Growth dynamics of fine *Hevea brasiliensis* roots along a 4.5-m soil profile

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ABSTRACT: To monitor root growth dynamics of rubber trees (RRIM 600) along a deep soil profile, a permanent access-well ~ 4.5 m deep was built and operated since the end of 2006. This facility allows the direct observation of root growth dynamics using so-called "root windows", through which roots can be observed at regular time intervals. Using this access-well, we could estimate root length density and the decay of root tissues at various soil depths. Initial results were based on a 17-month observation. Some root incubations were also conducted for one year. Result from these experiments indicated that: A root growth peak occurred between May and June at a soil depths shallower than 150 cm, while it generally did not occur before November deeper in the soil profile; Fine roots growing at all depths had a life expectancy of months rather than weeks and a large proportion survived for 12 to 17 months without showing any clear sign of senescence; Fine root length density decreased by more than one order of magnitude from 5 to 50 cm while fine root biomass found below 100 cm still accounted for more than a third of the overall fine root biomass of the studied rubber trees; The decay rate of dead root material at a soil depth of 400 cm was slow, with a half-life on the order of 21 months. Together with long fine roots' survival, this indicates that the residence time of carbon originating from fine rubber tree roots spans several years.
Keywords: *Hevea brasiliensis*, root growth dynamics, root turnover, root decay, deep rooting

Introduction

Most root studies focus on the first 50 to 100 cm of the soil profile (Canadell et al., 1996; Jackson et al., 1996), as it is generally assumed that this is where the majority of root biomass is found. Besides, to collect deeper root samples is time consuming and costly (Pierret et al., 2005). However, based on a comprehensive literature review, personal communications and observations, Stone and Kalisz (1991) produced a reference data-set on maximum vertical and radial root extents which clearly indicates the inherent capability of many tree species to develop deep and/or far-reaching roots in the absence of restrictive soil or substrate characteristics. Stone and Kalisz (1991) also reported that assessing maximum rooting depth in small soil pits is often misleading as roots that apparently end abruptly or branch horizontally over layers of high soil strength generally penetrate much deeper through soft spots (e.g. joints, shrinkage cracks, fractures) that inherently exist in such layers (Poot and Lambers, 2008).

The rubber tree plantation area in NE Thailand increased by 50% from 2001 to 2005 and currently

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covers a total surface area of 150,000 ha. Work conducted by our team at a small-holder plantation in NE Thailand since 2005 showed that the fine roots of ~ 13-year old rubber trees (RRIM 600), extended much deeper than 1 m. Deep fine roots are particularly important for woody perennials, particularly in environments which seriously constrain their growth. This is *a priori* the case in the context of rubber tree plantations in NE Thailand. Soils in this region are generally poor and the climate is characterized by a long dry season during which rubber trees are likely to rely on their deeper root system to take up water and other essential resources. Indeed, eco-physiological measurements conducted at our study site concluded that inter-individual competition for water between trees was likely to occur in this plantation, a process likely to worsen the effects of punctual water stress when a short dry spell occurs during early stages of tapping (Do et al., 2006; Isarangkool Na Ayutthaya et al., 2007).

In this paper we report the early results of an analysis of the root growth dynamics of rubber trees (RRIM 600) over a 17-month period and along a deep soil profile using a permanent access-well, ~4.5 m deep. The main purpose of using this facility was to monitor root growth dynamics along a deep rooting profile, using so-called "root windows", through which roots can be observed/imaged at regular time intervals. The residence time of fine-root carbon in soil and fine-root dynamics is one of the least understood aspects of the global carbon cycle and plant function, respectively (Strand et al., 2008). In an attempt to document this we also estimated the decay of root tissues in the soil, as a function of soil depth.

Materials and Methods

Location and climate

The study was conducted within a young stand of RRIM 600 rubber trees with spacings of 2.5 x 7 m. The site was located at Ban Sila (N15° 16' 23.6" E103° 04' 51.3") near Satuk district, NE Thailand. The average annual rainfall observed over the 1995-2005 period was about 1200 mm, which is marginal for rubber trees. Indeed, to ensure unconstrained rubber tree growth, a minimum of 1,400 mm of annual rainfall is recommended (Jacob, 2009). In addition, the annual rainfall pattern at the study site is highly seasonal with more than 90% of all rainfall events occurring between April and October, imposing major water constraints to the trees between November and March. Prior to the establishment of a rubber tree plantation, the site was used for sugar cane cultivation.

