Spatial distribution of *Eucalyptus* roots in a deep sandy soil in the Congo: relationships with the ability of the stand to take up water and nutrients†

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**Summary** Spatial statistical analyses were performed to describe root distribution and changes in soil strength in a mature clonal plantation of *Eucalyptus* spp. in the Congo. The objective was to analyze spatial variability in root distribution. Relationships between root distribution, soil strength and the water and nutrient uptake by the stand were also investigated.

We studied three, 2.35-m-wide, vertical soil profiles perpendicular to the planting row and at various distances from a representative tree. The soil profiles were divided into 25-cm² grid cells and the number of roots in each of three diameter classes counted in each grid cell. Two profiles were 2-m deep and the third profile was 5-m deep.

There was both vertical and horizontal anisotropy in the distribution of fine roots in the three profiles, with root density decreasing sharply with depth and increasing with distance from the stump. Roots were present in areas with high soil strength values (> 6000 kPa). There was a close relationship between soil water content and soil strength in this sandy soil. Soil strength increased during the dry season mainly because of water uptake by fine roots. There were large areas with low root density, even in the topsoil. Below a depth of 3 m, fine roots were spatially concentrated and most of the soil volume was not explored by roots. This suggests the presence of drainage channels, resulting from the severe hydrophobicity of the upper soil.

**Keywords:** forest, plantation, root system, root distribution.

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**Introduction**

It is well known that *Eucalyptus* spp. can access water in deep soil layers and can deplete groundwater in catchments by extending roots to the water table (Cohen et al. 1997, Le Maitre and Versfeld 1997). Indirect methods, especially isotopic techniques, have been used to determine the depth at which water and mineral uptake by trees occurs (Farrington et al. 1996, Dambrine et al. 1997). However, there are few accurate descriptions of root system distribution of forest plantations growing in deep soil. Such information is essential to model water flows in the soil and to interpret variability in soil nutrient concentration (e.g., Bruckler et al. 1991). Knowledge of root system characteristics may also inform the choice of silvicultural practices (weeding and fertilization) to optimize water and nutrient uptake by the stand.

The aim of this study was to analyze accurately the spatial variability of root distribution within the environment of one representative tree in a mature *Eucalyptus* stand. Relationships between root distribution, soil strength and the characteristics of water and nutrient uptake by the stand were investigated.

**Materials and methods**

**Study site**

*Eucalyptus* plantations extend along the Atlantic coast (Bas-Congo) of the Congo for about 30 km inland, at 4° S, 12° E. The climate in this region is characterized by high relative humidity (mean 85%) with low seasonal variation (2%) and a mean annual rainfall of 1200 mm with a dry season from May to September. Mean annual temperature is high (25 °C) with seasonal variations of about 5 °C.

Most plantations are located on a plateau between 80 and 120 m elevation. The geological bedrock is composed of thick detrital layers of continental origin dated from the Plio-Pleistocene (Jamet 1975). The soils are arenosols (FAO classification) characterized by their depth, color (from grayish in upper soil layers to ochre in deep layers), texture (sand content over 85%), low ionic content (Table 1) and poor water retention.

**Plant material**

The stand was planted at 4.7 × 4 m spacing in a flat zone with...
one of the most productive clones of the *Eucalyptus* PF1 hybrid. These clones were obtained from natural crosses between two or three individuals of *Eucalyptus alba* Reinw. *ex* Blume (female tree) and a group of poorly identified eucalypt hybrids (male tree) that came from a Brazilian arboretum (Delwaulle 1988).

Before planting, the savanna was burned, the soil ripped into planting rows, and an initial fertilization (150 g of N:P:K; 13:13:21 per cutting) was applied. Chemical weeding was carried out three times, resulting in depressions at the soil surface from vehicle tracks. The stand was 6.5 years old at the time of our study in July 1998. Mean tree height was 27.1 m and mean stem circumference (diameter at breast height) was 61 cm.

**Spatial distribution of roots**

One tree with a basal area corresponding to the mean basal area of the stand was selected. Three vertical soil profiles perpendicular to the planting row at various distances from this representative tree were studied (Figure 1). Vertical profiles were divided into 5 × 5 cm grid cells and, in each grid cell, roots were exposed by using a small knife to remove the surrounding soil. We used the root impact counting method (Tardieu 1988), where root impact is defined as any intersection of a root with the vertical profile under study. The number of intersections of roots in each of three diameter classes (fine roots between 0.1 and 1 mm, medium-sized roots between 1 mm and 1 cm, and big roots over 1 cm) were counted in each grid cell. The soil profiles at a distance of 2 m from the representative tree in the planting row (P2) and under the stump (P0) were 2 m deep and 2.35 m wide (half of the distance between planting rows). Root impacts in the soil profile at 1 m from the tree (P1) were counted to a depth of 5 m.

