesquioxides, most likely eluviated from upper horizons (Klinge, 1965; Bravard and Righi, 1989; Horbe et al., 2004; Montes et al., 2011; Lucas et al., 2012); however, the genesis and classification of these soils are still debated (Bravard and Righi, 1989; do Nascimento et al., 2004). These podzols are common in central Amazonia north of Manaus and in the Guyana Shield as well as in isolated areas in Colombia and Peru

(Quesada et al., 2011). They exhibit a particular vegetation type, consisting mainly of small-stature trees growing in high densities (Klinge, 1965).

In some cases, forests growing on these hydromorphic podzols may present low values of aboveground biomass and aboveground NPP, but large values of fine-root biomass and belowground productivity (Duivenvoorden and Lips, 1995; Aragao et al., 2009; Jimenez et al., 2009). For example, data from the Colombian Amazon show that aboveground NPP is 53 % higher in a high-stature forest growing on an plinthosol soil than in a low-stature forest growing on a hydromorphic podzol. However, belowground NPP is 36 % higher in the podzol soil than in the phlinthosol soil, which suggest a compensation between carbon investments above and belowground. Differences in total NPP are only 16 % between these two sites, an indication that soils exert a strong control on ecosystem carbon allocation and the carbon balance of these systems (Jimenez et al., 2013).

In addition, vertical transfers of dissolved organic carbon (DOC) in hydromorphic podzols can be significant. Montes et al. (2011) estimated transfers of DOC from the A to the E horizon as $55.5\,\mathrm{g\,m^{-2}\,yr^{-1}}$, and from the E horizon to the Bh horizon as $16.8\,\mathrm{g\,m^{-2}\,yr^{-1}}$ in podzols near São Gabriel da Cachoeira city, Brazil.

Together, these results from Colombia and Brazil suggest that it is possible that forests growing under hydromorphic podzols not only present levels of total NPP as high as those observed under high-stature terra firme forests growing under more favorable conditions, but also have the potential to store large quantities of organic matter in an illuviation (ortsteinic) horizon where the carbon is tightly associated with sesquioxides of Fe and Al. In other words, high levels of belowground NPP can contribute significant amounts of carbon that can be latter stabilized by mineral interactions in the subsoil.

In this study, we used radiocarbon measurements to get insights on the soil carbon balance of two forests growing under contrasting soils, one under an alisol supporting a tall-stature terra-firme forest, and the other under a hydromorphic podzol supporting a low-stature highly-dense forest. Radiocarbon is a useful tracer to study soil organic matter dynamics; in particular, radiocarbon produced during nuclear bomb tests in the late 1940s and early 1950s helps to determine the speed of carbon accumulation and turnover in soils (Trumbore, 2009). Furthermore, measurements of radiocarbon respired from incubated soils can give additional insights about the different fractions comprising soil organic matter (Gaudinski et al., 2000; Sierra et al., 2012b).

To assess the carbon storage potential of the forest growing under the hydromorphic podzol, we were interested in testing two hypotheses:

- *Hypothesis 1* Higher fine-root production in the hydromorphic podzol relative to that in the alisol results in similar amounts of total carbon inputs to both soils and therefore similar amounts of carbon storage in the topsoil. Δ^{14}C values in both soils should not differ, indicating similar rates of soil C cycling in the topsoil. Evidence against this hypothesis, would imply differences in the rates of decomposition between the two forests.
- *Hypothesis 2* Significant rates of C transfer along the vertical profile in the hydromorphic podzol result in accumulation of radiocarbon with the Δ^{14}C signature of the bomb-spike. Failure to detect post-bomb Δ^{14}C values and rejection of this hypothesis would imply that accumulation of organic matter in the ortsteinic horizon is not necessarily related to elluviation from upper horizons.

