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Pre- and post-harvest fine root growth in *Eucalyptus grandis* stands installed in sandy and loamy soils

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Abstract

Information about fine root dynamics before and after harvest is scarce in eucalypt plantations. Knowledge of root system functioning is important to achieve sustainable production of these fast-growing species. This work evaluated fine root turnover in 9-year-old *Eucalyptus grandis* stands growing on a loamy soil (RED) and in a sandy soil (QTZ). On each soil type, the experimental area was divided into three plots that corresponded to the following time sequence: mature forest before harvesting (MF), after harvesting in summer (HS) and after harvesting in winter (HW). Fine roots (diameter < 3 mm) were sampled by sequential coring. Root length was obtained by imaging processing, distinguishing fine roots with diameter < 1 mm (FR1) and diameter between 1 and 3 mm (FR2). Fine root decomposition was estimated with litter bags incubated in three plots per soil. Root length density was higher for FR1 in QTZ than in RED for all plot types. There was a significant seasonal difference in FR1 density (FRD1) at a depth of 0–10 cm in RED (from 2.3 to 4.4 cm cm^{-3}) and QTZ (from 5.7 to 8.2 cm cm^{-3}), in winter and summer, respectively. Fine root dynamics was significantly altered after harvesting, mainly in the surface layer in both soils. An approx. 50% decrease in FRD1 was observed 60 days after harvesting in the two soil types. Root mass loss in litter bags was faster in RED than in QTZ. Decomposition of fine roots was faster after harvesting, which was directly related to altered environmental conditions (water availability, soil temperature).

Keywords: Fine root dynamics; Coppice; Clearcut; Root system; Eucalypt; Brazil

1. Introduction

Eucalypt plantations play an important role in the economy of several countries. In Brazil, *Eucalyptus grandis* and other clonal plantations cover about 3 millions ha (Mora and Garcia, 2000). This species has a fast initial growth rate and good regeneration capacity through stump sprouting (coppicing). Stored nutrients in the root system are involved in the fast initial shoot growth observed in eucalypt plantations after clearcutting (Reis and Kimmins, 1986; Barros et al., 1997; Teixeira et al., 2002).

Short rotation forestry sustainability has long been questioned, because extensive areas with low-fertility soils have been cultivated with high biomass and nutrient removal. As a result, mitigating actions have been undertaken, such as the adoption of reduced tillage practices, as well as log debarking on site to reduce nutrient removal (Gonçalves et al., 2004). Fine roots contribute significantly to soil organic matter and nutrient turnover in forest ecosystems (McClaugherty et al., 1982; Arunachalam et al., 1996). Soil water content, soil temperature, and nutrient availability are important factors controlling fine root turnover (Teskey and Hinckley, 1981; Hendricks et al., 1993; Joslin et al., 2001), but this process is also genotype dependent (Eissenstat, 1991; Wells and Eissenstat, 2001). Fine root decomposition is regulated by numerous environmental and biological factors, in particular: soil moisture, soil temperature, microbial activity, and biochemical characteristics of detritus (Melillo et al., 1982; Laishram and Yadava, 1988; Palm and Sanches, 1990; Bloomfield et al., 1993). Knowledge about fine root dynamics is important to improve weed management and fertilization regimes, in order to enhance water and nutrient use efficiencies (Nambiar, 1983; Bouillet et al., 2002). Despite the importance of fine root turnover in C and nutrient biogeochemical cycles in forest ecosystems, studies of fine root decomposition are scarce in eucalypt plantations (Gill and Jackson, 2000; Ribeiro et al., 2002; Laclau et al., 2003).

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Some methods such as ingrowth core and sequential root coring have been widely used alone or in combination to estimate fine root turnover (Majdi et al., 2005). Minirhizotrons allow temporal observations of the same root, which makes it possible to estimate root longevity. However, tubes introduced into the soil for root observations create an artificial environment for root growth (Majdi, 1996; López et al., 2001). To minimize this problem, tubes installed at an angle between 30° and 45° reduce underestimation and overestimation in the upper and lower soil layers, respectively (Bragg et al., 1983; Hansson and Àndren, 1987). Minirhizotrons and sequential root coring methods provide complementary information (Fabião et al., 1995). Sequential coring, although destructive and labor intensive, makes possible a accurate description of root systems in undisturbed forest soils.

The main objective of the present study was to assess the seasonality of fine root dynamics in coppiced eucalypt stands, before and after harvesting in two contrasting soil types. The effect of harvesting period on fine root decomposition was also studied in these soils.

2. Materials and methods

2.1. Site description

The study was carried out in two sites located in commercial *E. grandis* W. Hill Ex Maiden plantations of the Suzano Company, in the Western Plateau of the State of São Paulo, Brazil. These sites were originally occupied by shrubby savanna (Cerrado), typical native vegetation in the area. Mean rainfall over the time course of the experiment was 1686 mm year^{-1} and mean temperature was 22.2 °C. Average monthly values over 30 years are also shown in Fig. 1.

The soils were classified as a Typic Hapludox (dystrophic loamy soil—RED) at the most productive site, and as a Typic Quartzipsamment (sandy soil—QTZ) at the least productive site (USDA classification). Topography is flat to gently sloping (0–3%) at both sites, which soils are deep and well drained. Physical and chemical soil attributes are shown in Tables 1 and 2.

