

Fine-root dynamics, soil moisture and soil carbon content in a *Eucalyptus globulus* plantation under different irrigation and fertilisation regimes

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Abstract

The minirhizotron technique was used to study the temporal dynamics of fine-roots over a 10 month period in a *Eucalyptus* plantation in central Portugal. Four treatments were applied: a control without irrigation or fertilisation (C), fertilisation twice per year (F), irrigated without fertilisation (I), and irrigated and fertilised once each week with fertiliser in the irrigation water (IL). In I and IL a drip-tube system was used, and fertiliser rates were adjusted based on the estimated plant nutrient demand. Soil moisture content was measured during the same period at 5 cm depth intervals down to 90 cm depth. Soil carbon content was measured at planting, 30 months after planting and 54 months after planting. Interrelations between fine-root dynamics, soil moisture, and soil carbon content are discussed.

Fine-root counts peaked in late autumn in all treatments and declined thereafter until March. Fine-root growth in spring and summer seemed to be dependent on water supply; i.e. with an ample water supply (within rows, close to the drip-tubes in I and IL), root counts increased almost linearly between April and November. In the non-irrigated treatments (C and F, as well as between rows in I and IL), no marked increase in root counts occurred until late August, when it increased immediately after a heavy rain. Root growth in I was shallowest during spring and summer, while in F it was shallowest during autumn and winter. In general, treatment means of root counts were highest in IL, somewhat lower in I, and considerably lower in C and F. In addition to irrigation effects, treatment differences in soil water content were enhanced by differences in soil carbon content, which in turn could be attributed to root turnover, as reflected by the temporal dynamics of root counts. The carbon flow from the trees to the soil, which was probably associated mainly with root death, was highest in IL. Thus this treatment should have enhanced soil fertility.

Keywords: *Eucalyptus*; Minirhizotron; Roots; Soil carbon; Soil moisture

1. Introduction

Since the end of World War II, *Eucalyptus globulus* has become a widely used pulpwood species in Portu-

gal. Since production is limited by the dry Mediterranean summers and low soil fertility at many *Eucalyptus* sites, irrigation and fertilisation increase production considerably (Pereira et al., 1987). Maximum biomass production can be achieved if all nutrients are supplied at a rate corresponding to the plant's growth rate

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(Ingestad, 1988). In most cases enhanced plant growth leads to greater litter production and nutrient concentrations. The larger amount of more nutrient-rich litter should, in turn, lead to an increase in soil organic matter and faster nutrient mineralisation, and thus to an increased flow of nutrients in the soil. As a consequence, increases will occur in water holding capacity, cation exchange capacity, and base saturation, among other soil properties, resulting in improved soil fertility.

The turnover of fine tree roots represents a major contribution to the nutrient and carbon input to the soil each year (Ågren et al., 1980; Harris et al., 1980; Fogel, 1983; Persson, 1983; Hansson and Steen, 1984; Santantonio and Hermann, 1985). The turnover rate of roots is generally greater than that of leaves (Swift et al., 1979, p. 118f). In mature *Eucalyptus* plantations, the amount of root litter produced is at least equal to the annual leaf-litter fall (Ashton and Willis, 1982; Bray and Gorham, 1983). According to a review by Fogel (1985), between 40 and 73% of the net primary production in forest ecosystems is allocated below ground. Part of this carbon flow to the roots is exuded in gaseous form or dissolved in water. However, the main part of this flow is probably via root tissue (Newman, 1985).

In 1986, a field experiment was initiated to test the hypothesis that frequent irrigation and fertilisation can maximise pulpwood production while, at the same time, increasing the fertility of a nutrient-poor soil exposed to a Mediterranean climate (Pereira et al., 1989). The objectives of the work presented in this paper were to quantify the annual dynamics of fine-root growth and death (1), to determine the degree to which this root growth pattern was influenced by soil moisture and nutrient regime (2), and to determine the extent to which treatment differences and the temporal changes in carbon content in the soil during the first 54 months after planting could be explained by root litter accumulation and turnover (3).

2. Material and methods

2.1. Site description and treatments

The experimental site is situated in west-central Portugal, 80 km north of Lisbon at Quinta do Furadouro (39°20'N, 9°13'W, 30 m elevation), about 10 km from

Table 1

Monthly precipitation and irrigation (mm) between January 1991 and March 1992 at the experimental site

	Precipitation	Treatment ^a	
		I	IL
1991			
January	32	0	0
February	141	0	0
March	154	0	0
April	23	32	35
May	0	128	138
June	0	105	105
July	3	211	217
August	24	198	211
September	25	207	192
October	65	38	38
November	103	0	0
December	51	0	0
1992			
January	56	0	
February	22		
March	21		

^aI, irrigated; IL, irrigated and fertilized.

the Atlantic Ocean. The climate is of a Mediterranean type, tempered by oceanic influence. The annual mean temperature and precipitation at Caldas da Rainha, 12 km from the site (70 m elevation), are 15.2°C and 607 mm, respectively (Reis and Goncalves, 1981). Precipitation was measured at the experimental site between January 1991 and March 1992. Monthly values are shown in Table 1.

