Influence of controlled water supply on shoot and root development of young peach trees

N. A. HIPPS, 1,2 L. PAGÈS, 1 J. G. HUGUET 1 and V. SERRA 1

1 Station d’Agronomie, Centre de recherches d’ Avignon, Domaine Saint-Paul, 84143, Montfavet, France
2 Present address and corresponding author: Horticulture Research International, East Malling, West Malling, Kent ME19 6BJ, U.K.

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Summary Three controlled water supply treatments were applied to 1-year-old peach trees grown in root observation boxes. The treatments were: I 0, growth medium maintained at 50% field capacity; I 1, water supplied when daily net tree stem diameter change was negative or zero for 1 day; I 3 as for I 1 except that water was applied after net daily stem diameter change was negative or zero for 3 consecutive days.

Trees in treatment I 0 had the greatest mean daily first-order shoot growth rates, and trees in treatment I 3 had the lowest shoot growth rates. Because leaf production rate (apparent plastochron) of first-order shoots was unaffected by treatment, differences in shoot length were due to differences in internode extension and not to the number of internodes. Trees in treatment I 0 had a greater number of second-order shoot axes than trees in treatment I 1 or I 3. Furthermore, an increase in the rate of growth of the first-order shoot axis was associated with an increased tendency for branching (i.e., the development of sylleptic second-order shoots). Increased leaf length was also associated with more frequent watering.

Trees in treatment I 3 had the greatest root lengths and dry weights, and this was attributed to a greater number of first- and second-order (lateral) root axes compared with trees in the I 1 and I 3 treatments. The extension rate and apical diameter of first-order roots were reduced by the I 3 treatment. The density of second-order roots along primary root axes was not affected by any of the treatments.

Keywords: drought, internode extension, irrigation, leaf length, leaf production rate, Prunus persica, root branching, root diameter, root growth rate, shoot branching, shoot growth rate, stem diameter.

Introduction

In Mediterranean climates, the horizon near the soil surface becomes dry during spring and summer, and irrigation is often supplied soon after transplanting seedlings to alleviate the risk of drought stress. Localized irrigation increases the overall density of roots of mature fruit trees in the wetted zone of a soil and increases shoot extension (Goode et al. 1978, Levin et al. 1979, 1980, Huguet and Fourcade 1980, Hipps 1992). ‘Luxury’ root development in response to irrigation, that is, surplus to the minimum required to maintain shoot development can occur. Tan and Buttery (1982) reported that when 50% of the root system of peach seedlings were well supplied with water, nearly enough water was absorbed to meet the entire needs of the plants. A root system architecture with greater plagiotropic branching near the surface at the expense of less root growth lower in the soil profile is undesirable, because it is essential for long-term survival that roots penetrate quickly to access deep soil water reserves. Furthermore, deep roots may help maintain the surface root system when the surface soil dries (Glenn and Welker 1993). However, these relationships are not always simple. Cutting plagiotropic first-order lateral roots of loblolly pine (Pinus taeda L.) had a greater negative effect on leaf conductance and water potential than cutting only the deeper roots, because plagiotropic first-order laterals had both surface- and deep-growing second-order laterals able to tap a larger soil volume for water (Carlsen et al. 1988).

The relationships between drought stress and shoot and root development have often been studied using a gross morphological approach. Growth has been characterized by variables such as total length of shoots and roots, total number of leaves, and shoot and root dry weights. An architectural approach to leaf and root development has been used rarely (e.g., Remphrey and Powell 1985, Powell and Vescio 1986). Steinberg et al. (1990) reported that drought stress causes a reduction in total leaf production and lateral branching of young peach trees, but no distinction was made between leaves developed on first-order and second-order shoots, and no architectural analysis of the root system was presented.

The morphology of the tree can be analyzed in terms of (1) the development of the apical meristem, which itself can be separated into the processes of organogenesis (plastochronal activity) and extension activity (growth) (Crabbe 1987), and (2) the structure of its organs. The shoot system is made up of individual shoots of different branching orders. The shoots are composed of repetitive units called metamers. The meristem is defined as node + leaf + axillary meristem + internodal segment (White 1979). For roots, the meristem is less clearly defined (Barlow 1989); however, the root system can easily be broken down into different branching orders that may have different morphogenetic characteristics (Coutts 1987).