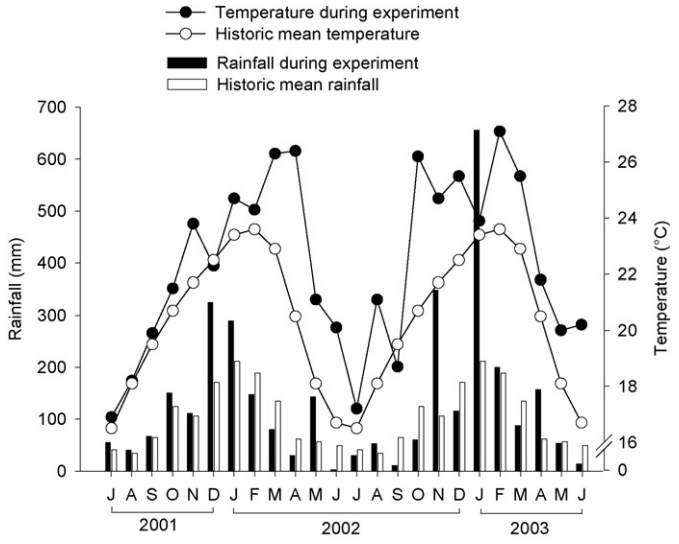

Fig. 1. Time course of rainfall and mean temperature at the sites from July 2001 to June 2003, and historic averages over 30 years.

Eucalypt seedlings were planted firstly in 1971–1972, after cutting down the native vegetation (Cerrado). Stands sampled in the present study were planted in 1992. *E. grandis* seedlings were obtained from a seed orchard established by the genetic improvement program of the Suzano Company. This genetic material both as seedlings and cuttings is planted also in commercial plantations in the region. Fine root dynamics was studied in seedling stands here to assess the general behavior of the species. Both sites were cultivated under the reduced soil tillage system (Gonçalves et al., 2004). Stem volume under bark was 273 m^3 ha^{-1} at age 9 years in the most productive forest site (23°55′S, 47°09′W, elevation 650 m a.s.l.) and was 191 m^3 ha^{-1} at age 9-year old in the least productive site (23°01′S, 48°61′W, elevation 700 m a.s.l.).

To establish these stands, the soil was ripped in lines at 3 m intervals to a depth of 40 cm and *E. grandis* seedlings were planted at 2 m intervals in ripped lines. NPK fertilizer (260 kg ha^{-1}, 06-30-06) was applied at planting with rock phosphate (partially acidulated, 330 kg ha^{-1}). Post-planting NPK fertilization occurred at ages 3 months (80 kg ha^{-1}, 20-00-20) and 2 years (300 kg ha^{-1}, 14-07-28).

At each site, the experimental area was divided into three plots (50 m × 100 m): a plot corresponding to the mature forest before harvesting (MF, which was not felled), a plot harvested in summer (HS) and a plot harvested in winter (HW). The plots were installed on the two soil types (RED and QTZ) in July 2001, after checking that stand growth and soil properties were homogenous within each experimental area. Tree felling was performed with a chainsaw 10 cm above-ground in January 2002 (HS) and July 2002 (HW). The MF plot was not felled until the end of the experiment (July 2003). Circumferences at breast height (CBH) were measured every 6 months in MF, in January 2002 in HS, and in July 2002 in HW. Height of sprouts was measured every 6 months after clearcutting.

2.2. Fine root density

The root mat in the forest floor was studied in MF plots by collecting 6–10 samples every 3 months from April 2002 to January 2003, using a 30 cm diameter steel ring. In the same plots, fine roots in the mineral soil were sampled before harvesting in July 2001 and December 2001, then every 3 months from January 2002 to July 2003 in MF plot to assess seasonal variations. After harvesting in January 2002 and July 2002, fine roots were measured monthly for 90 days in HS and HW plots, then every 3 months during 1 year. Fine roots were sampled close to five randomly selected trees (or stumps) on each sampling date in both soil types. In the present study, the spatial distribution of roots represented that of the stand, and not just of the nearest tree, because eucalypt roots can be found at more than 10 m from the trees (Baldwin and Stewart, 1987; Stone and Kalisz, 1991). At each sampling date, cores were taken using a stainless steel soil corer (45 mm internal

Table 1
Physical attributes of soils in the *Eucalyptus grandis* stands

Depth (cm)	Sand[a] (g kg^{-1})	Silt (g kg^{-1})	Clay[b] (g kg^{-1})	Bulk density (g cm^{-3})	Particle density (g cm^{-3})
Dystrophic loamy soil (RED)					
0–20	683	143	174	1.28	2.7
20–40	723	64	213	1.29	2.8
Sandy soil (QTZ)					
0–20	917	27	56	1.37	2.7
20–40	917	10	73	1.39	2.7

[a] Sieving.
[b] Pipette method (Embrapa, 1997).

Table 2
Chemical attributes of soils in the *E. grandis* stands

Depth (cm)	P-resin[a] (mg kg^{-1})	O. M.[b] (g kg^{-1})	pH[c]	Exchangeable cations[a] (cmol$_c$ kg^{-1})			
				K^{2+}	Ca^{2+}	Mg^{2+}	Al^{3+}
RED							
0–10	12	42	3.5	0.12	0.55	0.35	3.58
10–20	5	19	3.9	0.06	0.13	0.20	2.69
20–30	4	19	3.9	0.05	0.12	0.13	2.58
30–50	3	14	3.9	0.04	0.17	0.13	2.32
50–100	3	13	4.0	0.04	0.12	0.14	2.06
QTZ							
0–10	10	30	3.5	0.10	0.25	0.19	2.06
10–20	6	14	4.0	0.08	0.08	0.05	1.37
20–30	3	11	4.0	0.07	0.08	0.11	1.11
30–50	3	10	4.0	0.07	0.08	0.03	1.11
50–100	1	8	4.1	0.06	0.08	0.03	1.11

[a] Ion exchange resin (Raij et al., 2001).
[b] Potassium dichromate and sulfuric acid extraction.
[c] $CaCl_2$ 0.01 mol L^{-1} (soil to solution ratio 1:5).

diameter) in the planting row and inter-rows, at distances of 100 and 150 cm, respectively, from the 5 selected trees (10 positions per plot). Cores were sampled stepwise for the soil depths 0–10, 10–20, 20–30, 30–50, and 50–100 cm, to avoid compaction.