In this stand, recent litter fall was closely associated with the dense root mat covering the mineral soil. As a result, it was not possible to count root impacts in the forest floor because of the soil characteristics in the *Eucalyptus* stand (reference to air-dry material, except for particle size and element analysis expressed for material dried at 105 °C).

<table>
<thead>
<tr>
<th>Soil layer (cm)</th>
<th>Particle size distribution (%)</th>
<th>N tot (%)</th>
<th>C/N</th>
<th>Total elements (%o)¹</th>
<th>CaO</th>
<th>MgO</th>
<th>K2O</th>
<th>P</th>
<th>Al2O3</th>
</tr>
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<tbody>
<tr>
<td>A11 0–5</td>
<td>3</td>
<td>3.6</td>
<td>93.4</td>
<td>1.14</td>
<td>0.47</td>
<td>14.0</td>
<td></td>
<td></td>
<td>0.11</td>
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<tr>
<td>A12 5–70</td>
<td>4</td>
<td>3.7</td>
<td>92.3</td>
<td>0.66</td>
<td>0.31</td>
<td>12.3</td>
<td></td>
<td></td>
<td>0.09</td>
</tr>
<tr>
<td>B1 70–120</td>
<td>3</td>
<td>6.3</td>
<td>90.7</td>
<td>0.36</td>
<td>0.18</td>
<td>11.7</td>
<td></td>
<td></td>
<td>0.16</td>
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<tr>
<td>B2 120–200</td>
<td>1.8</td>
<td>5.9</td>
<td>92.3</td>
<td>0.19</td>
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<td>11.0</td>
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<tr>
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<td>3</td>
<td>6.5</td>
<td>90.5</td>
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<td>0.18</td>
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<tr>
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<td>7.4</td>
<td>88.7</td>
<td>0.12</td>
<td>0.09</td>
<td>8.6</td>
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</table>

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<th>Soil layer (cm)</th>
<th>pH²</th>
<th>Exchangeable cations (cmol, kg⁻¹)³</th>
<th>BC⁴</th>
<th>CEC⁵</th>
<th>BC/CEC (%)</th>
<th>P avail.⁶ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>K</td>
<td>Ca</td>
<td>Mg</td>
<td>Mn</td>
<td>Na</td>
</tr>
<tr>
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<td>0.11</td>
<td>0.08</td>
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<tr>
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<td>0.01</td>
<td>0.08</td>
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<tr>
<td>B3 200–400</td>
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<td>0.01</td>
<td>0.08</td>
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<tr>
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<td>0.08</td>
<td>0.02</td>
<td>0.01</td>
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</tr>
</tbody>
</table>

¹ Acid digestion and ICP determination of elements.
² pH in water.
³ Cobalti-hexamine extraction, ICP determination of cations.
⁴ BC = Sum of base cations.
⁵ CEC = Cation exchange capacity.
⁶ Duchaufour and Bonneau (1959) method.

**Table 1.**
high root density. Therefore, forest floor material was collected in 12 randomly chosen quadrats (0.25 m²) and roots were separated by hand and dried at 65 °C to assess the biomass of the root mat on the forest floor.

Soil strength and soil water content

Soil strength was measured in each profile every 10 × 10 cm for P0 and every 10 × 20 cm for P1 and P2, to a depth of 2 m. Soil strength measurements and root impact counting were both performed during the same period of the dry season. A hand penetrometer (06.01 Set B, Eijelkamp Agrisearch Equipment, Giesbeek, Netherlands) was used with a 2 cm² cone in the first 10 cm of the upper soil and a 1 cm² cone for depths > 10 cm. The cone was horizontally inserted in the vertical soil profile by applying constant pressure on the grips. The speed of penetration was about 2 cm s⁻¹ and the depth of penetration was 4 cm.

During the rainy season, 40 soil cores were collected at depths between 0.50 and 1.50 m with polyethylene cylinders (10 cm in diameter and 15 cm long). Soil strength and water content were measured every day in five randomly chosen soil cores, as they air-dried over 7 days. The Eijelkamp hand penetrometer was used with cones of 3.33, 2 and 1 cm², according to the soil strength of the cores.

Water flows in the soil

Five replicate TDR (Time Domain Reflectometry) probes were inserted horizontally in the soil at depths of 0.15, 0.50 and 1 m and three replicates were inserted at depths of 2, 3, 4 and 5 m. Soil water content was measured every 3 h from July 1998 to July 1999.