The soil is sandy and classified as a Spodosol (FAO/UNESCO, 1985) with a low clay content (less than 4%) throughout the soil profile (Madeira and Pereira, 1990/1991). The natural fertility of the soil is low. In 1986, before the experiment was started, total C and N (0–70 cm depth) varied between 0.23 and 0.28%, and between 0.017 and 0.028%, respectively; pH(H₂O) was around 6, available K varied between 23 and 31 $\mu\text{g g}^{-1}$ and available P varied between 8 and 9 $\mu\text{g g}^{-1}$, in the upper 90 cm of the soil. Soil characteristics were described in detail by Madeira and Pereira (1990/1991). Until 1985, the experimental site had supported a mature stand of *Pinus pinaster* and, during 1 year, seedlings of *Eucalyptus globulus*. After ploughing to a depth of 80 cm, 3-month-old seedlings of *Eucalyptus*

globulus Labill. were planted at 3 m × 3 m spacing in March 1986.

The experiment was initially laid out in a randomised block design with two blocks (Pereira et al., 1989). However, one of these blocks was needed for other purposes in 1991. Therefore, our experiment was conducted on only one block, i.e. observed treatment differences were not possible to test statistically. However, since no marked trends in topography or soil properties were observed within the block used for the experiments reported here (M. Madeira, personal observation) the determination of variables at randomly chosen locations within one treatment can be considered as replicates. In view of the limitations of these pseudo-replicates, the calculated means were subjected to analysis of variance with LSD used for assessing differences between means. A significance level of 5% was used.

Each of the four plots had an area of 0.3 ha and was bordered by a two-row buffer zone. Four treatments were applied, named C, F, I and IL. The control (C) was rain-fed and unfertilised. In the fertilised treatment (F), solid fertiliser was applied in March and October each year. The amounts of nutrient elements supplied in F during 1991 were (kg ha⁻¹) 62 N, 20 P and 55 K. A drip-tube system (3 m between tubes) was used for daily irrigation (I) and for irrigation and liquid fertilisation (IL) from April to October. The drip-tubes were installed as close as possible to the trees. The drip-holes were spaced out at 1 m distance, i.e. at 0.5 and 1.5 m distance from the centre of each tree. During 1991, I and IL received a total of 919 mm and 936 mm irrigation water, respectively (Table 1). A complex nutrient solution was supplied weekly in the tube system in IL according to the forecasted needs of the stand (Ingestad, 1988). The total amounts of nutrient elements supplied in IL during 1991 were (kg ha⁻¹) 60 N, 20 P and 53 K.

In March 1992, i.e. 6 years after planting, total above-ground biomass was 84 kg, 99 kg, 130 kg and 142 kg per tree (or 9 m²) in D, F, I and IL, respectively. Corresponding stem biomass was 66 kg, 80 kg, 109 kg and 120 kg per tree. Total below-ground biomass was 24 kg, 23 kg, 27 kg and 40 kg per tree, of which fine-roots (diameter 2 mm or less) accounted for 1.4 kg, 1.7 kg, 1.9 kg and 3.0 kg per tree, respectively (Fabião et al., 1995).

2.2. Fine-root dynamics

Altogether, 42 minirhizotron tubes were installed vertically in the field trial between 7 and 16 March 1991. Seven trees were randomly chosen in each treatment. At 1.5 m distance from each of these trees, i.e. at half the distance to an adjacent tree, one tube was installed between the rows. In both I and IL we installed one additional tube within the rows, i.e. along the drip-tube, 1.5 m from the selected tree. Each set of seven tubes is called a 'location', of which there are one each in F and C, and two each in I and IL. These four locations are referred to as I(bet) and IL(bet), and I(in) and IL(in) for tubes installed between rows and within rows, respectively.

The minirhizotrons consisted of acrylic tubes (internal diameter 36 mm, external diameter 40 mm, length 1 m), that were sealed at the bottom with an acrylic lid (Andrén et al., 1991). A grid was painted on the tubes using fine-pointed, waterproof marker pens. Each tube was divided vertically into six equal sections of 21 mm; the horizontal sections were 20 mm.

Holes were drilled using a spade auger with an external diameter of 40 mm. The minirhizotrons were carefully inserted into these holes down to 950 mm depth. Plastic lids were used to shield the tubes from light and rain. To avoid condensation forming inside the minirhizotrons, a nylon bag filled with silica gel was fastened to a hook under each lid and replaced after each sampling occasion. The viewing unit described by Andrén et al. (1991) was used for making the observations.