In woody species, drought stress has been assessed by meas-
uring shrinkage of the tree stem (Schroeder and Weiland 1956). By monitoring (1) the decrease and cessation of daily growth in stem diameter, and (2) the daily shrinkage, which increases as water stress becomes more severe, Huguet et al. (1992) were able to study water stress during the vegetative growth phase of peach trees. We used a structural analysis of the root and shoot system and measurement of stem shrinkage to examine the effects of three different irrigation regimes on shoot and root development in young peach transplants.

Methods

The experiment was conducted in a greenhouse at the Avignon INRA Centre in southern France. Twelve 1-year-old homozygous peach (Prunus persica (L.) Batsch.) rootstocks cv ‘GF305’ with a basal diameter of 10–12 mm were selected for uniformity in size and shape. The stem and top root of each selected tree were pruned to 30 and 15 cm, respectively. Three thick lateral roots were pruned to 7.5 cm, and all other roots were removed. One tree was planted in each of twelve root observation boxes (i.e., one tree per box) on March 29, 1993. After planting, three first-order shoots (originating directly from the stem) per tree were allowed to grow and all others were removed at the bud stage.

Each root observation box had a capacity of 5.3 l (internal dimensions 27 × 2.5 × 78 cm) and was made of PVC except for one side (27 × 78 cm) that was made of transparent polycarbonate and through which the roots could be observed when an outer, nontransparent plastic cover was removed. Each root box was filled with 488 g (dry weight) of substrate, a 2/1 (v/v) mixture of perlite and ‘Floragard TRS 2 Instant’ potting compost, sieved to less than 5 mm. Field capacity, determined as the water held by the substrate after free drainage for 24 h, was 4.2 g H$_2$O g$^{-1}$ substrate. The substrate was initially maintained at 50% field capacity (2.1 g H$_2$O g$^{-1}$ substrate) in all of the boxes. Five cm of expanded burnt clay granules (8–16 mm diameter) was placed on top of the medium as a mulch to reduce water loss by evaporation. The boxes were placed at an angle of 15° from the vertical, with the transparent face on the underside, and protected from direct sunlight by reflective aluminum foil.

Changes in stem diameter were continuously recorded with Linear Variable Differential Transformers (LVDT, DFG/5.0 Solation Metrology, Bagnor Regis, U.K.) connected to Pepista dataloggers (Copa Informatique, St. Etienne du Gres, France). The sensor (5 μm accuracy) and its holder have been described by Huguet (1985) and Li et al. (1989).

Treatments

Treatments were begun on April 27, 1993 (Day 0) and continued for 45 days. The treatments were: I$_0$, growth medium maintained at 50% field capacity; I$_1$, irrigation supplied when net daily change in stem diameter was ≤ 0 μm; and I$_3$ as for I$_1$ except that irrigation was not supplied until net daily change in stem diameter was ≤ 0 μm for 3 consecutive days. The quantity of water supplied in I$_1$ was approximately 1.6 times the mean daily amount of water lost from the root boxes in treatment I$_0$, but after Day 36, it was reduced to 1 times the water loss of I$_0$, root boxes to reduce the risk of loss by drainage. For the I$_3$ treatment, the same quantity of irrigation was supplied as for I$_1$, but for 1 day only. Treatments I$_1$ and I$_3$ were applied on a tree by tree basis, so that trees in a particular treatment were not necessarily watered on the same day.

All the boxes were weighed individually at 3- or 4-day intervals. Trees in treatment I$_0$ were supplied with water to return the growth medium to 50% of field capacity on each of these days, and on every other day, a quantity of water (based on the previous known loss) was added to keep the growth medium for each tree at approximately 50% field capacity. Water use for each tree was calculated from the difference in weight between weighings allowing for any supplementary water added (no allowance was made for plant growth). Drainage loss did not occur, and evaporative losses from the medium were calculated based on a root box with no tree, which was weighed at the same time as the other root boxes. The water use of each tree was corrected to exclude evaporative loss from the medium.