Roots were carefully washed under a gentle flow of tap water over a 550 μm mesh sieve to remove adhering soil (Böhm, 1979). Remaining soil particles, leaf fragments and other debris were separated with tweezers in a white tray. Live roots were separated from dead ones based on visual attributes: lighter color, translucent appearance, and because they did not break easily when bent (Tennat, 1975; Vance and Nadkarni, 1992; Gonçalves and Mello, 2000). The tetrazolium test (Knievel, 1973; Ruf and Brunner, 2003) confirmed the accuracy of these visual attributes. In this test, the formation of the colored product triphenyl formazan (TPF), which is produced after the reduction of the triphenyl-tetrazolium chloride (TTC) in living roots was used as an indication of dehydrogenase activity (Altman, 1976).

The roots were placed in vessels containing a 70% alcohol solution (Johansen, 1940), which allowed root structure fixation and preservation at the original sampling dimensions. Thereafter, digitized images of the roots were obtained with a flatbed scanner, over which they were placed on a glass tray (21 cm × 30 cm and 1 cm height) containing the roots immersed in a water film. During the preparation of samples on a glass tray, roots were separated into 2 diameter classes: roots < 1 mm (FR1) and roots between 1 and 3 mm in diameter (FR2). Roots were classified with the aid of templates displaying the limiting diameters. The images were recorded at 100 dpi resolution in the pcx format, at 256 shades of gray. Once the digitized root images were obtained, the root length was estimated through SIARCS (Sistema Integrado para Análise de Raízes e Cobertura do Solo—Integrated System for Root and Soil Cover Analysis), developed by EMBRAPA/CNPDIA (Jorge et al., 1996).

2.3. Root decomposition measurements

Mesh bag were used to assess root decay, which is otherwise difficult using sequential soil coring (Majdi, 1996). The decomposition study was conducted during a period of 1 year within each of the three plots (MF, HS and HW) at both sites. Live fine roots were collected in July 2001, January 2002 and July 2002 in MF, HS and HW, respectively. About 5–7 g air-dried roots (McClaugherty et al., 1984) were divided into two diameter classes (FR1 and FR2) and placed into litter bags (10 cm × 20 cm and 0.5 mm mesh). The litter bags were randomly placed around 10 trees (replicates) in each plot, one half on the forest floor and the other half at a depth of 10 cm in mineral soil. In each plot, 40 bags were retrieved every 3 months. Samples from each bag were cleared of adhering soil

particles and oven-dried at 65 °C until constant mass. Annual decay constant (k) was calculated following the negative exponential decay model (Olson, 1963):

$$k = -\frac{\ln(X/X_0)}{t},$$

where X_0 is the initial dry weight, X the dry weight remaining at the end of the incubation and t is the time interval.

2.4. Soil sampling and analytical procedures

Soil samples were collected adjacent to root sampling points and at the same depths, with the stainless soil corer used for root sampling. Next, pH (in 0.01 M $CaCl_2$), labile P, K, Ca and Mg, and total soil C and N were determined using the procedures described in Raij et al. (2001). Soil textural analysis was performed by the pipette method for clay content, the sand content was determined by sieving, while the silt content was determined by the difference between sand and clay content (Embrapa, 1997). The volumetric ring method was used for bulk density determination, and soil particle density was determined using the volumetric flask method (Embrapa, 1997). Soil water content (SWC) was measured gravimetrically also on soil samples, collected next to the fine root sampling points and at the same depths. Maximum and minimum temperatures were measured by digital thermometers (with a data logger) in the central area of each plot, one at a 10 cm depth and the other in the forest floor.

2.5. Statistical analysis

Results were analyzed using analysis of variance (SAS Institute, 1996). One-way ANOVA was used to compare fine root length density of FR1 (FRD1) in the rows and between planting rows, for each depth. Two-way ANOVA was used to test the variation in FRD1 between soils and times, by each depth. Whenever the ANOVA indicated a significant difference between the means ($P < 0.05$), these were compared from the Tukey HSD multiple range test. Statistical analyses were not performed on FR2 because the number of samples was to low.

Table 3
Fine root density in the forest floor (cm of root per cm^2 of area) before harvesting from samplings performed at different dates in the two soil types

Month of sampling	Fine root density (cm cm^{-2})			
	RED		QTZ	
	FRD1	FRD2	FRD1	FRD2
April 2002	1.33 a	0.11	2.36 b	0.03
July 2002	6.36 a	0.13	2.55 b	0.04
October 2002	6.96 a	0.02	4.40 ab	0.04
January 2003	9.81 a	0.40	10.18 a	0.06
Mean	6.12	0.17	4.87	0.05

Means followed by the same letter in each column are not significantly different ($P < 0.05$).

3. Results and discussion

3.1. Stand growth after harvesting

Sprout height was higher in RED than in QTZ (Fig. 2). Mean values of height were 4.5 m (RED) and 3.8 m (QTZ) 12 months after harvesting in summer (HS). Further, the growth of coppice stands was influenced by the season of harvest. Large differences in precipitation (about 36%) throughout the first year of growth occurred according to the date of harvest (Fig. 1). Mean values of precipitation and temperature during the experimental period were higher than historic mean data. The amounts of rainfall accumulated were 1310 and 1787 mm from January 2002 to December 2002 (HS) and from July 2002 to June 2003 (HW), respectively. As classically observed in eucalypt plantations, height growth was highly influenced by rainfall amounts (Stape et al., 2004).