Roots were counted 15 times between 15 May 1991 and 11 March 1992. Counts were made in three alternating of the six vertical sections in each tube until 3 October and in two sections (selected by chance) thereafter. The number of roots in each 21 mm × 20 mm square was counted. Roots coarser than about 2 mm in diameter were not counted. Further, it was not possible to distinguish between living and dead roots. Consequently, the root-counts refer to total fine roots (living and dead thinner than 2 mm). One branching root was counted as two roots, and a single root extending over several squares was counted several times, once in each square. Values were pooled for each tube, depth, sampling date and location, providing a data set of about 29 000 observations. The mean root depth (D_m) for each minirhizotron and date was calculated according to the following equation (Hansson and Andrén, 1987)

$$D_m = \sum(n_i D_i) / \sum n_i$$

where n_i is the root-counts at depth level i and D_i is the depth in centimetres at the middle of the observed depth level i .

2.3. Soil moisture measurements

Soil moisture was measured gravimetrically on seven dates between 16 May 1991 and 4 February 1992. Samples were taken at about 0.5 m distance from three randomly chosen minirhizotron tubes at each location at the depth levels 0–10, 10–20, 20–40, 40–60, and 60–90 cm. To convert the gravimetric water contents to volume base, dry soil bulk density values of 1.54 g, 1.54 g, 1.51 g, 1.59 g and 1.69 g cm⁻³ (M. Madeira, personal observation, 1992) were used for the corresponding depth strata from 0–10 to 60–90 cm.

Soil moisture was also monitored between 16 May 1991 and 6 March 1992 on 16 occasions using a capacitance probe (Malicki, 1983; Dean et al., 1987; Andr n et al., 1991) lowered into the 42 minirhizotron tubes. These moisture readings were made within 16 depth intervals to 90 cm depth. The measured depth strata ranged from 0–15 cm to 75–90 cm. Linear regression analysis was applied to calibrate the capacitance measurements with the gravimetrically determined measurements of soil moisture content as the independent regression variable. Corresponding depth levels were 0–10 and 0–15 cm, 10–20 and 5–25 cm, 20–40 and 20–40 cm, 40–60 and 40–60 cm, and 60–90 and 60–90 cm for gravimetric and capacitance measurements, respectively. Only the capacitance values of those tubes in the vicinity of gravimetric sampling points were included in the calibration. The slope and intercept of the regression ($n = 210$; $r^2 = 0.67$; $P < 0.0001$) for the calibration of the capacitance soil moisture measurements was 0.95 and -0.67 , respectively. The standard error of the estimated regression parameters was 0.05 and 0.33 for the slope and intercept, respectively.

2.4. Soil carbon content

Soil samples were taken in October 1990 at 15 randomly chosen sampling points at each of the six locations at the midpoint between trees, i.e. corresponding to the positions of the minirhizotrons. Soil carbon con-

tent was determined by dry combustion for 10 cm intervals down to 40 cm depth.

3. Results

3.1. Root counts

Mean root counts down to 93 cm depth increased during spring and summer 1991 at I(in) and IL(in) (Fig. 1). At the other locations, root counts remained fairly constant between May and August. In August they increased following a period of rainfall (24 mm). Mean root numbers peaked between late October and mid-November at all locations. Thereafter they decreased significantly at all locations until February or March 1992. On all sampling occasions except the first, mean root counts at the irrigated in-row locations were significantly larger than those at all other locations. In 1991, mean root counts at IL(in) were significantly greater than those at I(in) from spring up until the beginning of September. Root counts at the other four locations did not differ significantly on any of the dates. However, the dynamics at location F seemed to differ from that at C; i.e. root counts were smaller at F than at C until the end of August, thereafter, the relationship was reversed, however, differences were not statistically significant.

Mean root counts for each of the depth strata 0–10, 10–20, 20–40, 40–60, and 60–90 cm were calculated for all locations on all dates (not shown). The main difference in temporal dynamics between these five depth strata and their mean (Fig. 1) was the more pronounced increase of roots in F during September and October, especially at 0–10 and 10–20 cm depth. After a sharp increase in September, root counts in F remained significantly larger than those in C until March 1992, and were significantly larger than those in I(bet) and IL(bet) on some dates, at both 0–10 cm and 10–20 cm depth.

In early summer 1991 (30 May, 14 June, and 27 June), mean root depth at I(in) was significantly deeper than that at C (Fig. 2). During winter, mean root depth was deepest at F. To characterise the temporal trends in mean root depth, a linear regression model was fitted to the results from each location. The regression gradients were negative for C and F, and positive for the other four locations (r^2 ranged from