Soil water potential was measured from February to July 1999 with three replicate tensiometers located at depths of 0.15, 0.50, 1 and 2 m. The replicate TDR probes and tensiometers were inserted to take account of the spacing of the soil profiles from the planting row.

Soil solution chemical properties

In December 1997, throughfall was collected with three replicates each of three gutters (1.90 m × 0.16 m), which were placed in such a way as to integrate the heterogeneity of the forest canopy. Four replicate lysimeters were also installed at various distances from the planting row in the forest floor (zero tension lysimeter) and at depths of 0.15, 0.50, 1, 2, 3, 4 and 6 m (porous cup-lysimeters were maintained at a suction of 600 hPa). Changes in calcium concentration in the soil solution were determined. This nutrient was chosen because the calcium requirements of mature stands are large (Laclau et al. 2000). Soil solutions were collected once a week from April 1998 to April 1999, stored at 4 °C and mixed every 4 weeks. Calcium was measured by inductively coupled plasma (ICP) emission spectroscopy in each replicate following filtration (0.45 µm).

Statistical analyses

The numbers of intersections of fine and medium-sized roots per grid cell are presented as fine root density (FRD) and medium-sized root density (MRD).

In each profile, FRD and MRD distributions were analyzed based on spacing from the planting row, depth and soil strength. Two statistical tools were used to map FRD, MRD and soil strength.

Automatic classification was performed in each profile (TREE procedure using SPLUS software (MathSoft, Inc., Seattle, WA)). This technique builds an explicative model of root density according to the spatial coordinates of the values observed. The algorithm divides the profile into areas based on variability for the variable by successive dichotomy on both coordinates, detecting the threshold at which the criterion of deviance is optimum (Breiman et al. 1984).

Kriging was performed in each profile using ISATIS software (Geovariances SA, Avon, France). This method is based on the experimental variogram expressing the variance of the values measured according to the spacing and direction between measurements (Goovaerts 1997). The kriged value of a variable z for a point s_i is given by the equation:

$$z(s_i) = \sum_{i=1}^{n} \alpha_i z(s_i),$$

where n is the number of measured values and s the number of observed sites. Kriging calculates the weights \(\alpha_i\) in order to obtain an unbiased estimation error with minimal variance (Isaaks and Srivastava 1989).

After modeling the variogram, kriging makes it possible to assess the values that were not measured and smooths the data, thus preserving the main spatial features of the variable, including independence and anisotropy.

Additionally, a one-way analysis of variance was performed on calcium concentrations in the soil solutions by the GLM procedure of the SAS statistical software package (SAS Institute, Cary, NC).

Results

Spatial distribution of fine roots

Distribution of roots in the upper 2 m of soil

The fine root density (FRD) automatic classification showed high heterogeneity in each profile and among the three profiles (Figure 2). The main difference among the profiles was a high FRD in P0 under the stump down to a depth of 2 m. Outside of this area, the FRD distribution between 20 cm and 2 m depth was similar in the three profiles. There was a significant decrease in FRD with depth in all three profiles. In all profiles, the surface soil layer (5–10 cm depth) was characterized by a high FRD. The FRD generally decreased from the planting row to the middle of the inter-row in this surface layer. Despite this gradient, there were some sharp local increases in FRD in the upper soil under the depressions caused by the tractor wheels.

Under the surface soil layer, there was a 10–20-cm-thick
layer with an FRD value about half that observed in the upper layer. A layer extending to a depth of 70–80 cm with intermediate FRD values was observed in all three profiles. Below this layer, FRD continued decreasing to a depth of 2 m. Automatic classification indicated that distances from the planting row had no strong influence on FRD in the deep layers except under the stump.

**Distribution of roots in the profile P1 to a depth of 5 m**  
The number of root impacts counted in the first 15 cm of surface soil accounted for 24, 55 and 75% of the total root impacts down to 5, 1 and 2 m depths in P1, respectively. Kriged maps of FRD showed a concentration of fine roots below a depth of 2 m and also demonstrated that most of the soil volume at a depth of 2.5 m was not explored by fine roots (Figure 3). The areas where roots were concentrated tended to be vertically aligned. In addition, auger sampling to a depth of 12 m demonstrated that fine roots were present down to at least 9 m.

Areas with very low FRD were found in the three profiles, even in the upper layers (Figure 3). The FRD gradient was vertical in P2 and became oblique close to the stump with an angle of about 45° in P0. This result was confirmed by the results of the variogram analysis (data not shown). The FRD increased under tractor wheel tracks at a distance of about 1.80 m from the planting row in all three profiles. However, the tractor wheel tracks did not seem to have a marked influ-
ence on FRD at other distances from the planting row.