2 Methods

2.1 Study sites and sample collection

The study site is located in the Colombian Amazon in the vicinity of the city of Leticia. In February 2011, we collected samples of the organic layer and the mineral horizon at different soil depths of an Ortsteinc Podzol and a Haplic Alisol, both located on permanent forest plots at El Zafire Biological Station, ZAR-01 and ZAR-04 respectively. Additional details about the permanent plots are provided in Aragao et al. (2009); Jimenez et al. (2009); Quesada et al. (2010). Mean annual temperature for the region fluctuates in a small range around 25 °C; mean annual precipitation was measured as 3335 mm between the years 1973 and 2006 at the Vásquez Cobo airport in Leticia. The Haplic Alisol (ZAR-04) is well-drained and supports a tall-stature terra firme forest, while the Ortsteinc Podzol (ZAR-01) is seasonally inundated supporting a low-stature highly-dense forest, locally known as Varillal. This podzol soil is covered by a thick root-mat in the A horizon, on top of an E-horizon that consists mostly of white sand. This soil is often characterized as one of the nutrient poorest soils in Amazonia (Table 1, Quesada et al., 2010). Both forests can be considered primary in the sense that we are not aware of any indication of previous anthropogenic disturbance and their protection status as forest reserve.

We sampled the litter layer and the mineral horizon using a percussion soil corer of 5 cm diameter and 5 cm depth. Five random points were located inside the permanent plots to sample the topsoil. Additionally, we sampled the subsoil in profiles dug outside the permanent plots. At ZAR-01, we sampled the same soil profile described in Quesada et al. (2011), and at ZAR-04 we sampled a new profile. In these profiles we used the same soil corer sampling at depths 10, 50 and 70 cm, which correspond to the A, E, and Bh horizons in ZAR-01. At ZAR-04 we sampled at depths 5, 15, and 55 cm, which correspond to the A, E, and B horizons of the alisol.

All samples were stored in plastic bags, air-dried, and pre-processed at the laboratory of Natural Products and Seeds of the National University of Colombia at Leticia. Samples were passed through a 2 mm sieve excluding all stones and big roots (> 2 mm in diameter).

2.2 Laboratory analyses

Soil samples were analyzed in the laboratory for carbon and nitrogen content by dry combustion with a CN analyzer (Elementar vario Max). Additionally, the radiocarbon signature of bulk soil carbon and respired CO_2 derived from soil incubations were analyzed by Accelerator Mass Spectrometry (AMS). Differentiating between radiocarbon signatures of bulk soil carbon and respired CO_2 allows for differentiating the age of more stable carbon associated with minerals and more readily available carbon for microbial consumption. We incubated the soil in closed glass jars at 25 °C until heterotrophic organisms released a sufficient amount of C for graphitization and radiocarbon measurements, 1.8–2.0 mg of carbon corresponding to a CO_2 concentration of 2 % in the glass jars. The CO_2 concentration in the jars was monitored using an infrared gas analyzer (Li-6262). Incubation time varied among samples depending on their C concentrations, from a few days to up to a month. After incubation, the air inside the jar was transferred into injection bottles, which were connected to a vacuum extraction line separating the CO_2 from water vapor and other gases, and transferring it into reaction tubes containing Zn and TiH_2 (Gaudinski et al., 2000). The reaction tubes were heated to 550 °C, reducing the CO_2 to graphite and precipitating it on iron powder. The graphite-iron-mixture was pressed and subsequently analyzed for its radiocarbon signature by AMS. Radiocarbon measurements were carried out at the WM Keck Carbon Cycle AMS facility at the University of California at Irvine, USA.

2.3 Radiocarbon model

To interpret the results obtained from the radiocarbon analysis, we used a compartment model with two pools of different decomposition rates (fast and slow) that transfer carbon along the depth profile. The approach is similar to other models previously developed to interpret radiocarbon data (e.g. Trumbore et al., 1995; Gaudinski et al., 2000; Baisden and Parfitt, 2007; Sierra et al., 2012b). The model is mathematically defined as a set of differential equations of the form

$$\frac{dC_{\text{ft}}}{dt} = \gamma I - k_1 C_{\text{ft}}$$

$$\frac{dC_{\text{st}}}{dt} = (1-\gamma)I - k_2 C_{\text{st}}$$

$$\frac{dC_{fs}}{dt} = \alpha_{3,1} k_1 C_{ft} - k_3 C_{fs}$$
$$\frac{dC_{ss}}{dt} = \alpha_{4,2} k_2 C_{st} - k_4 C_{ss}, \quad (1)$$