3.2. Fine root dynamics

FRD1 in sandy soil was significantly lower in April and in July than in summer (Table 3). FRD2 contributed relatively little to total root length (1–8%) in the forest floor. Mean values of FRD1 ranged from 1.3 to 10.2 cm cm^{-2} according to the sampling date. The lack of significant difference in FRD

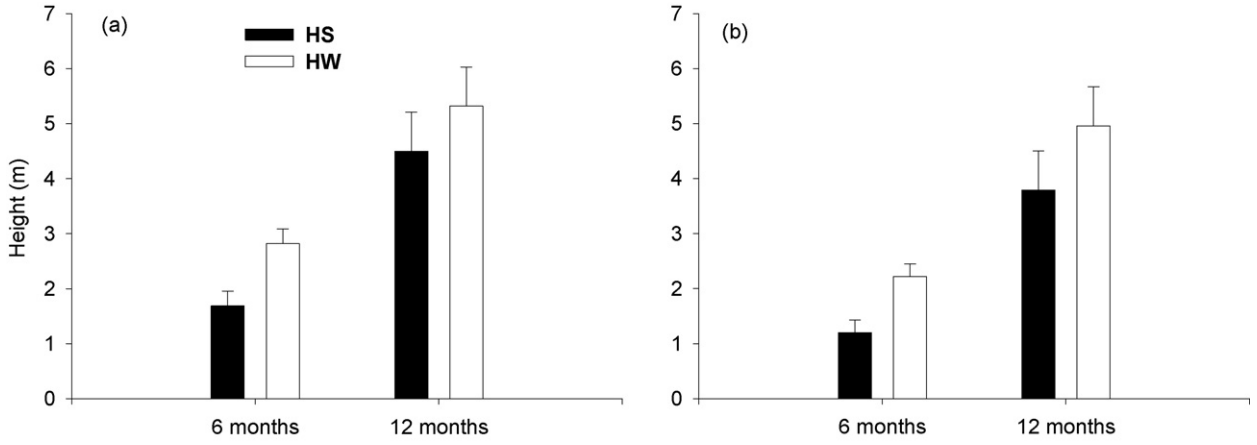

Fig. 2. Mean height of eucalypt sprouts 6 and 12 months after harvesting in summer (HS) and after harvesting in winter (HW). (a) RED; (b) QTZ. Bars indicate standard deviation ($n = 100$).

between soils was attributed to the high spatial variability of fine roots in the forest floor. The superficial root mat should not be neglected, because other studies in tropical forests show that these roots have an important function for forest nutrition to prevent nutrient leaching (Vance and Nadkarni, 1992; Sayer et al., 2006) and contribute efficiently to the quick cycling of nutrients in eucalypt ecosystems (Laclau et al., 2004). The proportion of fine roots in the forest floor was about 10% of the total length measured on a ground surface area basis in MF (forest floor + mineral soil down to 1 m). For example, fine root length in January 2003 on RED in the forest floor and the first meter of mineral soil amounted to 10^7 and 99×10^6 m ha^{-1}, respectively. Witschoreck et al. (2003) measured 30×10^6 m ha^{-1} of fine roots in the upper 60 cm of soil under a 10-year-old *Eucalyptus urophylla* stand, but differences in sampling methods and soil depth make comparisons difficult. Future studies should focus on the processes controlling the response of roots to heterogeneity of resource availability, which is variable in both time and space.

FR1 represented more than 90% of total root length. Similar results were found by Baldwin and Stewart (1987) and Mello et al. (1998) for the same species. Fine roots represent a much higher specific surface area for water and nutrient uptake when compared with coarse roots, in addition to the lower investment in carbon (Tyree et al., 1998). However, turnover rates of fine roots are likely to be higher in upper soil layers than in deep soil horizons (Kern et al., 2004; O'Grady et al., 2005).

Seasonal changes in FRD1 were found in the two soil types at the end of the rotation (Fig. 3). From winter to summer, FRD1 in the top soil (0–10 cm) increased significantly from 2.3 to 4.4 cm cm^{-3} in RED and from 5.7 to 8.2 cm cm^{-3} in QTZ, respectively. In winter, FRD1 decreased with depth from 2.3 cm cm^{-3} in the upper layer to 0.4 cm cm^{-3} in the 50–100 cm layer and from 5.1 to 0.4 cm cm^{-3} in RED and QTZ, respectively. In summer, FRD1 decreased with depth from 4.4 to 0.7 cm cm^{-3} and from 8.2 to 0.8 cm cm^{-3} in RED and QTZ, respectively. FRD1 was higher in the upper soil horizons in all sampled cores in this study. This pattern might due to more favourable soil water status and higher concentrations of nutrients in the surface horizon. The high density of fine roots in the top soil is frequently observed in eucalypt stands (Fabião et al., 1995; Mello et al., 1998; Misra et al., 1998; Teixeira et al., 2002; O'Grady et al., 2005).

Although FRD1 declines with depth, deep roots play an important role in water uptake during dry seasons in eucalypt plantations (Laclau et al., 2001). Nepstad et al. (1994) showed that deep roots are essential to supply water to trees, especially in tropical forests, with well-defined dry seasons. Furthermore Hendrick and Pregitzer (1996) found that, when compared with roots in surface layers, deep roots generally had greater