Soil water content and rainfall

Water content measurements were obtained fortnightly using a neutron probe inserted into an access tube located at a distance of 4 m from the well. Measurements were made at 20 cm increments, between 10 and 170 cm from the soil surface. Rainfall was automatically recorded using a Skye (http://www.skyeinstruments.com/ accessed on Oct. 30, 2009) MiniMet weather station.

Tapping system

The measurements were made during the fifth year of tapping (initial tapping in June 2003, 2d/3 1/2s). Largely based on climatic conditions, tapping is usually discontinued every year for three to four months to allow the trees to cope with the dry conditions that prevail between November and March.

The tapping panel system used is A1-A2-A3-B4-B5-B6, which is the standard system for this region.

Soil properties

The soil in the studied area was developed on fine sand to coarse silt deposits with a homoegeneous sandy loam texture throughout the profile. The Ap horizon was a 25 cm thick remnant from previous cane cultivation (Hartmann et al., 2006). Clay, silt and sand contents were 100, 100 and 800 g/kg, respectively. The clay content increased with depth: from 150 g/kg in Bt1 (25-50 cm) to 200 g/kg in Bt2 (50-100 cm). The silt content was rather similar in all soil layers throughout the soil profile (100 g/kg) while sand decreased to 700 g/kg at a depth of 100 cm (Hartmann et al., 2006). From 100 to about 400 cm, these properties remained fairly stable, although, the weathered bedrock was found in the deeper zone.

The soil was acidic with a pH ranging from 5.0 to 5.3. Soil organic carbon content was present in amounts lower than 10g/kg in the topsoil. The CEC of this soil was positively correlated with its clay content. A more detailed description of soil properties is available in Hartmann et al. (2006). Soil water content values measured at the beginning of the 2007 rainy season are reported in **Figure 1b. Figure 1a** shows a typical bulk density profile of the soil in this plantation, down to a depth of 3 m.

Root growth monitoring

A well 1 m diameter and 4.5 m deep was built in June 2006 and was subsequently instrumented with "root windows" (McDougall, 1916) to allow direct observation of root growth dynamics. The well was dug manually at equal distance (1.6 m) from two trees (**Figure 2a**). Its walls were lined with molded

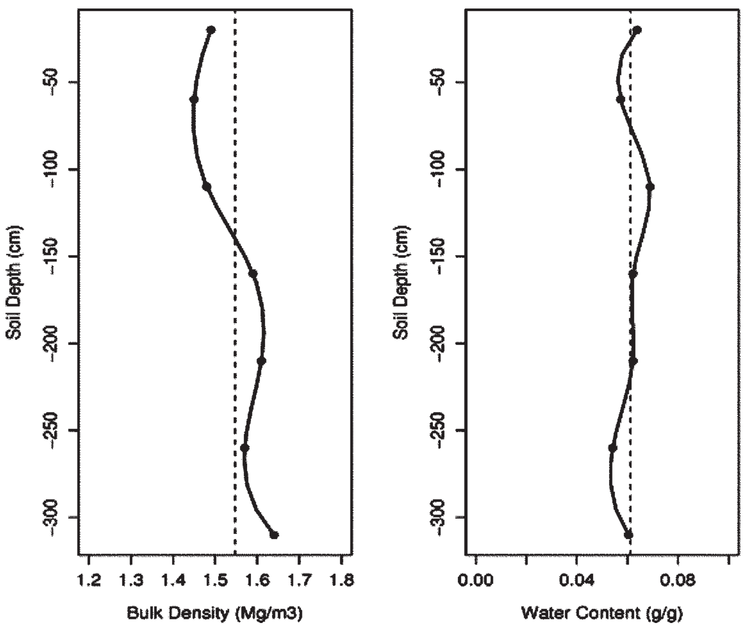


Figure 1 Soil bulk density and soil water profiles June 2007.