**Spatial distribution of medium-sized and large roots**

Lateral roots exhibited high root impacts. Only the spatial distribution of medium-sized roots was analyzed, because large roots were found only in profile P0 under the stump.

Automatic classification revealed a high variability in MRD between and among profiles (Figure 4). The MRDs were similar in profiles P1 and P2, and decreased sharply with depth. In both profiles, the highest MRD values were measured in the upper 20 cm of soil, at distances between 35 and 80 cm from the middle of the inter-row.

The distribution of the density of medium-sized roots (MRD) to a depth of 2 m close to the stump (Profile P0) differed from that observed in P1 and P2. Automatic classification for P0 showed no influence of depth on MRD except under the stump. Automatic classification revealed a strong influence of distance from the planting row on MRD, with higher MRD values under the stump. Beyond 40 cm from the planting row, MRD in P0 was similar to the values observed in P1 and P2 between 0.20 and 2 m in depth.

Kriged maps of MRD confirmed that the distribution of medium-sized roots in the first 2 m of the upper soil was similar in P1 and P2 (Figure 5). Medium-sized roots were rare below a depth of 2 m, and they were generally concentrated in the same areas as fine roots.
Soil strength

Spatial variability  Kriged maps of soil strength showed that the highest soil strengths occurred at a depth of about 1 m in the three profiles and that soil strength decreased sharply below a depth of 1.50 m (Figure 6). Soil strength was generally < 2000 kPa in the upper 5 cm of the surface soil. It was below 5000 kPa between depths of 5 and 50 cm, with a large variability depending on distance from the planting row. In profiles P1 and P2, a low soil strength close to the planting row was the result of subsoiling carried out at a depth of 50 cm before planting. In the three profiles, there was no relationship between soil strength of the topsoil and tractor wheel tracks.

Relationship between soil water content and soil strength  There was a sharp increase in soil strength as the undisturbed soil cores dried out in the cylinders (Figure 7). In the field, TDR probes indicated that the soil water content was at the wilting point (the soil water content at which plants become unable to absorb soil water) to a depth of between 1 and 2 m at the time of study. Because the soil water content of the soil below a depth of 1.50 m was higher than that of the soil above a depth of 1.5 m, the increase in soil water content could account for the decrease in measured soil strengths at depths > 1.5 m (Figure 6).

Relationship between root density and soil strength  Values of FRD of between 1 and 4 were found in the three profiles over a large range of soil strengths (0–6000 kPa), indicating that soil strength did not prevent root development (Figure 8). Values of FRD between 0 and 6 were observed in areas with high soil strengths (> 6000 kPa). Areas exhibiting low soil strength in the upper soil had the highest FRD (> 6). Between depths of 0.50 and 2 m, soil strength tended to increase in the three profiles when FRD increased, although variability was high (data not shown).

In P1 and P2, medium-sized roots occurred in a much more limited range of soil strengths than fine roots, between 2000 and 6000 kPa. In P0, medium-sized roots were also found in the upper soil layer with very low soil strength.
Spatial variability of water flows in the soil

Measurements of soil water content showed a high spatial heterogeneity in drainage. One replicate of the TDR probes located in an area of preferential drainage showed drainage to a depth of 4 m after the first rain (80 mm) following the dry season, whereas the other replicate probe showed drainage to a depth of only 1 m (Figure 9). During the rainy season, heterogeneity in soil water content was high in the first 2 m of the surface soil but was more homogeneous below 3 m. Drainage under the stump was much less developed than in the inter-row, and there was a preferential penetration pathway located under a depression about 1 m from the planting row.

One of the three replicate tensiometers was inserted in a preferential drainage channel. Measurements of the soil water potential to a depth of 2 m indicated that drying out at the beginning of the dry season occurred much more quickly in this area than in the other areas sampled.

Changes in calcium concentrations of the soil solution

The highest calcium concentrations in throughfall were measured during the dry season (Figure 10). Calcium concentrations were systematically lower under the forest floor than in throughfall. Calcium concentrations in leachates decreased sharply with soil depth, with concentrations in the soil solution collected at a depth of 15 cm significantly lower ($P < 0.001$) than those under the forest floor. However, there was no significant difference at the 5% threshold between solutions collected at depths of 0.15 and 4 m.

Discussion

We demonstrated high spatial heterogeneity in the distribution of Eucalyptus roots and a decreasing root density with soil depth (cf. Santantonio et al. 1977, Nambiar 1983). The trees had an extensive network of fine roots (about 500 kg ha$^{-1}$) at the forest floor in contact with forest litter.