where I represents the amount of C inputs to the soil; C_{ft} the amount of carbon stored in the fast pool in the topsoil; C_{st} the amount of carbon in the slow pool in the topsoil; C_{fs} the amount of carbon in the fast pool in the subsoil; and C_{ss} the amount of carbon in the slow pool in the subsoil. γ is a partitioning coefficient that indicates the proportion of carbon inputs that goes to the fast cycling pool in the topsoil. The transfer coefficients $\alpha_{3,1}$ and $\alpha_{4,2}$ represent the proportion of decomposed carbon from the fast and slow cycling pools in the topsoil that move downward to the subsoil, respectively. The subscript of these transfer coefficients follow the conventions described in Sierra et al. (2012a) for this type of models, in which 3,1 represents transfers from pool 1 to 3; and 4,2 transfers from pool 2 to 4. To test differences between the two forests in the amount of carbon transferred from the topsoil to the subsoil, we will focus in finding differences in the $\alpha_{i,j}$ coefficients.

The radiocarbon version of this model is given by

$$\frac{dFC_{ft}}{dt} = \gamma I F_a - k_1 FC_{ft} - \lambda FC_{ft}$$
$$\frac{dFC_{st}}{dt} = (1-\gamma) I F_a - k_2 FC_{st} - \lambda FC_{st}$$
$$\frac{dFC_{fs}}{dt} = \alpha_{3,1} k_1 FC_{ft} - k_3 FC_{fs} - \lambda FC_{fs}$$
$$\frac{dFC_{ss}}{dt} = \alpha_{4,2} k_2 FC_{st} - k_4 FC_{ss} - \lambda FC_{ss}, \quad (2)$$

where λ is the radioactive decay constant, F_a the fraction of radiocarbon in atmospheric CO_2, and F is the radiocarbon fraction expressed as absolute fraction modern, i.e. the

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absolute ratio of sample to standard, corrected for radiodecay in the year of measurement y (c.f. Stuiver and Polach, 1977)

$$F = \frac{\left.\frac{^{14}\mathrm{C}}{^{12}\mathrm{C}}\right|_{\mathrm{sample},-25}}{0.95\left.\frac{^{14}\mathrm{C}}{^{12}\mathrm{C}}\right|_{\mathrm{OX},-19} e^{(y-1950)/8267}}. \tag{3}$$

We implemented this model in the R environment for computing using the SoilR package (Sierra et al., 2012a). Atmospheric radiocarbon data was obtained from the IntCal09 dataset (Reimer et al., 2009) for the pre-bomb period, and the dataset from Levin and Kromer (2004) afterwards. All code and data to reproduce all results presented here are provided as Supplement.

3 Results

3.1 Topsoil

Within each plot we found statistical significant differences in the C concentrations between the organic and the mineral horizons (p-value = 0.004; analysis of variance F-test with plot and horizon as factors), but we did not find significant differences among the two plots in terms of their C content (p-value = 0.085). Similar results were found for N content (Fig. 1a, b).

The radiocarbon signature of the bulk soil and the respired CO_2 from the incubations showed no significant differences between plots or horizons (p-value > 0.1 in all cases; analysis of variance F-test). The mean $\Delta^{14}C$ in bulk soil measured across plots and horizons was 91.69 ± 26.12‰, while the mean $\Delta^{14}C$ in respired CO_2 was 85.5 ± 12.06‰. The positive values of $\Delta^{14}C$ in both cases indicate that the carbon in the topsoil is mostly post bomb, i.e. incorporated in the forest biomass after 1950, but without significant differences among the two forests (Fig. 1c, d).

These results are consistent with hypothesis 1; i.e. similar amounts of carbon inputs to both soils results in similar amounts of carbon contents in the litter layer and the first 5 cm of the mineral soil. In addition, Δ^{14}C values in the bulk soil and heterotrophic respiration showed that rates of carbon cycling are similar in the topsoil of both systems.

3.2 Subsoil

In the high-stature forest (ZAR-04), organic carbon decreased with depth exponentially as expected for well-drained profiles (Jobbágy and Jackson, 2000; Quesada et al., 2011). In contrast, organic carbon was higher deeper in the profile for the low-stature forest (ZAR-01) because of the presence of the Bh horizon in this podzol, which stores more carbon than the upper A horizon (Fig. 2a).