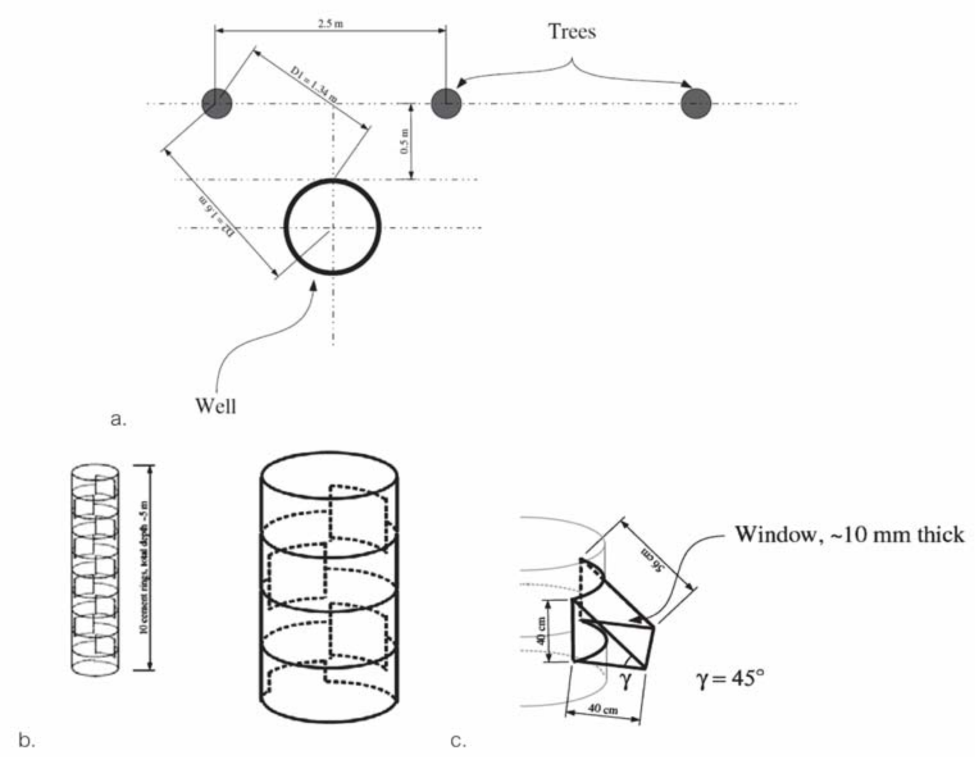


Figure 2 Schematic view of the root access-well. a. Location of the well in relation to the tree row (horizontal projection). b. General arrangement of the concrete rings. Note the openings cut to allow root window installation. c. Side view of the soil volume excavated for root window installation.

cement rings 50 cm high readily available from the local building materials outlet. To allow subsequent setup of root windows, an opening 40 cm wide and 20 cm high was cut on one edge of each ring using an electric diamond disc saw (**Figure 2b and 2c**). A total of nine openings were thus created, encompassing a soil depth range of 4.5 m by 0.5 m increments. In order not to weaken the structure formed by the concrete rings, openings were positioned in staggered rows: (with 1 and 0.5 m horizontal and vertical spacing, respectively). Each root window included a specifically designed metallic frame supporting, on its upper side, a piece of 8-mm thick glass (25 x 30 cm) pressed against the soil at a 45° angle by means of two threaded rod actuators; on the frame's lower side, and two guide rails allowed the insertion of a flatbed scanner. Two access ladders were affixed to the well wall, diametrically opposite each series of root windows.

Root growth monitoring was achieved following a procedure similar to that described by Maeght et al. (2007): images of the nine root windows were scanned at monthly intervals, for 17 months using a HP Scanjet 4370 Photo scanner. These images of the soil and roots in direct contact with each window can be used for a range of purposes, such as estimating root length, diameters, branching intensity and most importantly, times of root appearance/disappea rance (from which root turnover can be inferred).

Root length density and root biomass

Destructive sampling was used to estimate root length density down to a depth of 4 m were processed and analyzed according to the protocol described in Pierret et al. (2007a). Specific root length (SRL) values, i.e. the length of root per gram of dry root biomass, obtained for the first meter of the soil profile were used to obtain a root dry biomass distribution along the 4-m soil profile accessed using the well, based on the following equation:

$$RDB_{[z]} = RLD \times [Z]/SRL \qquad \text{eq. 1}$$

where $RDB_{[z]}$ (in Mg/ha) is the root dry biomass for a depth increment [Z], RLD is the root length density (m/m^3), [Z] (m) the depth increment corresponding to a given RLD value and SRL is the specific root length i.e. the length of root per unit dry weight (m/g).