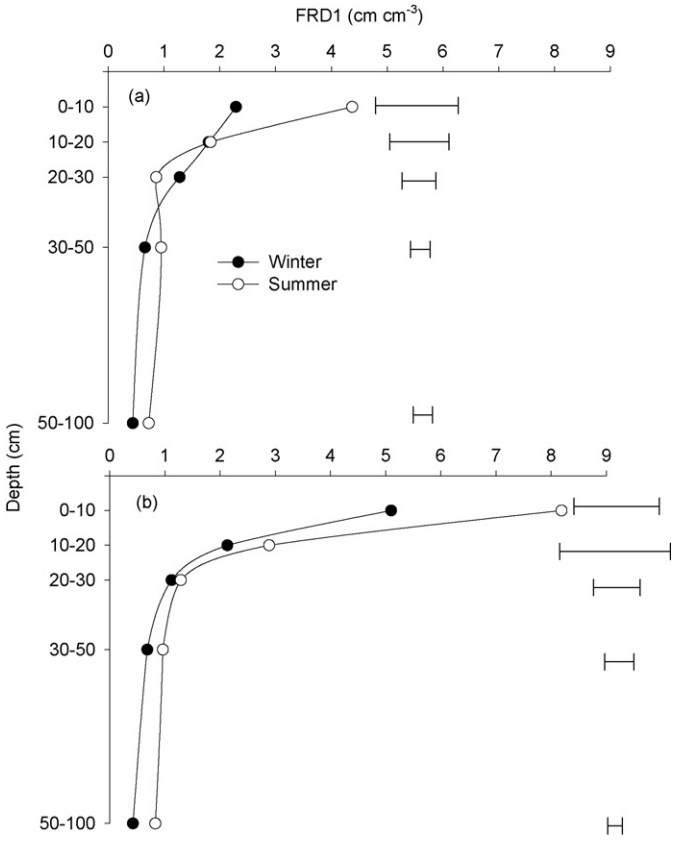

Fig. 3. Mean values of FRD1 from samplings taken in July 2001 (Winter) and December 2001 (Summer) before harvesting in RED (a) and in QTZ (b). Bars refer to the least significant difference (LSD) at 5% probability level ($n = 10$) given by the Tukey HSD test.

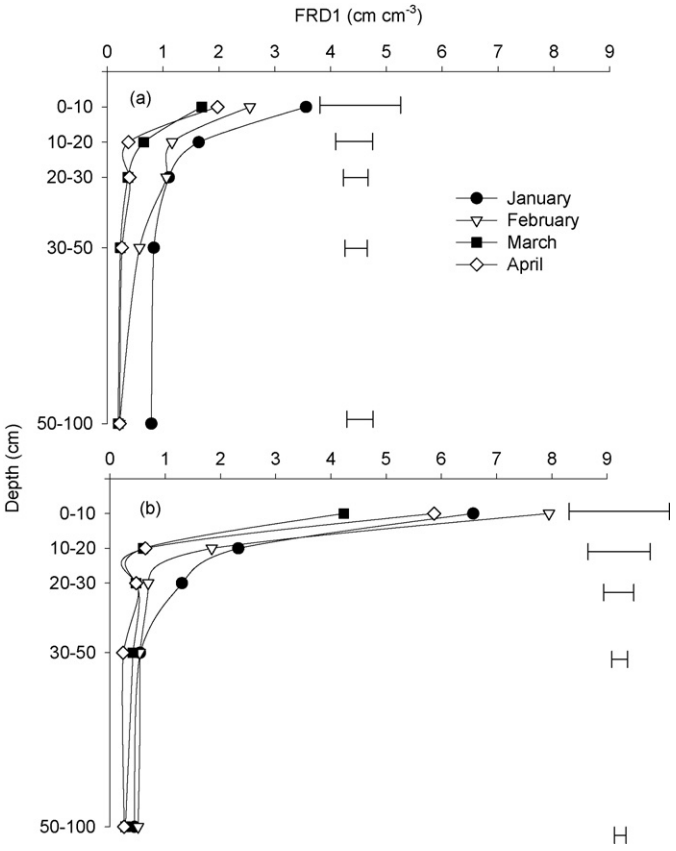

Fig. 4. Mean values of FRD1 after harvesting in summer (January 2002) and during the three subsequent months in RED (a) and QTZ (b). Bars refer to LSD at 5% probability level ($n = 10$) given by the Tukey HSD test.

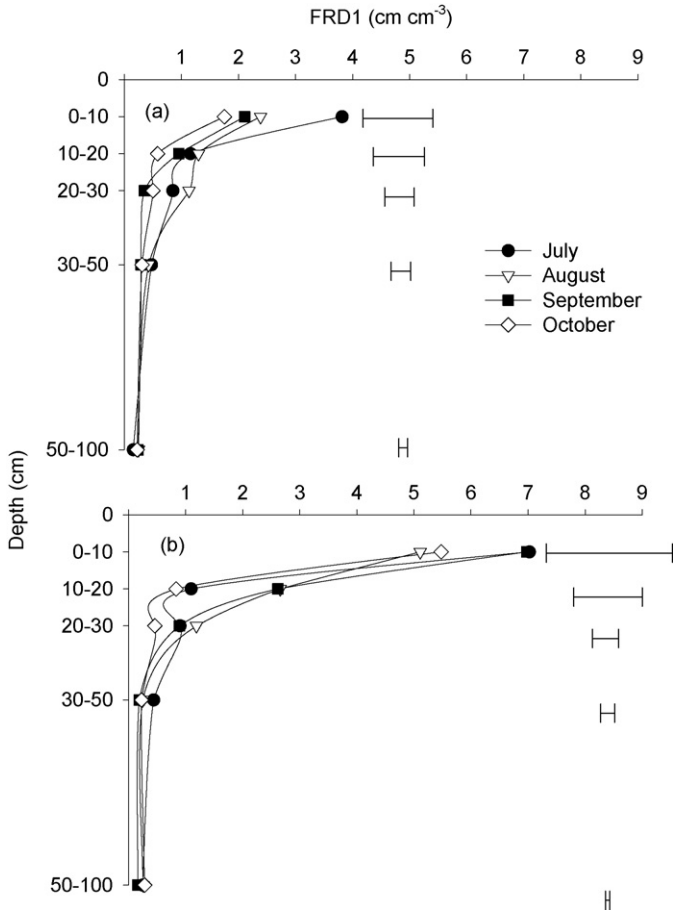

Fig. 5. Mean values of FRD1 from samplings performed after harvesting in winter (July 2002) and during the three subsequent months in RED (a) and in QTZ (b). Bars refer to LSD at 5% probability level (n = 10) given by the Tukey HSD test.

longevity, i.e., they remained physiologically active for a longer period of time.