The amount of carbon respired during the incubation period also decreased exponentially with depth in the alisol soil following the same trend as the carbon content (Fig. 2b). In the podzol soil, the amount of carbon respired during the incubation was lower in the upper A horizon than in the Bh horizon, also an indication that the amount of respiration was proportional to the amount of carbon content at each horizon. In the A horizon, the amount of C respired in the podzol was much lower than what was respired in the alisol; while in the Bh horizon of the podzol, at 70 cm depth, the respired C was higher than what it was respired in the B horizon of the alisol at 55 cm depth.

The Δ^{14}C values of soil carbon also decreased with depth in both soils (Fig. 3), indicating that the age of carbon increases with depth. Only in the first 5–10 cm it was possible to observe dominant proportions of recent carbon fixed after 1950. Interestingly, the Δ^{14}C values between the alisol and the podzol were relatively similar at the deepest sampled points.

The Δ^{14}C values of the respired CO_2 for the different depths in the alisol were all positive (Fig. 3), indicating that the more readily decomposed C in these soils was recently fixed (after 1950) while a larger proportion of old carbon was not preferentially decomposed by microorganisms and it is perhaps bounded to mineral surfaces. In contrast, the Δ^{14}C values of the respired C in the podzol where negative in the Bh horizon and far from the values expected in the case carbon fixed after 1950 AD had been incorporated in this horizon. Therefore, the readily available C for decomposition in the Bh horizon is much older than C fixed after 1950 AD.

3.3 Model results

Fitting the obtained radiocarbon data to the model described by Eq. (2) showed that there are important differences between the two forests in terms of the amount of carbon transferred from the topsoil to the subsoil (Table 2, Fig. 4). While in the terra firme forest 90 % of the carbon that decomposes from the fast pool in the topsoil is transferred to the subsoil ($\alpha_{3,1} = 0.9$), in the podzol soil this proportional amount of C transfer is only 1.7 % ($\alpha_{3,1} = 0.017$). The transfer of C in the slow pool from the topsoil to the subsoil is even lower for the two forests, 0.3 % in the terra firme forest and 0.25 % in the podzol soil (Table 2).

4 Discussion

The carbon content as well as the radiocarbon values obtained here indicate important differences in the overall carbon dynamics between the two soils. In agreement with our first hypothesis, we did not find differences between the two forests in terms of the carbon concentrations and the rates of carbon cycling in the topsoil. However, contrary to our second hypothesis, we found important differences in the rates of vertical C transfer between the two soils. We will discuss these differences between topsoil and subsoil C dynamics in the next sections.

4.1 Topsoil carbon dynamics

Despite important differences in aboveground NPP between the two forests, we did not observe differences in carbon and radiocarbon concentrations in the litter layer and the topsoil at both sites. The low-stature forest had 50 % more fine-root production than the high-stature forest, which results in relatively similar amounts of total carbon inputs to both soils (Table 1). Total carbon inputs to the topsoil are key determinants of the total carbon storage in tropical soils (Trumbore et al., 1995) and our results confirm this idea.

With similar amounts of C inputs and concentrations in the topsoil, it seems plausible that decomposition rates of litter and soil organic matter in the first 5 cm of both soils are similar at an annual basis, despite important differences in soil hydrology. High water-table levels are commonly associated with important decreases in decomposition rates (Jungkunst and Fiedler, 2007), and it is likely that decomposition rates are reduced during the wet season when the podzol soil is under water stagnation. However, in order to maintain similar carbon concentrations in the first 5 cm than in the well-drained alisol, either decomposition rates increase significantly in the podzol when the water table is low or there are significant transfers of carbon vertically or horizontally. Our results rule out the possibility of significant rates of vertical C transfers, therefore the only two possibilities to explain similar C contents in the litter layer and the first 5 cm of the mineral soil are higher decomposition rates during the low water-table conditions or significant lateral C transfers.