Root decay

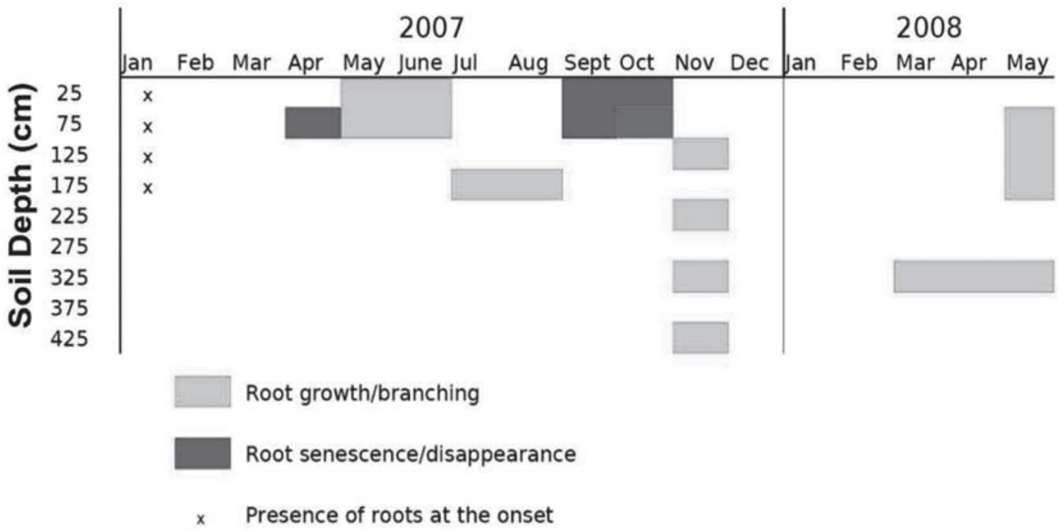
To estimate root decay, root residues were collected at the study site in October 2006, oven dried for 48 h at 65 °C then air dried for a month and cut into small segments with no longer than 5 cm. This material was inserted below three root observation windows at depths of 1.65, 2.9 and 4.05 m in January 2007. At each depth increment, three fine nylon bags (mesh size >100 µm) filled with 10 g of root material including fine roots 0.54 to 3.75 mm in diameter and 3 bags filled with 20 g of root material including coarser roots 3.85 to 14.64 mm were inserted in a ~50 cm long augered hole (~50 mm in diameter). Each nylon bag was filled with soil taken from the depth increment at which the hole was augered. The precise dry weight of the root material contained in each bag was measured with a precision balance (+/- 0.01g). Care was taken to ensure that there was the best possible contact between the root material and the soil enclosed in the bags as well as between the bags and the walls of the augered hole. The root material introduced at 3 depth increments was, thus, left to incubate for one year and was recollected in January 2008. Root remnants were then carefully washed free of adhering of soil, oven dried at 65°C for 48 hours and weighed. The weight difference between the two successive weightings was used to estimate the amount of root material broken down in one year. From this measurement, the coefficient of a simple exponential law was derived so as to establish the half-life of root material at the 3 depth increments investigated.

Results and Discussion

Root growth monitoring

Most of the roots that grew along the root windows during the 17-month observation period (January 2007 to May 2008) were fine roots less than 5 mm in diameter, most likely tertiary and quaternary axes. The peaks of root growth and branching along the 4-m deep soil profile are reported in **Table 1**: overall, down to approximately 150 cm, most root growth occurred between May and July 2007 which is clearly associated with the occurrence of the first significant rainfall events of the 2007 rainy season (**Figure 4b**) and the subsequent increase in soil water content (**Figure 4a**). Within the first meter, although some roots were present at the onset and remained for the whole observation period, there was also a noticeable root turnover, some of which was clearly due to the predatory behavior of soil invertebrates such as termites (**Table 1, Figure 3**).

Table 1 Synopsis of the root growth and decay peaks as a function of soil depth over the 17-month observation period.