Shoot measurements

A distinction was made between first- and second-order shoots, and the rank of origin of the second-order shoots was recorded. All second-order shoots were sylleptic, because they developed to form branches without evident intervening periods of rest of the lateral meristems (Champagnat 1954, Hallé et al. 1978, Powell and Vescio 1986). Shoot lengths were measured, and the numbers of folded and unfolded leaves were counted at 3- or 4-day intervals when the root boxes were weighed. The lengths of all fully extended leaves and internodes, and their ranks were measured on the longest first-order shoot per tree on Day 45.

A mean growth rate was calculated for the development of each metamer. For peach trees, the leaf and internode extensions are synchronous and occur mainly during leaf unfolding. The average unfolding time (the time period in which the leaf passes from the “just visible” stage to the “unfolded” stage) was 8 days. The growth rate of the first-order axis during the development of each metamer was calculated by interpolating the time at which each leaf was unfolded, and then interpolating the shoot length ($l_n$) at this time and again 8 days earlier ($l_{n-8}$). Thus growth rate (cm day$^{-1}$) was calculated as ($l_n - l_{n-8}$)$/8$ (Pagès et al. 1993) for all metamers on all first-order shoot axes.

Root measurements

Root growth and apical diameters were measured at the same times as the shoots. The growth of first-order roots directly originating from the old root system and their second-order laterals were recorded per tree at each date by tracing all visible roots with a colored pen on an acetate sheet. A different color was used to record new root growth at each consecutive measurement occasion. The growth of two roots per tree was analyzed by means of a semi-automated data processing system (Colin-Belgrand et al. 1989).
Water relations

Water potential was measured on two fully developed leaves per tree with a pressure chamber (Scholander et al. 1965) on Day 44. Water loss after excision was minimized by placing each sample in a humid plastic bag and processing rapidly. Stomatal conductance was measured with a diffusion porometer (Model MK-2, Delta T Devices, Cambridge, U.K.) on the abaxial surface of four fully developed, unshaded leaves per tree on Day 29. Both measurements were made between 1200 and 1400 h on sunny days.

Final plant measurements

Trees were removed from the root observation boxes on Day 45, and the growth medium was gently removed from the roots. The leaves, shoots and roots were separated and dried in an oven at 60 °C for 3 days. Before drying, the number of second-order (lateral) roots was counted on four first-order roots per tree, and the total root length was measured with a Comair root length scanner (Commonwealth Aircraft Corp. Ltd., Melbourne, Australia).

Environmental measurements

Solar irradiance between 400 and 700 nm (i.e., photosynthetic active radiation, PAR) and temperature behind the aluminum foil shading were measured with a silicon pyranometer and two copper constantan thermocouples, respectively. Solar irradiance was accumulated over each day to give a total in kW h m$^{-2}$. All of the sensors were connected to a 21X data logger (Campbell Scientific Ltd., Cambridge, U.K.).

Data analyses

Both exploratory and conventional methods of data analysis were used. When the data were particularly variable, we used the nonparametric technique of kernal smoothing with the ‘S’ software package (Becker et al. 1988). Conventional analyses were performed with Genstat (Payne et al. 1988). For data measured at a single time point (e.g., final dry matter weights), an analysis of variance was used. For data measured over time, regressions were fitted and analysis of variance was used to compare the slopes (e.g., leaf production rates). These analyses were for a completely randomized design with three treatments and four single tree replicates.

A logistic regression was used to relate the proportion of branched axils to the growth rate of first-order axes (Collett 1991).

Results

Mean daily temperature and the daily total photosynthetic active radiation in the greenhouse during the experimental period are shown in Figure 1.

Shoot development

The total length of the first-order shoot axes generally increased linearly with time (Figure 2). Growth rates of first-order shoot axes were therefore calculated as the slope of a linear regression relating growth to time for each tree. Trees in treatment I$_1$ had the greatest mean daily growth rate (3.3 cm day$^{-1}$), whereas trees in treatment I$_2$ grew less quickly (2.5 cm day$^{-1}$), and trees in treatment I$_3$ grew the slowest (2.2 cm day$^{-1}$). (P = 0.08, standard error of difference between two treatment means (SED) = 0.45 cm day$^{-1}$, degrees of freedom (df) = 9).

The increase in total number of unfolded leaves on first-order shoot axes per tree was also linear with time (Figure 2). Leaf production rates were calculated from a linear regression for each tree. Differences between treatments in the rate of increase of leaf production per day were not significant (P = 0.92). The rate of production of leaves per single shoot axis was not significantly different between trees (data not presented).