Water and nutrient uptake by the stand

Changes in calcium concentration indicated that the stand was able to take up nutrients quickly from both the forest floor and the upper soil layer. Severe hydrophobicity at the soil surface increased the period of water contact with organic litter comprising the forest floor. Thus, hydrophobicity improved the ability of the stand to take up water and nutrients from the forest floor after brief rain events (generally less than 1 mm) during the 5-month dry season. A comparison between calcium concentrations under the forest floor and in the soil solution collected at depths of 0.15 and 4 m indicated a strong uptake of calcium by the Eucalyptus root systems in the upper soil layer. Low calcium concentration in the soil solution collected at a depth of 4 m, where root density was very low, indicated that the release of calcium by weathering was low in this sandy soil.

When the study stand was 5.5 years old, Sana (1997) used sap flow methods to compare the depletion of soil water reserve with tree transpiration. He reported that most soil water uptake during the dry season occurred down to a depth of 5 m. In pine plantations on deep sandy soils, it has also been shown that roots in the subsoil play a major role in supplying water to trees when the surface soil is dry (Nambiar and Sands 1992). In our study, the root distribution supported stem growth increments of 26 m$^3$ ha$^{-1}$ year$^{-1}$ at 7 years of age, despite the low availability of nutrients and water in the soil during the 5-month dry season.

Influence of soil strength on root distribution

Sands et al. (1979) showed that root distribution of radiata pine (Pinus radiata D. Don) in a sandy soil varied according to soil strength, and that root growth stopped at soil strengths over 3000 kPa. In our study, Eucalyptus roots were found in soils compacted to over 6000 kPa. However, during the wet season, all of the soil was moistened and its strength remained below 3000 kPa regardless of depth. The presence of fine roots in dry soil exhibiting high soil strength might be associated with exploration of the soil by roots during the wet season, whereas the uptake of water by fine roots during the dry season causes drying of the soil, thereby increasing its strength.

![Figure 10. Changes in calcium concentrations in the solutions collected in the Eucalyptus ecosystem.](http://heronpublishing.com)
Influence of distance from the nearest tree

Roots preferentially explored the soil under the stump, but root density decreased sharply below 50 cm under the stump. In a 46-month-old radiata pine plantation, Nambiar (1983) observed the opposite trend, with root density increasing at the midpoint of the row, suggesting that the roots of trees from adjacent rows were intermingling. In our study, mean stemflow was 1.5% of incident rainfall, and nutrient concentrations in stemflow were much higher than in throughfall. Under the stump, roots were located in an area of preferential water input, which transported large amounts of nutrients.

Relationships between fine root distribution and stand nutrition

The ability of *Eucalyptus* fine roots to concentrate under areas of preferential infiltration might explain both the root distribution observed, and the rapid drying of the soil in areas of preferential drainage. High FRD in preferential drainage channels could result from both low soil strength in wetter areas of the soil, and high nutrient inputs in the soil solution transported by gravity to these areas. In this sandy soil with low weathering fluxes, nutrients in the leachates represented a large portion of the nutrients available to the stand.

Drainage channels in this sandy soil may result from the severe hydrophobicity of the surface soil. Ritsema (1998) has shown that, in sandy soils in The Netherlands, hydrophobicity leads to preferential drainage channels under areas where hydrophobicity is low. After successive rainfalls, drainage systematically occurs in the same areas, and becomes uniform beyond a specific depth. Although trees were planted in a flat zone, hydrophobicity of the topsoil might have caused runoff toward the depressions where infiltration occurred. Hydrophobicity might thus explain the sharp increase in FRD observed under depressions caused by tractor wheels.

In summary, we found a dense root mat in the forest floor, a high density of fine and medium-sized roots in the first 20 cm of the upper soil, and a marked decrease in root density in deep soil layers. Roots were found in areas with high soil strength. However, the soil strength of these areas decreased during the wet season, allowing the roots to grow.

Severe hydrophobicity at the soil surface might account for the preferential drainage channels in the soil. The ability of *Eucalyptus* fine roots to concentrate in these areas might explain the rapid nutrient uptake observed in soil solutions, which would help to reduce nutrient losses caused by deep drainage. This root distribution allows high wood production on a nutrient-poor soil. We conclude that these plantations play an important role in nutrient dynamics of the soil. Large amounts of nutrients transferred to the drainage channels are lost by deep drainage if they are not taken up by the dense network of fine roots in the soil upper layer (Bouillet et al. 1997).

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