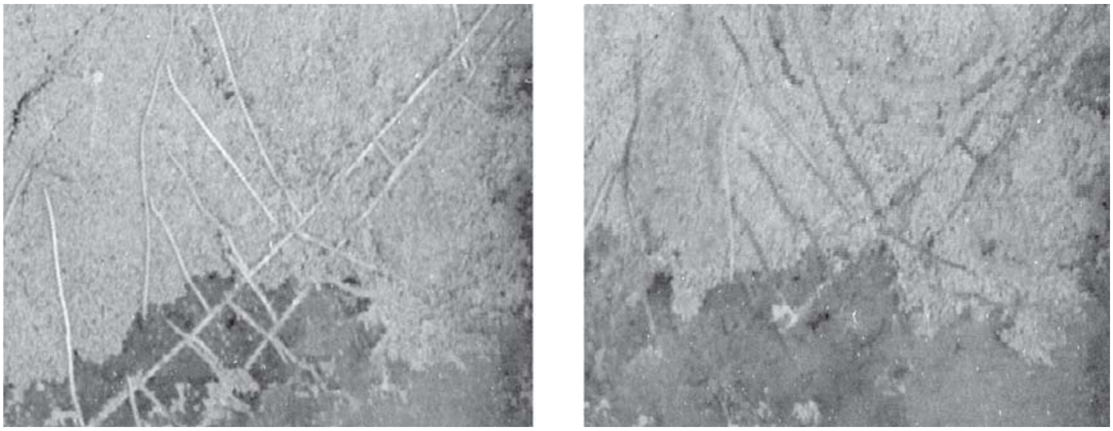
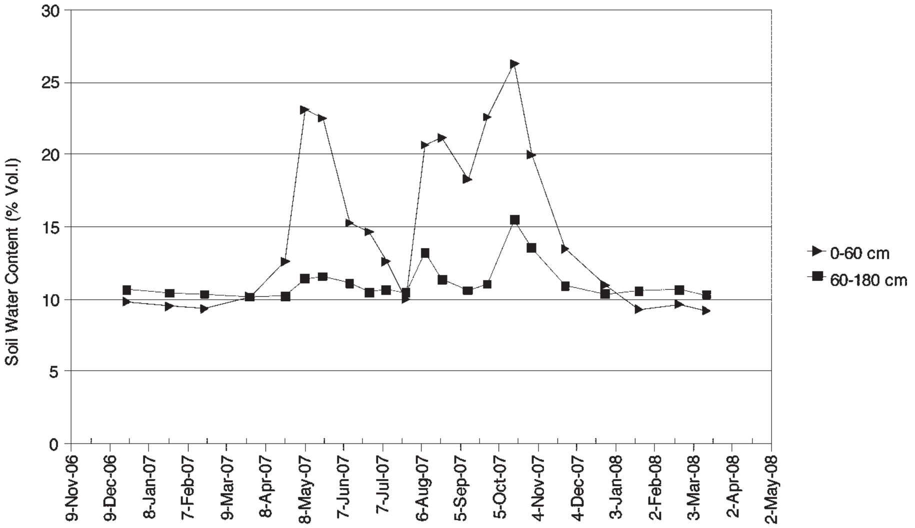


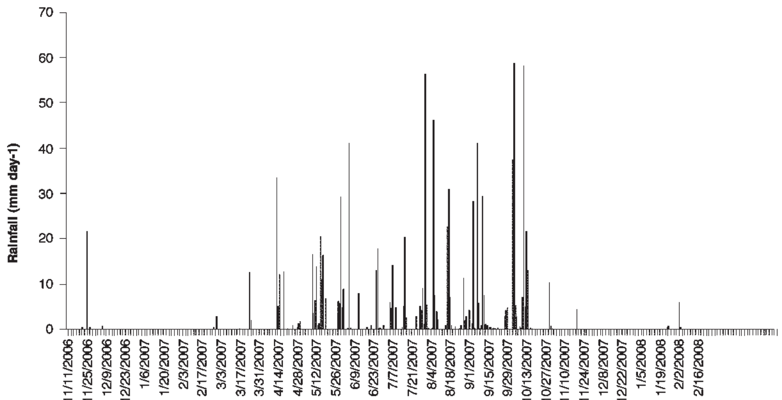
Figure 3 Example of root decay related to termite activity at a soil depth of ~75 cm. Images of the same roots taken on 08 August 2007 (a) and 15 October 2008 (b). The field of view covered by the images is 75 mm.