4.2 Subsoil carbon dynamics

Our radiocarbon data and the modeling results provide strong evidence against the hypothesis of significant vertical C transfers in the podzol soil. Δ^{14}C values in the bulk soil and the respired C from the incubated samples of the ortsteinic horizon did not provide indications of incorporation of bomb radiocarbon. Furthermore, the more readily available carbon for decomposition and trapped as CO_2 gas in the incubations was mostly of pre-bomb origin, contrary to what was found for the alisol.

Our results are at odds with estimates presented by Montes et al. (2011) about the magnitude of DOC transfers in podzols in Brazil in the vicinity of Sao Gabriel da Cachoeira city. These authors estimated an annual vertical transfer to the Bh horizon equivalent to 16.8 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, while our simulations predict only 1.9 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$

of vertical transfers for the podzol we studied, that is a factor of 8 less from this previous prediction. In contrast, our model predicts vertical transfer in the alisol as 11.4 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$, almost six times more than what was predicted for the podzol.

Our data also challenges the assumption that this white-sand soil is actually a true podzol. By definition, podzols are characterized by elluvation of clays and organic materials, but this elluviation processes had either stopped at certain point in time or never occurred at our site. Other authors had previously questioned the classification of white-sand soils as podzols in Amazon forests (Klinge, 1965; Bravard and Righi, 1989; do Nascimento et al., 2004). For instance, Klinge (1965) suggested that the deep organic horizon may not be necessarily of elluvial origin, but instead a buried A horizon. Another possibility, suggested by do Nascimento et al. (2004) in his model of podzolization for the Amazon, is that this soil is in a very late stage of development, and true podzolition has already occurred. It is also likely that the genesis of the soil we studied differs considerably from previously studied podzols in the central Amazon Basin.

To our knowledge, only one study had previously measured the radiocarbon content in the illuvial horizon of a podzol in the Amazon Basin. Horbe et al. (2004) measured the isotopic composition of the organic matter in a podzol north of Manaus. They found conventional radiocarbon ages between 1960 and 2810 yr BP and suggested that the organic matter in the Bh horizon was of relatively recent origen. These radiocarbon ages however, are difficult to interpret for two reasons: (1) there are important deviations between the true age of a sample and the radiocarbon age given the temporal variability of the atmospheric radiocarbon record (Reimer et al., 2009). (2) Additions and losses of carbon over time are better tracked with a model that incorporates the atmospheric radiocarbon record, the rates of organic matter decomposition, and radiocative decay, all processes occurring simultaneously (Trumbore, 1993, 2009). Our modeling approach incorporated all these processes and more confidently can attribute the observed Δ^{14}C values to differences in the rates of organic matter decomposition and transfers along the profile.

5 Conclusions

Measurements of organic carbon and radiocarbon contents in two contrasting soils of western Amazonia showed similar rates of carbon cycling despite large differences in aboveground NPP between the two sites. A low-stature forest growing under a podzol soil showed large values of fine-root production and therefore similar rates of total carbon inputs to the soil compared to a high-stature terra firme forest growing under a well-drained alisol. Both soils presented no differences in their carbon content and Δ^{14}C values measured in the litter layer and the topsoil (first 5 cm).

Important differences between the two forests were found in the subsoil. While in the alisol carbon contents decreased exponentially, the ortsteinic Bh horizon presented large C contents at 65 cm depth in the podzol, with larger C contents than in the A horizon of the same soil. However, our radiocarbon measurements do not provide evidence for this organic horizon formed as a result of significant vertical C transfers. In contrast with the alisol, Δ^{14}C values measured in this horizon did not incorporte radiocarbon signatures from the atmospheric radiocarbon bomb period. With the aid of a simulation model, we predict 8 times less vertical C transfers than what has been previously predicted for this type of soils, challenging previous assumptions about the formation of the organic horizon of this podzol soil.

Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/10/3341/2013/ bgd-10-3341-2013-supplement.zip.

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Table 1. Basic description of the two sites, soil properties, and productivity. Soil data from Quesada et al. (2010) and productivity from Jimenez et al. (2013). Labile P is defined here as the sum of resin P, bicarbonate Pi, and bicarbonate Po as in Yang and Post (2011).