In the 0–10 cm depth, FRD1 was higher in the sandy soil than in the loamy soil. High FRD values were also observed in sandy soils under eucalypt stands by Keyes and Grier (1981), Reis et al. (1985) and Fabião et al. (1987). As a consequence of the low water holding capacity and nutrient availability in sandy soils, roots have to explore a large soil volume to supply water and nutrients to trees. The higher FRD1 in the 0–10 cm layer of the sandy soil might reflect on adaptative strategy of trees to capture quickly water and nutrients after precipitation events (Kasola and Eissenstat, 1994).

FRD1 decreased until about 60 days (March 2002) after harvesting in summer (Fig. 4). Proportionally, FRD1 decline was similar in the two soil types; e.g., FRD1 in March was about half of that found in January. Low regrowth of fine roots was observed in the surface layer (0–10 cm) 90 days (April) after harvesting in both soil types, although it was not statistically significant. The spatial variability of FRD1 was high in the two soils types after harvesting, which suggested that the mortality of fine roots occurred preferentially in some soil regions.

FRD1 gradually decreased until 90 days (October 2002) after harvesting in winter (HW) in both soil types (Fig. 5). There was a significant decrease in FRD1 in the surface soil layer (0–10 cm) from July to August in QTZ. The same trend was observed in RED, but differences were not significant.

Selective measurements suggested higher soil water content (SWC) in RED than in QTZ and an increase in SWC following harvesting (data not shown). Martins et al. (1997) found an increase in soil water availability after harvesting in *E. grandis* plantations, which was attributed to the ceasing of stand transpiration. An increase in temperature was observed after harvesting in summer, and more pronounced in the forest floor than in the top (0–10 cm deep) of mineral soil (Fig. 6). The increase in temperature magnitude after harvesting was lower in winter than in the summer (Fig. 7). The largest ranges of temperature were recorded in the litter layer, with a decrease in mean minimum temperature from 17.7 to 6.7 °C in RED and from 12.7 to 5.4 °C in QTZ. High correlations between fine root growth, SWC (Nambiar, 1983; Kätterer et al., 1995; López

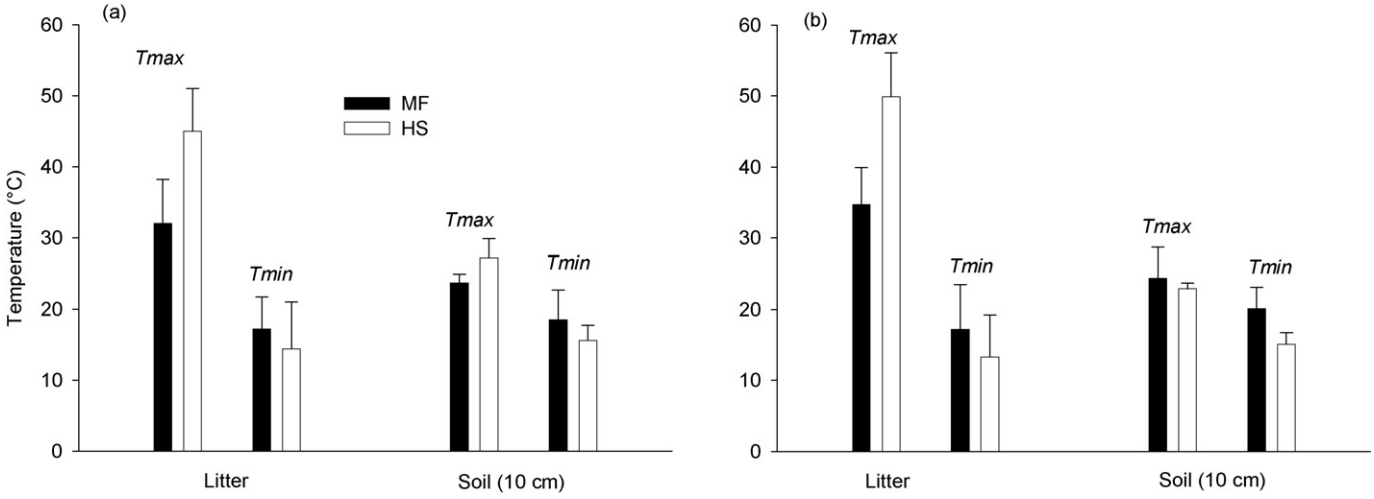

Fig. 6. Mean maximum (T_{max}) and minimum (T_{min}) temperatures recorded weekly during 3 months in the litter layer and at 10 cm depth in RED (a) and in QTZ (b). MF: mature forest; HS: harvesting in summer. Bars indicate standard deviation.