Root dynamics below 150 cm appeared very different from that nearer the soil surface: overall, root growth did not start before November 2007, i.e. seven months after the onset of the rainy season, which reflects the late increase in soil water content at depth compared to that nearer the soil surface (**Figure 4a**). While some authors demonstrated a straightforward influence of rainfall and soil moisture on root growth dynamics near the soil surface (0-15 cm) in tropical environments (Green et al., 2005), results from this study showed that such effects can be much more complex and delayed at greater soil depths.

Root longevity of most roots was remarkably high at all depths: many fine tertiary and quaternary roots less than 2 mm in diameter survived the whole 17-month observation period (**Figure 5**). From the



a.



b.

Figure 4 a. Variations in volumetric soil water content over the course of the root observation period. Note that changes in water content in the 60-180 cm layer are delayed and of lower magnitude compared to that in the 0-60 cm. b. Plot of rainfall events from November 2006 through to February 2008.

onset of the experiment until May 2008, root senescence and decay only occurred within the first meter of the soil profile (**Table 1 and Figure 3**). This has to be compared with life expectancies of 50 to 90 and 10 to 70 days for tertiary and quaternary roots, respectively observed by Le Roux (1994) in young GT1 rubber trees Although Le Roux (1994) also noticed that 10 to 30% of tertiary roots become perennial, our observations indicate that far more fine roots than previously reported potentially have a longer life expectancy. This slow turnover might be partly related to the fact that, in this work, we used a different clone, under the marginal pedo-climatic conditions that prevail in NE Thailand. A direct consequence of the rare occurrence of root mortality in the dataset collected so far is that a proper root survival analysis could not be completed. The monitoring of root growth dynamics must therefore be continued at the same