Property	Low-stature forest	High-stature forest	Units
WRB classification	**Ortsteinc Podzol**	**Haplic Alisol**	
% sand	74.75	58.05	%
% clay	0.64	20.25	%
% silt	24.61	21.70	%
pH	4.27	4.13	
ECEC	0.71	2.6	$\mathrm{cmol_c\,kg^{-1}}$
Sum of bases	0.64	0.24	$\mathrm{cmol_c\,kg^{-1}}$
Total reserve bases	0.33	8.01	$\mathrm{cmol_c\,kg^{-1}}$
Al	0.07	2.35	$\mathrm{cmol_c\,kg^{-1}}$
Total P	25.65	31.44	$\mathrm{mg\,kg^{-1}}$
Labile P	14.37	8.6	$\mathrm{mg\,kg^{-1}}$
Occluded (residue) P	3.01	9.41	$\mathrm{mg\,kg^{-1}}$
Fine-root production	2.98	1.53	$\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$
Litterfall	2.48	4.72	$\mathrm{Mg\,C\,ha^{-1}\,yr^{-1}}$
Plot name	ZAR-01	ZAR-04	
Coordinates	4.007° S, 69.901° W	4.007° S, 69.906° W	
Altitude	130	127	m a.s.l.

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Low vertical C transfer in an Amazon podzol

C. A. Sierra et al.

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Table 2. Model parameters for the podzol and the alisol soils obtained from the radiocarbon measurements. Values of k_i in units of yr^{-1}, all other parameters are unitless.

Parameter	Podzol soil	Alisol soil
k_1	2.0000	2.0000
k_2	0.1100	0.1000
k_3	1.0000	1.0000
k_4	0.0002	0.0002
α_{31}	0.0170	0.9000
α_{42}	0.0025	0.0030
γ	0.1000	0.1000

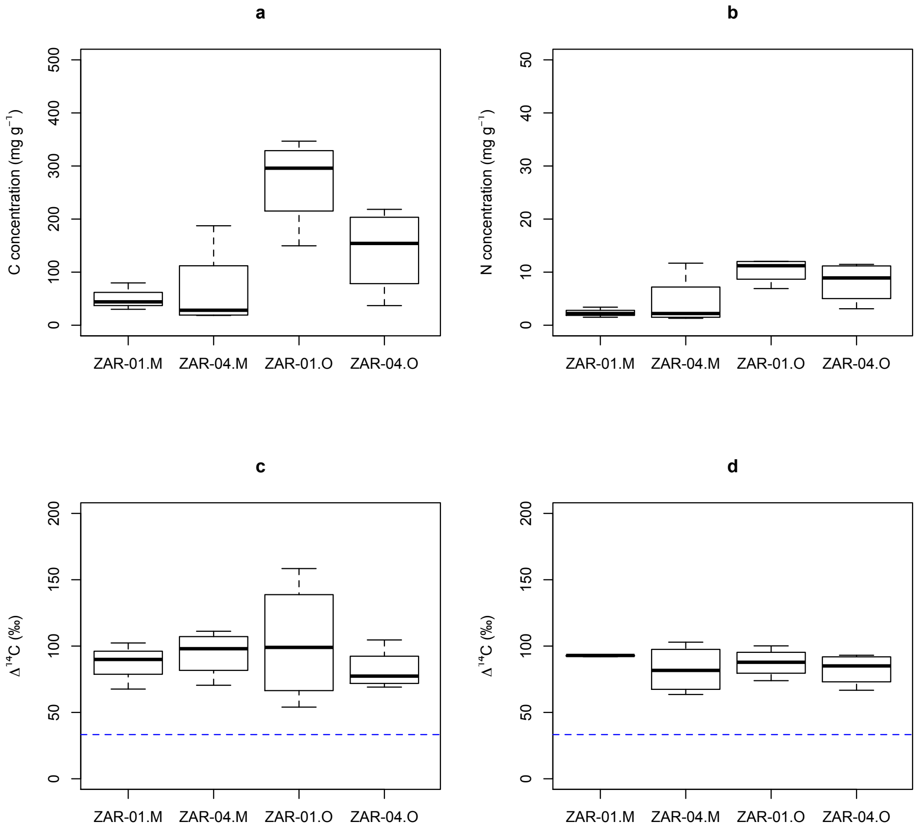

Fig. 1. Topsoil concentrations of **(a)** carbon, **(b)** nitrogen, and radiocarbon in the **(c)** bulk soil and **(d)** the respired CO_2 after incubations for the organic layer (O) and the mineral horizon (M). The broken line in the bottom panels represents the Δ^{14}C value of the atmosphere for the year of sampling.