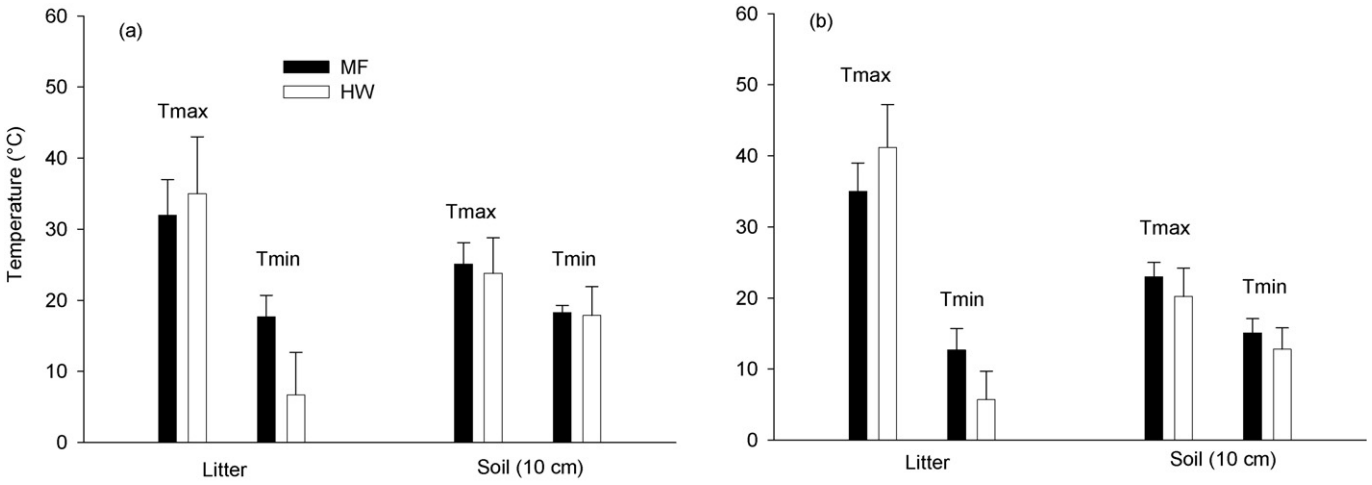

Fig. 7. Mean maximum (T_{max}) and minimum (T_{min}) temperatures recorded weekly during 3 months in the litter layer and at a 10 cm depth in RED (a) and in QTZ (b). MF: mature forest; HW: harvesting in winter. Bars indicate standard deviation.

et al., 1998) and soil temperature (Kern et al., 2004) were found in other studies.

Seasonal variations in FRD1 were observed in the mature stand from 2001 to 2003 (Fig. 8). These years presented marked differences in terms of precipitation (Fig. 1) and high variability in FRD1 occurs in forests due to environmental variations (Persson, 1983; Hendrick and Pregitzer, 1993; Green et al.,

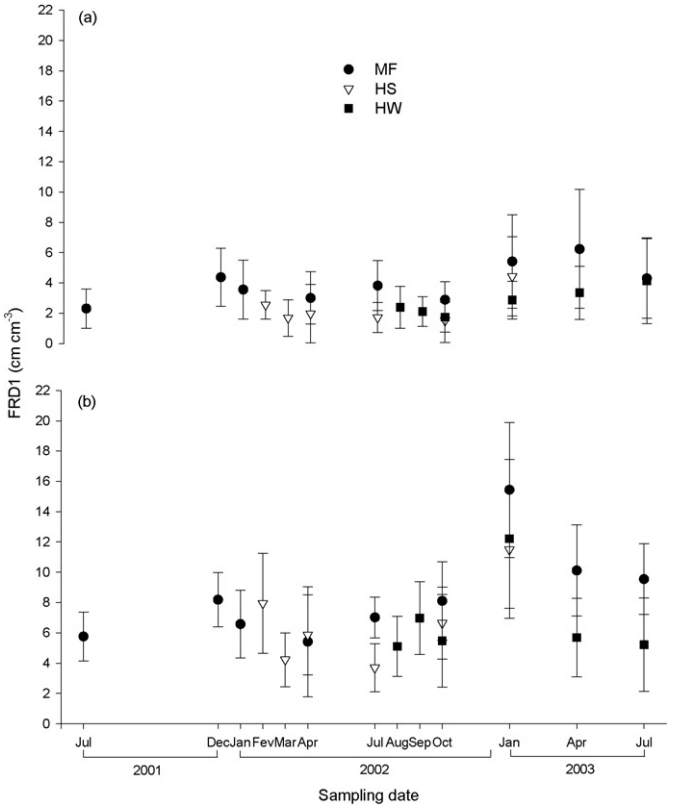

Fig. 8. Mean FRD1 in the top of soil horizon (0–10 cm) from July 2001 to July 2003 in (a) RED and (b) QTZ. MF: mature forest, HS: after harvesting in summer, HW: after harvesting in winter. Bars indicate standard deviation.

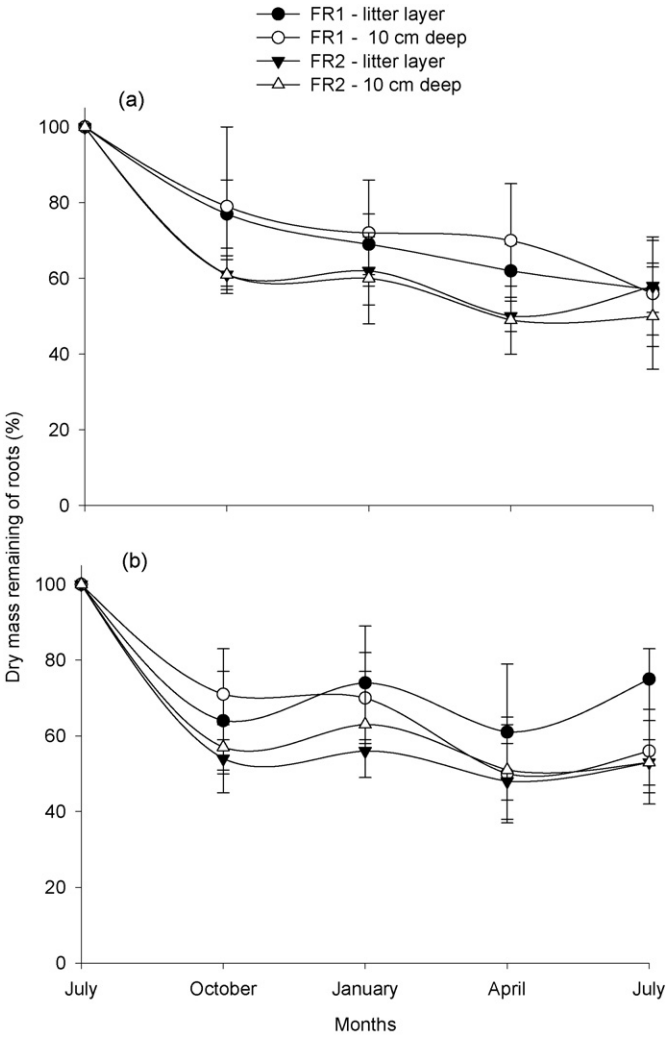

Fig. 9. Mean dry mass remaining of fine roots incubated in mature forest (MF) in the forest floor and in the soil at 10 cm deep over 12 months from July 2001 to July 2002. Bars indicate standard deviation. (a) RED; (b) QTZ.