Internode length increased monotonically from the base to the apex of the main axis for trees in treatments I$_0$ and I$_1$, whereas internode length tended to increase at first and then to decrease for trees in treatment I$_3$ (Figure 3). Treatment differences in internode lengths were greatest at the distal part of the shoot (i.e., during the later stages of the experiment). Internode lengths were longest for trees receiving the most water (I$_0$) and shortest for trees receiving the least water (I$_3$). Internode lengths for trees in treatment I$_1$ were intermediate between those in treatments I$_0$ and I$_3$.

The relationship between leaf length and rank (Figure 3) showed similar trends to those found for internode length and rank. Trees in treatment I$_0$ produced the longest leaves, and those in treatment I$_3$ produced the shortest leaves. Again, the greatest treatment effects were at the distal part of the shoot.
Second-order shoot axes

The number and size of second-order shoot axes were highly variable, which was reflected by large SEDs for these growth measurements. The mean total number of second-order axes per tree was 35, 27 and 13 for trees in treatments I₀, I₁ and I₃, respectively (P = 0.08, SED = 8.7, df = 9). The mean total number of leaves per tree on second-order shoot axes was 78, 43 and 39 in treatments I₀, I₁ and I₃, respectively (P = 0.50, SED = 34.2 cm, df = 9). The mean total length of second-order shoot axes per tree was 74, 25 and 29 cm in treatments I₀, I₁ and I₃, respectively (P = 0.46, SED = 42.6, df = 9).

The logistic regression showed that branching (production of second-order axes) increased significantly with growth rates of the first-order shoot axes (P < 0.001). At the lowest growth rates (< 0.2 cm day⁻¹), branching was < 10%, whereas at the highest growth rates (> 0.8 cm day⁻¹), it was > 30% (Figure 4). The rates of increase did not differ significantly among treatments.

Root development

The extension rates of the sampled first-order root axes (traced in the root boxes) are shown in Figure 5. The roots of trees in treatment I₃ grew more slowly and for shorter periods than trees in either of the other two treatments. The mean growth rate, defined as the ratio of total length to duration of growth, for first-order axes was 0.7, 0.8 and 0.4 cm day⁻¹ in treatments I₀, I₁ and I₃, respectively (P = 0.06, SED = 0.14 cm day⁻¹, df = 9). Thus, the root growth rate for trees in treatments I₀ and I₁ was similar, but both were greater than for trees in treatment I₃.

The mean lengths and time intervals for the production of visible second-order roots were not significantly different among treatments (data not presented). There was an indication that root apical diameter was influenced by treatment, but the effect was not statistically significant. The mean apical diameter of roots was 0.66, 0.68 and 0.51 mm for trees in

Figure 2. Shoot extension and leaf production rates of first-order (main) axes showing each linear regression line fitted for each individual tree. I₀ = irrigation every day, I₁ = irrigation when net daily change in stem diameter ≤ 0 µM, and I₃ = irrigation after net daily change in stem diameter ≤ 0 µM for 3 days.

Figure 3. Internode length versus rank and leaf length versus rank of first-order (main) axes. Curves derived by kernel smoothing. I₀ = irrigation every day (○), I₁ = irrigation when net daily change in stem diameter ≤ 0 µM (■), and I₃ = irrigation after net daily change in stem diameter ≤ 0 µM for 3 days (■).
treatments $I_0$, $I_1$, and $I_3$, respectively ($P = 0.11$, SED = 0.077 mm, df = 9).

The mean total root length per tree at harvest was 199, 86 and 57 m in treatments $I_0$, $I_1$ and $I_3$, respectively ($P = 0.02$, SED = 42.3 m, df = 9). The average distance (4 mm) on the first-order axis between second-order (lateral) roots (i.e., the branching density) was unaffected by treatment.

**Dry weights**

Trees in treatment $I_0$ had the greatest dry weights, and trees in treatment $I_3$ the least, with trees in treatment $I_1$ being intermediate between the other treatments (Table 1). These differences were due to the greater weights of new roots, shoots and, to a lesser extent, leaves of the trees that received more frequent irrigation. The significance levels for differences among treatments were $P = 0.01$ for new roots; $P = 0.07$ for shoots and $P = 0.10$ for leaves. The treatments had no effect on total root/shoot dry weight ratios, but there were large differences among dry weight ratios of new (white) roots/shoots (leaves + shoots). The ratios were 0.29, 0.19 and 0.15 for trees in treatments $I_0$, $I_1$ and $I_3$, respectively ($P = 0.02$, SED = 0.038, df = 9).