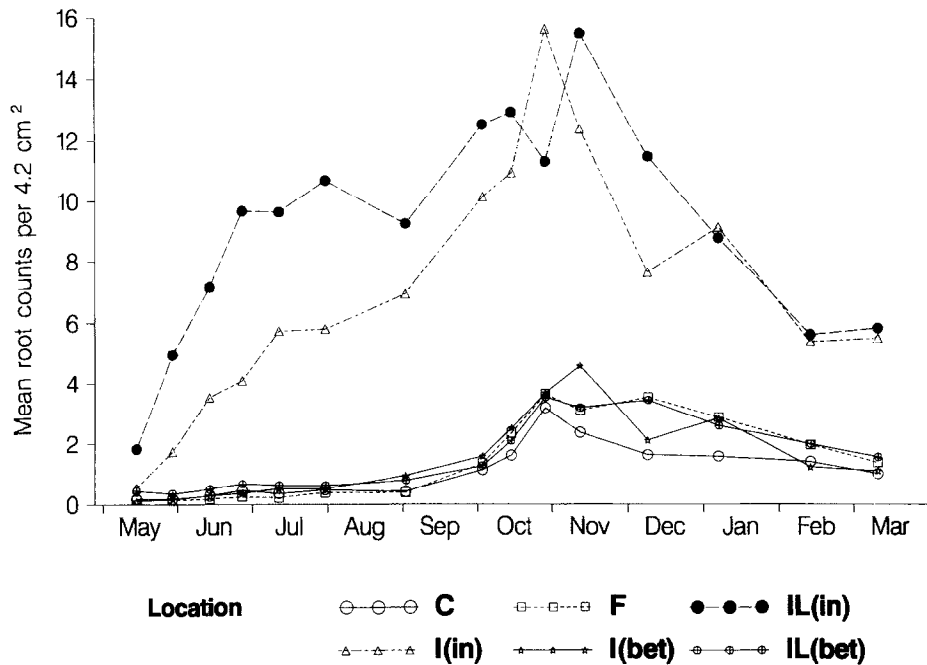


Fig. 1. Changes in the mean root counts per 4.2 cm² observation area in minirhizotrons from 0 to 93 cm depth between May 1991 and March 1992. Locations are: C, control; F, fertilized; I, irrigated; IL, irrigated and fertilized; the suffixes (bet) and (in) stand for 'between tree rows' and 'within tree rows', respectively.

0.07 to 0.91), i.e. while mean root depth was decreasing at C and F, it was increasing at all locations in the irrigated treatments.

The relative root-depth distributions at I(in) and IL(in), i.e. the percentage of the total root counts at each 2 cm interval (means over all sampling dates), are shown in Fig. 3. A larger percentage of the root system was located close to the soil surface in I(in) than in IL(in).

3.2. Soil moisture

The temporal dynamics of water (volume %) stored in the soil profile at the six locations down to 90 cm depth, i.e. the seasonal variation of the mean volumetric soil water content of 16 depth levels, is shown in Fig. 4. The impact of irrigation on soil moisture was pronounced until mid-October, when irrigation was stopped. Even after the irrigation period, the moisture contents were higher at I(in) and IL(in) than at the other locations. At the beginning and end of the

observed period (16 and 31 May 1991 and 6 March 1992), the within-row moisture content was significantly larger in IL than in I. In contrast, the relationship was reversed for between-row moisture content for the period as a whole. In both non-irrigated treatments, the soil water content decreased until the end of July. Thereafter it increased until mid-December owing to an increase in precipitation (Table 1). On average over all dates, the soil moisture content in treatment F was significantly lower than that at all other locations.

Generally, the water content at each depth level was similar to that of the mean water content of the whole profile (not shown). Even the temporal dynamics of soil moisture at each of the depth levels were strikingly similar to that of their mean. However, in the upper part of the soil profile (0–15 cm depth) the moisture content at I(in) was significantly larger than that at IL(in) on all sampling dates between 14 June and 14 October; this was also true at 5–20 cm depth on 26 July and 30 September. However, at 10–25, 15–30, and 20–35 cm depths, there was no significant difference in