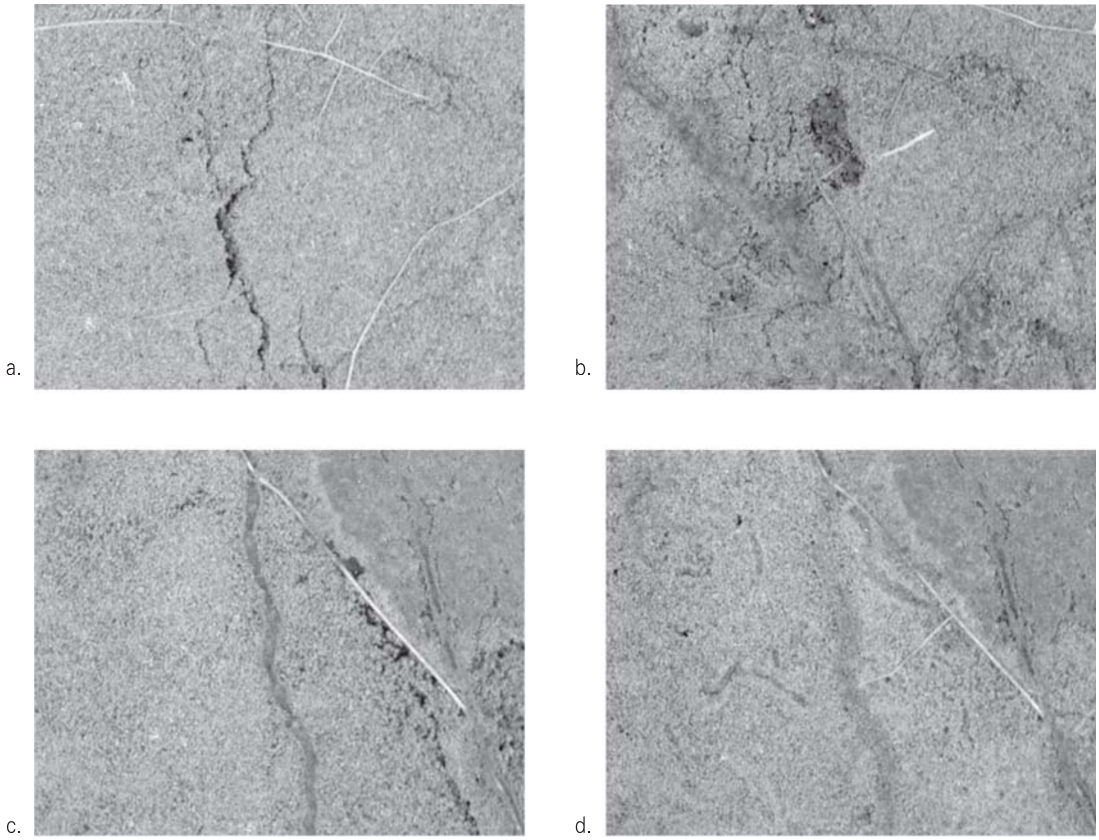


Figure 5 Root longevity. Images of the same roots taken on 23 Jan 2007 (a,c) and 8 May 2008 (b,d). The soil depths for (a,b) and (c,d) are 100 and 150 cm, respectively. Some roots changed color over the course of the observation period (a,b) which may be early signs of senescence. The field of view covered by the images is 75 mm.

study site for as long as necessary to collect sufficient data on root mortality and it is already planned that measurements will be conducted until mid-2010.

Fine root length density and biomass

Additional results based on destructive samplings of roots below 100 cm showed that while fine root length density decreased by more than one order of magnitude from 5 to 50 cm, it declined only slightly from 50 to 150 cm and remained fairly constant at greater depths (measured RLD between 383 and 419 cm was 27% higher than that between 137 and 177 cm) (**Figure 6a**). This result has important implications since the depth range throughout which this fairly low RLD was observed is considerable: based on an average Specific Root Length of 13.89 m/g (Pierret et al., 2007b), it indicates that fine root biomass located below 100 cm could amount for more than a third of the overall fine root biomass of the trees we measured (**Figure 6b**). It is noteworthy that, as there is no indication that the deepest depth increment sampled for this study is the maximum rooting depth of the studied trees, the root biomass present below 100 cm is likely to account for more than the figure we were able to estimate.

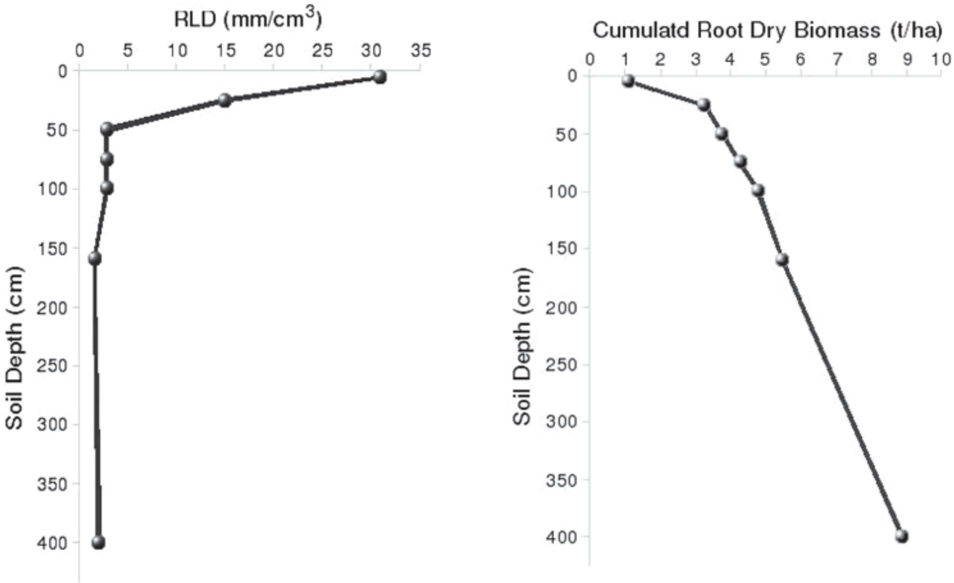


Figure 6 a. Root length density (RLD) profile. Note the fairly constant RLD for soil depths ranging from 150 to 400 cm. b. Cumulated fine root biomass profile estimated from destructive sampling.

Assuming a mean organic carbon content of approximately 47% for fine rubber tree roots (Wauters et al., 2008) data gained from this study indicated that the amount of carbon stored in rubber tree roots 0.5 mm in diameter or less, is of the order of 4.5 t C ha^{-1} on average, which is of the same order of magnitude, although slightly higher, than values reported by Wauters et al. (2008) for coarser roots (2.5-25 mm in diameter) of a range of clones including GT1, PB217, PB235, PB260, PR255 and RRIM600 from Western Ghana and Brazil. This means that an important carbon pool may have been overlooked by most studies. These results are also of the same order of magnitude as the value of 16.50 t C ha^{-1} reported by Cheng et al. (2007) for roots of all sizes, in rubber tree plantations at Hainan Island, China.