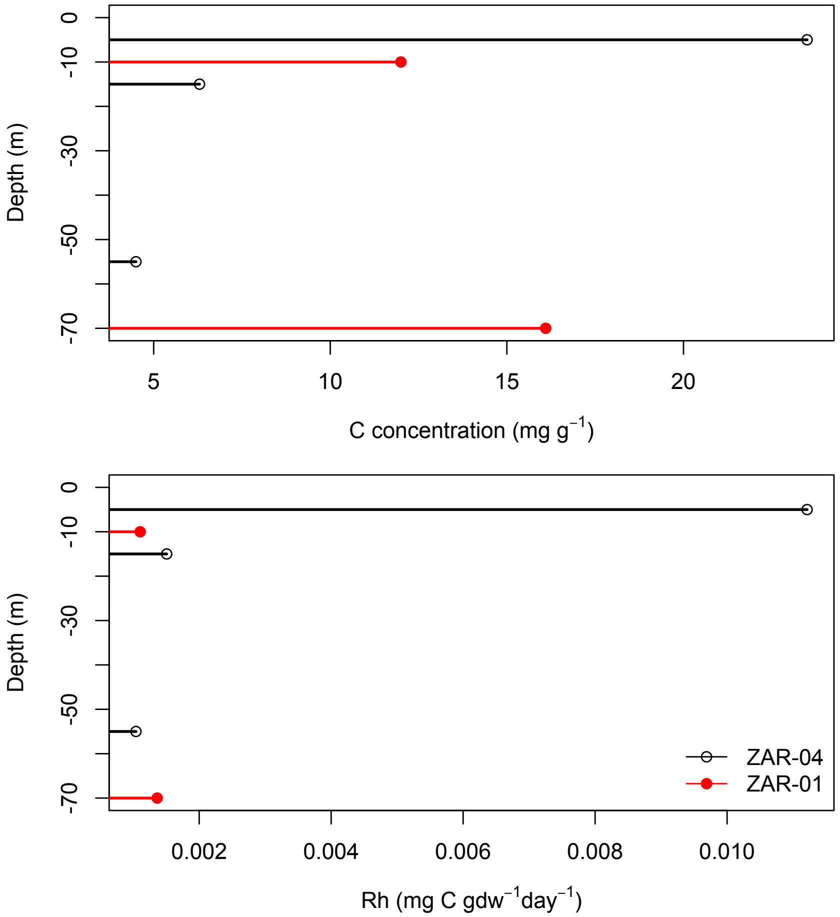

Fig. 2. Carbon content and heterotrophic respiration from samples collected at different depths in the alisol (ZAR-04) and the podzol (ZAR-01).