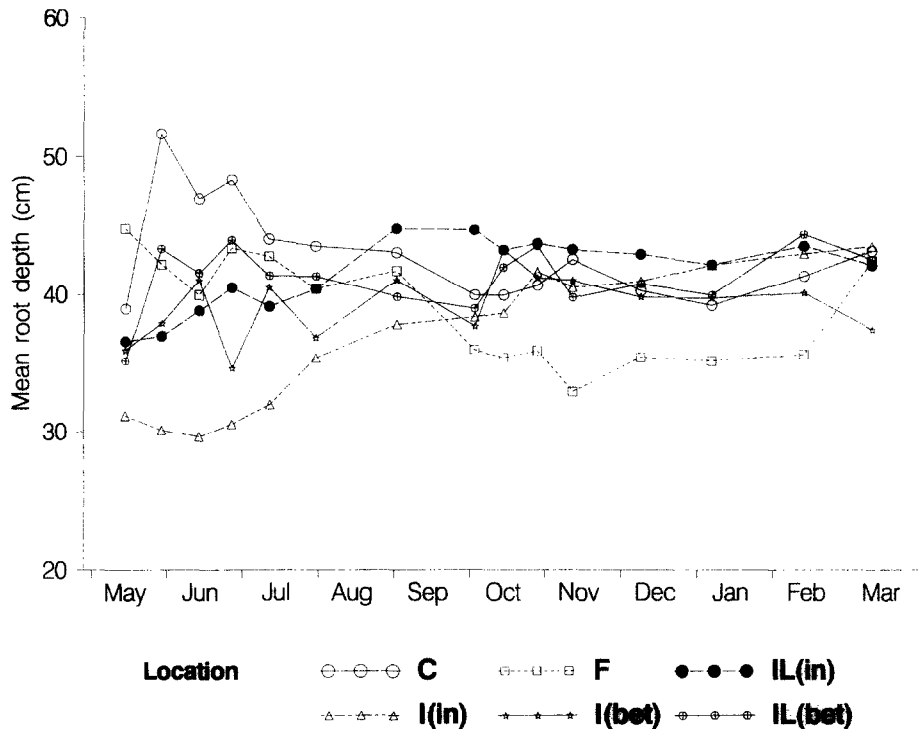


Fig. 2. Dynamics of mean root depth, measured in minirhizotrons, between May 1991 and March 1992. See Fig. 1 for explanation of abbreviations.

soil moisture between the two locations. At deeper levels, the soil water content was larger at IL(in) than at I(in) on several dates. During early summer, this difference was significant at almost all depths, as it was for the mean overall depth levels (Fig. 4).

3.3. Carbon content in soil

Whereas, relative to the soil carbon content in C, carbon content increased at 0–10 cm depth in F and at 0–20 cm depth at IL(bet), it decreased at I(bet), finishing at a level lower than the initial value in 1986 (Madeira and Pereira, 1990/1991) (Table 2). At I(in), the soil carbon content had increased in the upper 20 cm and was highest at 0–10 cm (0.77%). At IL(in) soil carbon content increased at all measured depths.

4. Discussion

In previous studies, angles at which the minirhizotron tubes were installed relative to the soil surface

varied from vertical to horizontal. Tubes installed at an angle between 30 and 45° seem to dominate in work on agricultural crops. Such angles have been favoured because a vertical installation is considered to lead to an underestimation and overestimation in the upper and lower soil layers respectively (Gregory, 1979; Bragg et al., 1983; Upchurch and Ritchie, 1983; Hansson and André, 1987; André et al., 1993). Because the minirhizotron tubes in our experiment were installed 1.5 m from the trees, the prevailing direction of root growth was probably horizontal. Therefore, the vertical installation was probably appropriate because the tendency of roots to follow the soil–tube interface should have been negligible and during field work, no such tendency was observed.

The autumn peaks in root counts at all locations conflict with the findings of other studies where root temporal dynamics have been examined for other tree species. For example, root growth in a Scots pine plantation in East Anglia peaked in April–May and then declined (Roberts, 1976). Lesham (1970) reported

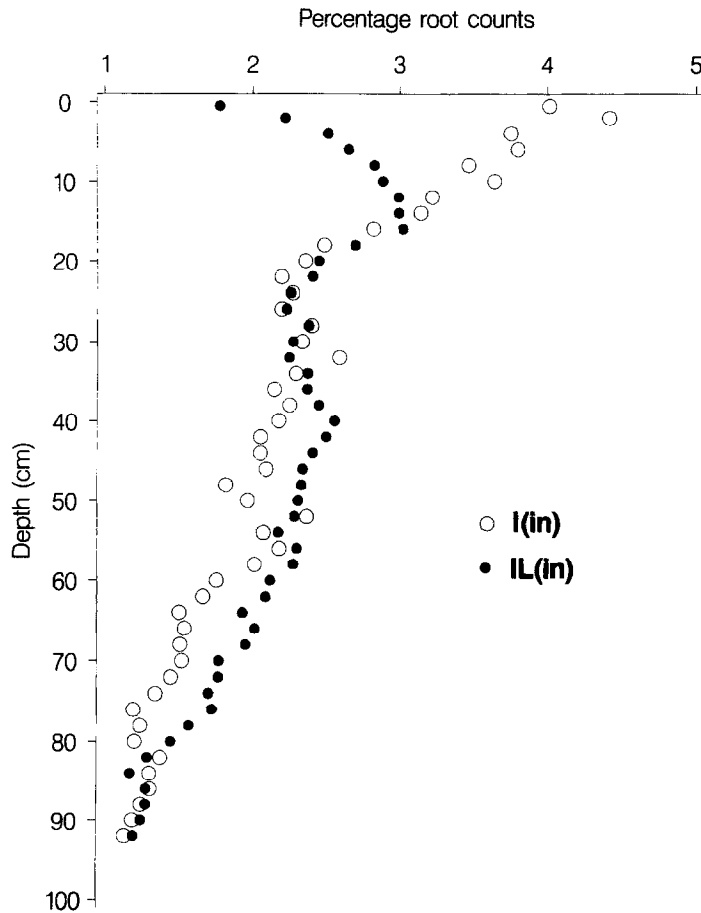


Fig. 3. Relative distribution of root counts at I(in) and IL(in), i.e. the proportions of root numbers (0–93 cm depth) accounted for at each 2 cm interval at each location (means over all sampling dates). See Fig. 1 for explanation of abbreviations.