Table 4
Annual decay constant (k) of fine roots incubated in litter and buried at a depth of 10 cm in mature forest (MF) and after harvesting in the summer (HS) and in the winter (HW)

Localization	FR1 (k)		FR2 (k)	
	RED	QTZ	RED	QTZ
MF				
Litter layer	0.56 (0.41–0.68)	0.33 (0.11–0.41)	0.57 (0.15–0.71)	0.63 (0.39–0.78)
10 cm deep	0.61 (0.41–1.13)	0.55 (0.27–0.92)	0.70 (0.26–1.10)	0.65 (0.34–0.98)
HS				
Litter layer	0.39 (0.13–0.63)	0.52 (0.25–1.10)	0.33 (0.16–0.40)	0.29 (0.08–0.48)
10 cm deep	0.88 (0.20–1.68)	0.52 (0.24–0.89)	0.27 (0.17–0.43)	0.25 (0.06–0.58)
HW				
Litter layer	0.98 (0.87–1.10)	0.76 (0.52–1.04)	0.21 (0.14–0.29)	0.24 (0.17–0.32)
10 cm deep	2.11 (1.75–2.68)	0.79 (0.58–1.06)	0.46 (0.25–0.68)	0.54 (0.41–0.67)

The range of decay is indicated between parentheses.

2005). Teixeira et al. (2002) also observed that peak root growth in eucalypts stands coincided with periods of high rainfall. Furthermore, fine root growth is negatively correlated with drought periods (Vogt et al., 1993; Burke and Raynal, 1994). FRD1 was slightly lower in HS and HW plots than in mature forest throughout the first year after harvesting, particularly in QTZ. This pattern suggests that regrowth of fine roots after harvesting was synchronized with the requirements on nutrients and water by the coppicing stands.

FRD1 values were not significantly different between soils sampled in the planting row and those in the inter-row. This pattern might be associated to stand age. In mature eucalypt stands, the distribution of fine roots is relatively more homogeneous in the top soil than in young forests (Misra et al., 1998; Moroni et al., 2003; O'Grady et al., 2005).

3.3. Fine root decomposition

Mass loss of fine roots was larger during the first 3 months of incubation (Fig. 9), most probably due to the decomposition of soluble compounds (sugars and non-structural carbohydrates), which are readily available energy sources by microbial organisms (McClaugherty et al., 1984; Bloomfield et al., 1993; Arunachalam et al., 1996). The period from 3 to 12 months after installation of litter bags was characterized by slower decomposition, which could be attributed to microbial immobilization of nutrients and a proportionally higher percentage of recalcitrant fractions. Arunachalam et al. (1996) found that nutrient release from decaying fine roots was influenced by seasonal cycles of mineralization and immobilization processes. Undecomposed fine root mass after 1 year represented about 50% of initial dry mass, as in the present study. The annual decay constant (k) was higher at 10 cm deep than in the litter layer. Before harvesting, k for FR1 was higher in litter in RED (0.56) than in QTZ (0.33) (Table 4). Likewise, the litter in RED was a more labile source of nutrients for microorganisms than in QTZ. Several studies have indicated that the chemical and biochemical quality of litter affects dry-weight changes during decomposition (Melillo et al., 1982; Vitousek et al., 1994; Moorhead et al., 1999; Paul and Polglase, 2004). There were similar k values for FR2 incubated either in litter layer or at 10 cm soil depth in both soil types.

Fine root decomposition of FR1 was influenced by harvesting. For example, k increased from 0.61 to 2.11 when FR1 were incubated at 10 cm depth in RED. The annual decay constant of fine roots (FR1 and FR2) was higher in HW than in HS. This pattern might be related to the pattern of precipitation and SWC in the period July 2002 to July 2003 when compared to the period January 2002 to January 2003 (Fig. 1). In HW, the remaining mass of FR1 after 1 year was only 12.7% of the initial dry mass incubated at 10 cm depth in RED. In contrast, the remaining mass of FR2 was about 80% in both soil types.

Mesh bag technique is questionable. Under natural conditions, the decomposition of fine roots would be different, because living roots collected for mesh bags would have differed from naturally senesced roots. When the roots are collected alive they contain carbohydrate reserves that could have been translocated to other tree components or respired during senescence. However, live root litter can be produced by certain disturbances such as clearcutting. In this case, fine roots would be a nitrogen sink (immobilized N) following a clearcutting. Moreover, litter bags provide an underestimation of mass loss of fine roots, because soil organisms larger than the mesh size are excluded by the bags and fragmentation and consumption is therefore minimized (Joslin and Henderson, 1987; Fahey and Arthur, 1994).

4. Conclusions

- Large changes in FRD were observed in the top soil (0–10 cm) at the end of stand rotation. Inter-annual climatic variations might be involved in the large variation of FRD observed.
- FRD was influenced by clearcutting in the top soil. In both soil types, FRD decreased until 60 days after harvesting in summer (HS), followed by regrowth of fine roots, mainly in the 0–10 layer of mineral soil. In HW, FRD decreased about 90 days after harvesting in the two soil types. One year after clearcutting, FRD1 of sprouts were about 25% lower than in

mature forest. FRD1 was lower than lower than in mature forest but a large spatial variability was observed.

- The decomposition of fine roots was accelerated after harvesting, which was probably related to higher soil temperature and water and nutrient availability. In loamy soil (RED), high nutrient availability to seemed to stimulate the mineralization processes. In contrast, slower decomposition rates in sandy soil (QTZ) probably prevented nutrient losses contained in fine roots.

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