**Micromorphometric stem diameter variation**

Two distinct phases of variation in stem diameter were observed for all trees. Figure 6 shows the pattern of diameter variations for a typical tree in treatment $I_0$. During the first phase (before treatment began) from Day $-15$ to Day $-5$, small daily variations in stem diameter (both shrinkage and swelling) were observed. The micromorphometric variation in diameter during this phase was probably of thermal origin, because it paralleled the diurnal change in temperature (i.e., maximum expansion occurred near midday) (Figure 6). The daily stem diameter change, measured from dawn until dawn, showed a net decrease.

During the second phase from Day $-4$ to Day 45, the net daily diameter change was less strongly negative than during the first phase. Daily increases in stem diameter were evident from Day $-4$ to Day 5. During the second phase, thermal swelling at midday ceased and transpiration-induced shrinkage became apparent (i.e., maximum swelling occurred just before predawn when water stress was minimal). Between Days 10 and 25, maximum daily shrinkage increased as transpiration loss increased, but there was no net increase in stem diameter.

![Figure 4](image-url)  
Figure 4. Proportion of axils with branches versus growth rate. Curves derived by kernel smoothing. $I_0$ = irrigation every day (solid line), $I_1$ = irrigation when net daily change in stem diameter $\leq 0$ $\mu$m (dotted line), and $I_3$ = irrigation after net daily change in stem diameter $\leq 0$ $\mu$m for 3 days (dashed line).

![Figure 5](image-url)  
Figure 5. Growth of two first-order roots per tree. The same symbols are used for the pair of roots from a single tree. Different symbols are used to distinguish among trees. $I_0$ = irrigation every day, $I_1$ = irrigation when net daily change in stem diameter $\leq 0$ $\mu$m, and $I_3$ = irrigation after net daily change in stem diameter $\leq 0$ $\mu$m for 3 days.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Dry weights (g)</th>
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<tbody>
<tr>
<td></td>
<td>New roots</td>
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<tr>
<td>$I_0$</td>
<td>2.5</td>
</tr>
<tr>
<td>$I_1$</td>
<td>1.0</td>
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<tr>
<td>$I_3$</td>
<td>0.6</td>
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<tr>
<td>SED (df = 9)</td>
<td>0.48</td>
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Table 1. Dry weights of new roots, old roots, stem, new shoots and leaves.
Figure 7 shows typical differences in shrinkage patterns for a tree in each treatment from Day 36 to Day 45. Net changes in stem diameters during this period were +100, +2 and −40 µm for trees in treatments I₀, I₁ and I₃, respectively. Diurnal variation in stem diameter was less for trees in treatment I₀ than for trees in the other treatments. From one dawn to the next, stem diameter of the tree in treatment I₁ decreased on the days without irrigation; however, on other days, irrigation alleviated the shrinkage allowing the stem to regain its initial diameter. Maximum daily shrinkage for trees in treatment I₁ was three times greater than for trees in treatment I₀. For the trees in treatment I₃, irrigation did not prevent the stem diameter shrinkage, and after irrigation, stem diameters did not return to previous dawn values. The maximum daily shrinkage for the treatments was in the order I₃ > I₁ > I₀.

Water relations

The trees in treatment I₀ exhibited large variability in total water use (transpiration); however, all trees except one had much greater transpiration than trees in the other treatments (Figure 8). Transpiration was less variable for trees in treatment I₁, although one tree consistently transpired less than the others. For trees in treatment I₀, transpiration was uniformly low. By Day 45, the mean total transpiration of trees in treatments I₀, I₁ and I₃ was 4325, 2107 and 923 g, respectively ($P = 0.007$, SED = 801.8 g, df = 9). Large differences occurred in water use efficiency for production of new growth. The total water (g) used per g dry matter of new growth (first- and second-order roots + first- and second-order shoots + leaves) was 406, 337 and 211 for trees in treatments I₀, I₁ and I₃, respectively ($P = 0.002$, SED = 37.0 g g⁻¹ dry matter, df = 9).