considerable root growth during winter in a *Pinus halepensis* stand in Israel. In contrast, no distinct seasonal pattern was observed in a young Scots pine stand in central Sweden (Persson, 1978). Santantonio and Hermann (1985), who studied Douglas-fir stands in western Oregon, reported that during years with dry summers, numbers of new root tips generally peaked in the spring and autumn. No such pattern was found when rain occurred during the normal summer drought season. Fabião et al. (1985), who studied root dynamics in *Eucalyptus* stands in Portugal with the mesh-bag technique, reported substantial root growth between May and July. Root growth during winter was comparatively high, but lower than in early summer. Since

no root observations were made between March and May in this experiment, a peak in root growth in spring could have been missed. Soil water availability is probably the main factor responsible for changes in a species' inherent root growth strategy, as was concluded by Hansson et al. (1994). The root growth dynamics observed in I(in) and IL(in) suggest that net root growth is genetically possible between March and November if water is in ample supply. At the dry locations, root growth between April and August was almost nil owing to the low soil water content. The reason why the high root growth during early summer observed by Fabião et al. (1985) was not reflected in our observations at the non-irrigated locations was

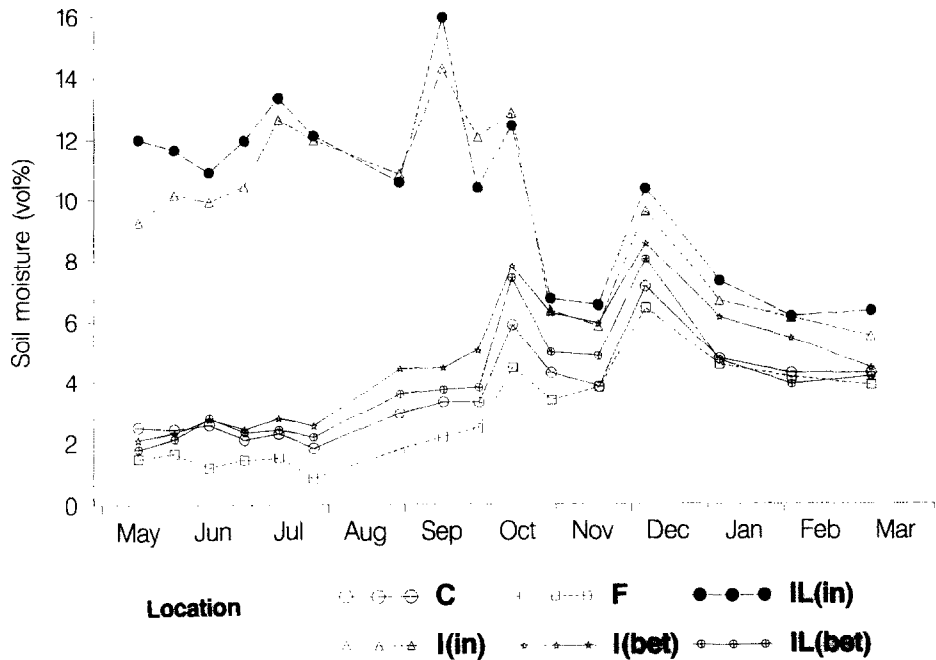


Fig. 4. Soil water dynamics from May 1991 to March 1992. Mean volumetric water content at 0–90 cm depth, calculated from capacitance measurements at 16 different depth levels and transformed according to the calibration with gravimetric samples. See Fig. 1 for explanation of abbreviations.

probably that the soil water stores were lower at our site because of the coarse texture of the soil. The decline in root counts after November occurred at all locations, i.e. root death and decomposition dominated over root growth.

Even on rather homogeneous sites, as in this study, spatial variability in moisture content can be large (Rajkai and Rydén, 1992). The standard deviations for the 210 means of capacitance and gravimetric data were as high as 59% and 80% of their means, respectively,

Table 2

Soil carbon content (% by weight) in October 1990, i.e. 54 months after planting, at various depths. Mean values and standard deviations in parentheses ($n=10$) at the locations C (control), F (fertilized), I (irrigated), IL (irrigated and fertilized); the suffixes (bet) and (in) stand for 'between tree rows' and 'within tree rows', respectively

Depth (cm)	Location						
	C	F	I(bet)	I(in)	IL(bet)	IL(in)	
0–10	0.25 (0.06)	0.34 (0.15)	0.20 (0.04)	0.77 (0.29)	0.32 (0.07)	0.76 (0.25)	
10–20	0.27 (0.11)	0.25 (0.12)	0.22 (0.05)	0.35 (0.08)	0.35 (0.16)	0.51 (0.16)	
20–30	0.28 (0.11)	0.30 (0.15)	0.23 (0.09)	0.38 (0.13)	0.28 (0.13)	0.47 (0.16)	
30–40	0.26 (0.15)	0.25 (0.08)	0.22 (0.05)	0.25 (0.11)	0.25 (0.13)	0.40 (0.16)	

which reflected the large spatial variability of the data. Nevertheless, the correlation coefficient of the calibration was acceptably high.