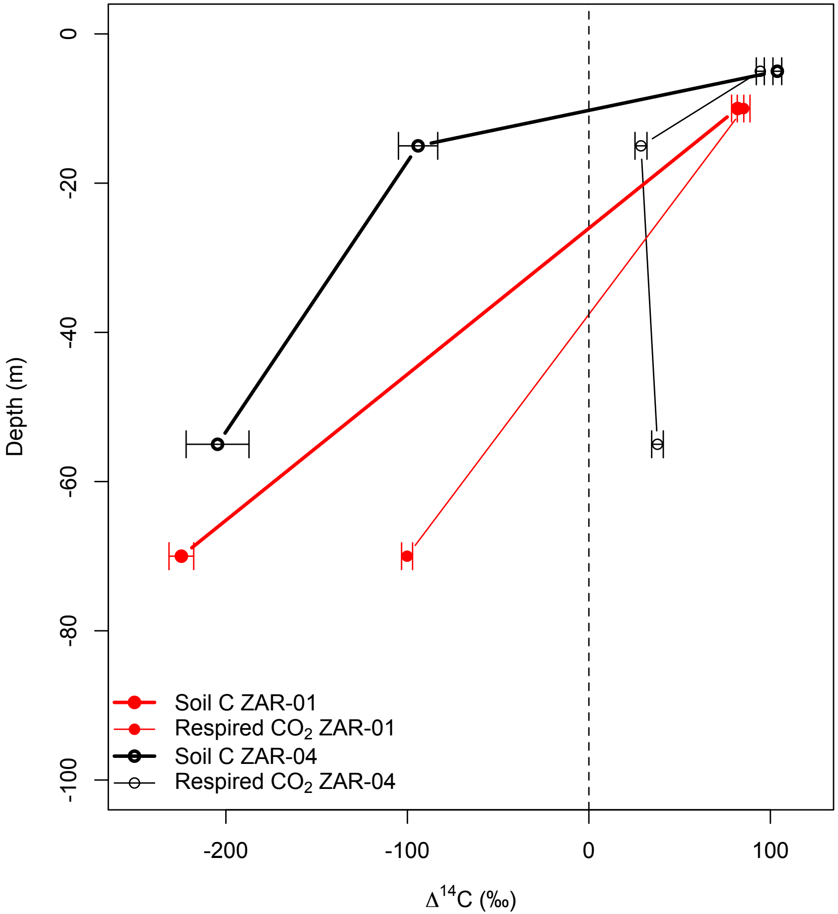

Fig. 3. Depth profile of the Δ^{14}C in bulk soil and respired CO_2 for the low-stature forest on a podzol soil (ZAR-01), and the high-stature forest on a well-drained alisol soil (ZAR-04).

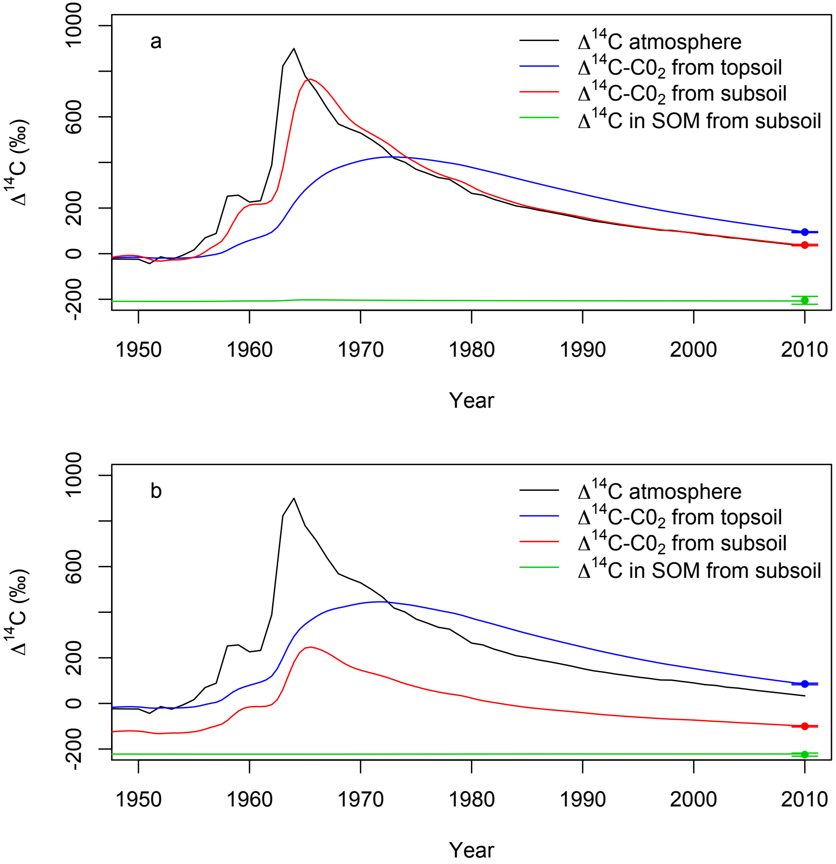

Fig. 4. Model predictions of the temporal behavior of radiocarbon during the bomb-period (after 1950) for the **(a)** high-stature forest on an alisol soil (ZAR-04) and **(b)** the low-stature forest on a podzol soil (ZAR-01). The points indicate measured Δ^{14}C values ± their standard deviation.