The treatments also influenced leaf water relations. Midday stomatal conductances on Day 29 were 0.40, 0.35 and 0.19 cm s⁻¹ ($P = 0.084$, SED = 0.085 cm s⁻¹, df = 9) and leaf water potentials on Day 44 were −1.51, −1.96 and −2.12 MPa ($P = 0.032$, SED = 0.197 MPa, df = 9) for trees in treatments I₀, I₁ and I₃, respectively.

Discussion

The rate of production of unfolded leaves (plastochronal activity) on first-order shoot axes was unaffected by irrigation...
regime, whereas internode extension increased with reduced drought stress. This confirms effects reported by Crabbe (1987), who stated that cellular extension is sensitive to environmental factors, but plastochronal activity (organogenesis) is more highly buffered against variations in temperature and water supply. This is because organogenesis requires proteins and other nitrogenous compounds, whereas cell growth requires carbohydrates for the construction of cell walls and water for extension (Boyer 1985, Dale 1985, Crabbe 1987).

The increased branching frequency (i.e., production of second-order shoots) associated with greater extension rates of the first-order shoot axes has been reported previously for peach trees (Champagnat 1954, Pagès et al. 1993) and for other genera (e.g., Powell and Vescio 1986). The increase in the number of second-order shoots on trees in treatment I₀ is attributed to the greater growth rates of first-order shoot axes as a result of greater water availability. Although the number of leaves developed on first-order shoot axes was the same for all treatments, trees receiving more frequent irrigation had a greater total number of leaves, because of their greater number of second-order axes. Steinberg et al. (1990) also reported a reduction in lateral shoots and new leaf production on young peach trees after drought stress was imposed.

Although we were not able to determine whether drought stress directly affects sylleptic second-order shoot development independently of the growth rate of first-order axes, our data indicate that drought stress affected not only the total size of the tree but also its architecture.

In the most severe water stress treatment (I₃), the extension rates of first-order root axes were reduced, but this treatment had no effect on the mean length and distance between second-order axes compared to the less severe drought treatments. Thus, the greater root lengths and dry matter of trees in treatments I₀ and I₁ compared to trees in treatment I₃ were the result of a combination of faster root growth and more first- and second-order axes. Peach tree root growth is also stimulated by irrigation (Richards and Cockcroft 1975). In juvenile peach trees, root growth continues throughout the growing season (Glenn and Welker 1993); however, when the tree starts bearing fruit, root development near the soil surface shows a bimodal distribution over time, with peaks in spring and autumn (Williamson and Coston 1989, Glenn and Welker 1993). Williamson and Coston (1989) attributed this effect to competition for assimilates between shoots and roots.
In established peach trees, white root growth precedes bud break (Glenn and Welker 1993), whereas in our experiment with transplants the reverse was true. The time between bud break and root elongation is critical in transplants (Johnson et al. 1984). The initial net decrease in stem diameter (Figure 6) was associated with an absence of visible roots in the root boxes, whereas the subsequent increase in stem diameter coincided with the first observation of white roots. It is unlikely that the initial net decrease in stem diameter was due to water loss because the transplants were in a moist medium and significant water loss could not occur until the leaves had unfolded and started to transpire. It may have been caused by the mobilization of organic reserves in the stem to aid the development of shoot buds and roots.

Simmonneau et al. (1993) have shown that diurnal changes in stem diameter of trees are associated with variations in water content. Our stem diameter measurements provided evidence that trees in treatments I1 and I2 suffered severe drought stress in the later stages of the experiment. On Day 44, water potentials of trees in treatment I2 were lower than those of trees in treatment I1, and trees in treatment I2 had lower water potentials than trees in treatment I0, thus supporting the observed differences in stem shrinkage.

We conclude that the architecture of the shoot system of peach trees was significantly influenced by the availability of water. Increased water supply stimulated growth of first-order shoots by increasing internode length, but not leaf production. Increased water supply stimulated growth of first-order shoots. Root system architecture was less sensitive to water supply. However, the first-order roots of trees receiving the least frequent irrigation grew less quickly and were thinner than roots in the other treatments. Second-order root development was not influenced by irrigation treatment.

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References