Besides the factors affecting the capacitance measurements discussed by Dean et al. (1987), the presence of roots may have also influenced them. Since root amounts were larger at I(in) and IL(in) than at the other locations (Fig. 1), the amount of water stored in root tissues at these two locations should have been larger, and thus soil water contents measured with the capacitance probe should also have been larger than at other locations. Furthermore, the moisture in the soil was not uniformly distributed. Canopy interception, precipitation throughfall and stem flow may have altered the distribution of water within the soil volume around the trees. I and IL received their irrigation water through drip-tubes. Since the drip-holes were 1 m apart, and the distance to the next tube was 3 m, the distribution of water in the soil volume was probably very heterogeneous. Finally, the minirhizotrons were installed midway between two trees within and between the tree rows, representing the driest and wettest points, respectively, in the trees' surrounding soil. The minirhizotrons' distance to the next drip-hole could have varied to some extent, thereby contributing to the variance of the data at the same location. However, since we were more interested in the variation in water content along the soil profile in the vicinity of the minirhizotrons than in absolute values for the whole field, the capacitance method was suitable for our purposes.

Soil moisture profiles reflect both the uptake of water by roots from different depths and its movement through the soil caused by gradients in water potential, which result from the removal of water by roots, evaporation, gravity and horizontal differences in water content, caused by drip-tube irrigation, among other factors. Consequently, a high overall correlation between soil water content and root counts should not be expected, particularly since their temporal dynamics are not synchronised, i.e. there were probably moist spots that had not yet attracted roots, moist spots that had already promoted root growth, and spots rich in roots that had been dried out by root water uptake (Andrén et al., 1991). However, for our future work the root and soil moisture data obtained here will provide needed inputs to models simulating heat and water conditions at the site.

During the non-irrigated period between November and March, the moisture content at the in-row locations of I and IL was about 2 vol% higher than it was at the other four locations. The higher water content could not fully be explained by the contribution of water stored in living roots. The increase of soil water content down to 1 m depth by 2 vol% corresponds to 2 kg water m^{-2} . The difference in root biomass (fine-roots only, or including intermediate and coarse roots) between the irrigated and non-irrigated treatments was less than 0.2 kg m^{-2} (Fabião et al., 1995). Even when considering a highly skewed distribution of roots between and within rows, the amount of water stored in roots probably did not exceed 0.4 kg water m^{-2} . The temporal dynamics of root counts, i.e. the large increase in fine roots during summer and autumn, and the decrease during late winter and early spring indicated that the input of dead roots to the soil was high, especially during the latter period, which probably resulted in a higher soil water holding capacity due to an increase in soil organic matter. It is now well established that root-derived material, as solids or solubles, is a major carbon input to the soil. For example, Atkinson (1985) observed that a large percentage of apple roots may become moribund within 4 weeks of initial root growth. Similarly, Roberts (1976) reported that the mean lifespan of Scots pine fine-roots (1 mm or less in diameter) was 4 weeks, but varied between 2 and 9 weeks. Root hairs may only persist for 2–3 days before being destroyed by microbes (Russell, 1977). Soluble exudate production can range from 1 to 10 g per 100 g of root dry weight increase (Newman, 1985).

The hypothesis that the input of carbon should have been highest at I(in) and IL(in) was confirmed by the fact that carbon content measured in the soil (Table 2) was highest at these in-row locations. In accordance with root counts (Figs. 1–3), the carbon content at IL(in) was higher than at I(in) at all depth levels below 10 cm on most sampling dates (Table 2). At 0–10 cm depth, however, both soil carbon content and root counts were higher at I(in) than at IL(in); the root counts at 0–10 cm depth were about 50% higher at I(in) than at IL(in) (Fig. 3). This difference in the depth distributions of both root counts and soil carbon content is interesting. Probably, nutrients followed the irrigation water down through the soil profile at IL(in), resulting in a generally deeper root distribution (Fig. 3) and an increase in soil carbon content at deeper

levels. At I(in), on the other hand, no fertiliser was supplied, and nutrient mineralisation was presumably concentrated in the upper 10 cm where the content of organic material was high. Mineralisation was presumably enhanced by the irrigation, resulting in higher root production and turnover compared with the non-irrigated locations.