Root decay

Weight losses measured at the three depth increments (1.65, 2.9 and 4.05 m) at which root material was incubated were used to compute average decay rates (*k*/yr) based on a simple exponential law. Compared to other studies conducted at temperate latitudes (Gill and Burke, 2002), there was no linear decrease of root decay rate with soil depth in this study. The slowest root decay rate was observed at the 4 m depth while it was fastest at 2.9 and intermediate at 1.65 m, with *k*=0.4, 1.03 and 0.65 per year, respectively (**Figure 7**). There was no significant difference in decay rates between the finer (0.54 to 3.75 mm in diameter) and coarser (3.85 to 14.64 mm in diameter) root fractions. The higher decay rate observed at 2.9 m might be related to locally wetter conditions at 2.9 m. For the soil type and latitude corresponding to this study site, the

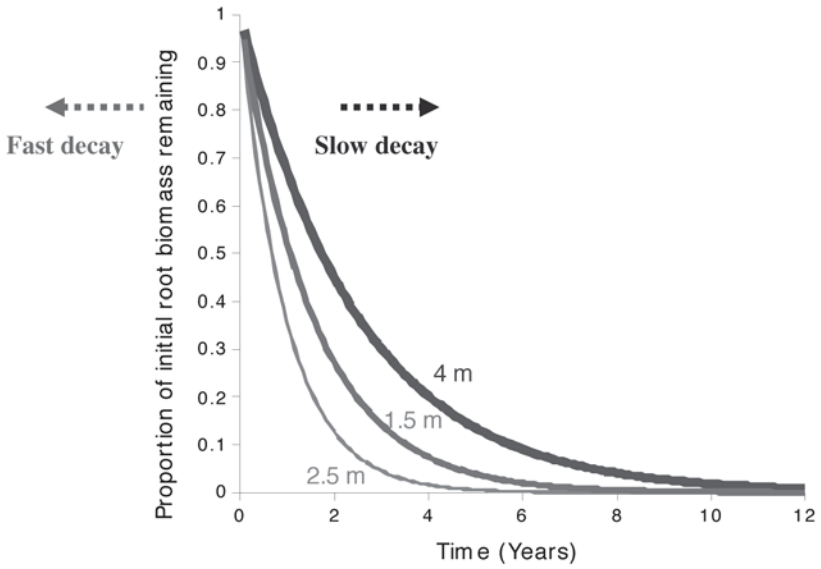


Figure 7 Estimated root decay functions for three soil depth increments

decay rates at 1.65 and 2.9 m were of the same order of magnitude as that reported by Silver and Miya (2001). However, the much slower root decay rate obtained at the 4-m depth increment clearly indicated that soil processes near the soil surface cannot be compared to those that prevail deeper in the soil profile. As a consequence, estimating root decay at depth, based on measurements made in shallow horizons is likely to be a misleading exercise.

Conclusions

Root turnover and decomposition play a key role in soil carbon sequestration and nutrient cycling and the carbon and nutrient dynamics associated with root decay represent significant components of the global carbon cycle (Silver and Miya, 2001). The permanent access-well proved a useful tool to study the root turnover and decomposition in the context of rubber tree plantations in NE Thailand. Initial results obtained during the first year and a half of the study showed that deep root dynamics below 150 cm was not as directly related to the rainfall pattern as that nearer the soil surface. Overall, fine root mortality was very low and most roots' longevity was of several months (up to 17 months); therefore, this experimental setup must be maintained for a sufficiently long period of time to obtain reliable data on root turnover. It was also found that fine root biomass below the depth of 100 cm potentially accounted for more than a third of the overall fine root biomass of the studied rubber trees. Finally, the decay rate of root tissues at 400 cm was slow, with a half-life of the order of 21 months. Together with long fine roots survival, this indicated that, under the agro-pedo-climate of the study site, the residence time of soil carbon that originated from fine rubber tree roots was of the order of several years. This could have wider implications for those rubber plantations that share a similar agro-pedo-climatic context.

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