The low soil moisture content in treatment F throughout most of the measurement period (Fig. 4) can be ascribed to higher water uptake in this treatment since the soil carbon content was the same or greater than at other non-irrigated locations. For many plant species, nutrient use efficiency is reduced by fertilisation (Ingestad, 1979; Lajtha and Whitford, 1989), which was probably the case in treatment F. Although water use efficiency appears to be inversely correlated with nutrient use efficiency in many species (Field et al., 1983; Lajtha and Whitford, 1989; Reich et al., 1989; DeLucia and Schlesinger, 1991), the higher above-ground production in F, compared with C (Fabião et al., 1995), should have also resulted in greater water losses from the soil in F owing to the higher rate of transpiration there.

Although the significantly higher root counts in shallow depth layers of F during September and thereafter (not shown), compared with all other non-irrigated locations, can explain the low moisture values during this period, they cannot explain why counts were also lower in spring and summer, when the difference in soil moisture between F and other locations was largest. Since the minirhizotron tubes were installed in April 1991, root counts reflected root growth after April. However, since fine-root accumulation up until April was not measured, we cannot exclude the possibility that the amount of fine roots at F was high even in spring, although almost no net root growth could be observed because the soil water content was too low.

The elevated soil carbon content at 0–10 cm depth at F, compared with C (Table 2), suggests that root turnover was higher at F than at the other non-irrigated locations at the same depths. This hypothesis is supported by the more pronounced temporal dynamics of root counts (Fig. 1), especially at this depth (not shown); the increase in root growth at shallow depth levels is reflected by the decrease in mean root depth that occurred after the rainfall period in August (Fig. 2).

Mean root counts at I(bet) and IL(bet) did not differ significantly on any of the dates. However, the soil carbon content was higher at IL(bet) (Table 2), probably because the turnover rate of roots was higher. This, in turn, can be attributed to the fact that the more nutrient rich litter at that location (M. Madeira, personal observation, 1992) should decompose faster than the litter at I(bet) (Swift et al., 1979). Another possible explanation for the higher carbon content at IL(bet) could have been the contribution of carbon from herbs and shrubs growing at IL(bet), whereas at I(bet) such vegetation was almost absent. The lower soil carbon content at I(bet) could not explain why the water content was higher at I(bet) than at IL(bet) throughout the observation period (Fig. 4). The only other logical explanation is that the transpiration-induced water demand in treatment IL was higher, since above-ground production in this treatment was higher (Fabião et al., 1995).

Before the *Eucalyptus* stand had been planted, the soil carbon content was very small, varying between 0.23 and 0.28% in the layers down to 70 cm depth (Madeira and Pereira, 1990/1991). By autumn 1988, 30 months after planting, the soil carbon content had almost doubled at 0–10 cm depth at the in-row locations in the irrigated treatments (Madeira and Pereira, 1990/1991). However, increases at deeper depth layers were moderate and non-significant, as were the increases in F at all depth levels. The trend indicated by the results from autumn 1988, i.e. generally, no change in soil carbon content at C, moderate increases at F, larger increases in treatment I (mean of I(in) and I(bet)) and the greatest increases in treatment IL (mean of IL(in) and IL(bet)), was confirmed by our measurements in 1990. For testing the hypothesis that the increases in soil carbon content was caused by root turnover, IL(in) was selected, where this increase was largest. During a 54 month period, the soil carbon content down to 40 cm depth at IL(in) had increased by 0.28% by mass (Table 2), i.e. by about 0.43 vol%, or about 1.7 kg C m^{-2} . Consequently, the annual average increase was about 0.38 kg C m^{-2} . The maximum number of roots, counted in the minirhizotrons on 29 November, was about three times higher than root counts in March 1992. Fine-root biomass in March at IL(in) contained approximately 0.15 kg C m^{-2} , assuming 50% carbon concentration in the fine-roots (calculated after Fabião et al., 1995). Assuming the

same dynamics in fine-root biomass as observed in the minirhizotrons, fine-root biomass contained about 0.45 kg C m⁻² at its maximum. The corresponding amount in treatment C, where the soil carbon content had not changed during the 54 month period, was 0.15 kg C m⁻². We can make the following five assumptions: (1) fine-root growth and mortality during the previous years was similar; (2) the mean lifespan of an individual root is about 5 months; (3) the decomposition rate of dead fine-roots is 50% year⁻¹; (4) 50% of the remaining carbon is available for decomposition during the following year; (5) 50% is being stabilised as recalcitrant organic carbon. Then the higher annual carbon input via root-turnover at IL(in) compared with treatment C (0.3 kg m⁻²) could fully explain the measured increase in soil carbon content, i.e. about 0.38 kg m⁻². Therefore, the tested hypothesis, that the increase in soil carbon content was caused by root turnover, may be true.

Later analyses of soil organic matter quality (carbon:nitrogen ratio) and cation exchange capacity (CEC) in the soil will show whether the trends for these parameters correspond to that for soil carbon content. If this is the case, there would be no doubt that soil fertility has been improved through irrigation and repeated nutrient application.

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