Water Availability in Three Artificial Substrates during *Prunus ×cistena* Growth: Variable Threshold Values

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ABSTRACT. In nursery plant production, optimum water use is important to maintain productivity and make this production environmentally sound. Water should be supplied when it becomes difficult to extract for the plant, at a bulk soil water potential threshold value that may vary with environmental conditions, species and substrate properties. The objective of this study was to determine the threshold value at which availability of water rapidly drops for three newly developed substrates to be used in the production of *Prunus ×cistena*. Xylem water potential and potential at the soil-root interface were used as indices of water availability and were compared with bulk soil water potential. Water was easily available (no drop in xylem or soil-root interface water potential) from container capacity down to a bulk soil water potential of about –10 kPa when xylem water potential was used as an indicator and –8 kPa when the soil-root interface water potential was chosen as the indicator. No significant differences in the threshold values were found between substrates, consistent with the absence of differences in the substrate physical properties. The differences in water availability among substrates were consistent with an observed difference in salt content. The important variability observed in the threshold suggests that plant based measures may be preferred to soil based measures in assessing water availability in artificial mixes.

Increased environmental and economic pressures have fostered renewed interest among nursery growers and agriculturalists to optimize irrigation strategies. Such strategies must consider the efficiency of the irrigation system and must rely on frequent monitoring of substrate water status to ensure a uniform and adequate, but not excessive, application volume (Fare et al., 1992). Frequency and amounts of irrigation must be strictly controlled to limit water losses, which are often as high as 80% of the volume of water applied (Beeson and Knox, 1991). Economic and environmental advantages of reducing water losses are obvious because of the fixed cost associated with each irrigation, and the pollution of groundwater and streams caused by fertilizers. Reducing the frequency of irrigation requires waiting for complete depletion of the soil water held at tensions above a threshold, at which stress

begins, before watering. This avoids the risk of leaching, water loss to surface evaporation or water running off from the surfaces that are not covered by the pots in the nursery or in the greenhouse. With greenhouse and nursery substrates, the water available to plants has been estimated from the concept of easy and constant availability of soil water from container capacity down to about –5 kPa of bulk soil water potential, a threshold potential value beyond which water is thought to become increasingly difficult to extract by the plant and yield is expected to decrease (de Boodt and Verdonck, 1972; Verdonck and Gabriëls, 1991). The value of container capacity is the volumetric water content retained in the substrates after saturation and free drainage and depends on the substrate physical properties and the container geometry (Spomer, 1975; Fonteno, 1989). The water held between container capacity and the stress threshold has been termed easily available water (Verdonck and Gabriëls, 1991).

Some authors have found the threshold to vary with plant species (Marfa et al., 1983). A value for a threshold of –10 kPa has been experimentally determined for *Ficus* (de Boodt and de Waele, 1968) in a two-treatment experiment (–1 to –10 kPa and –10 to –33 kPa). Röber and Hafez (1982) suggested a much higher threshold water potential of about –3 kPa for two artificial substrates with *Chrysanthemum* sp. With the same species and with different artificial substrates, Spomer and Langhans (1975) ob-

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tained maximum yield at water potentials between -2 and -5 kPa. For greenhouse tomato (*Lycopersicon esculentum* Mill.), Goodman (1983) suggested an ideal potential between -3 and -6 kPa while Frenz and Lechl (1981) obtained maximum yield at -6 kPa.

Other factors that apparently affect the value of this threshold are the evaporative demand (Ritchie, 1973) and the nature of the substrate itself. Röber and Hafez (1982) and Spomer and Langhans (1975) have reported different threshold values for different substrates. Bernier (1992) has presented data showing pronounced differences in water availability between sand and peat and even among types of peat (Bernier et al., 1995). Others have suggested a continuum of water availability with decreasing soil water potentials instead of distinct thresholds (Richards and Wadleigh, 1952; Sharma et al., 1986).

Given the practical importance of threshold values of soil water potential, this study was carried out with two objectives. The first was to determine the threshold bulk soil water potential of water availability for three newly developed peat substrates, to recommend adequate irrigation set points for nursery use. The second was to determine if differences in chemical or physical properties of the substrates could explain any observed difference among the substrates in their threshold water potentials.

Materials and Methods

PLANT GROWTH. An experiment comparing seven porous substrates was set up at Université Laval in 1991. Black plastic pots (5-L, 21 cm in diameter $\times$ 18 cm high, with four 2-cm drainage holes at the bottom) were filled with specific substrates. One rooted stem cutting of *Prunus $\times$ cistena* was planted in each pot. Details of this experiment can be found in Allaire et al. (1996). Out of the seven substrates, three substrates presenting contrasting differences in plant growth [substrates 1, 3, and 6 from Allaire et al. (1996)] were retained for further study of water availability, hereafter designated substrate PSS, PBSC, and PBS. Substrate PSS was made of a 2 brown peat (a slightly humified sphagnum peat, with a corresponding color of H4-H5 on the von Post scale) : 1 sand : 2 sawdust mixture (volume basis), substrate PBSC was made of a 12 brown peat (H4-H5 on the von Post scale) : 5 bark : 2 sand : 1 compost and, finally, substrate PBS was a 3 brown peat (H4-H5 on the von Post Scale) : 6 bark : 1 sand mixture.

Substrates were top-dressed with 25 g/pot of a slow release fertilizer (Nutricote 14-14-14 type 140) at the beginning of each year and fertilized weekly with a 1-L liquid application per pot containing 300 mg $\cdot$ L $^{-1}$ of N from a solution of 20-20-20 (in mg $\cdot$ L $^{-1}$: 200 N, 132 P, 166 K, 1 Fe, 0.5 Mn, 0.5 Zn, 0.5 Cu, 0.2 B, and 0.005 Mo). Water was drip-supplied at a rate of 1 L per irrigation per pot when the bulk soil water potential reached -5 kPa. Further details regarding the effect of irrigation and fertilization practices on substrate performance can be found in Université Laval (1993).

In August 1992, that is, after two seasons of plant growth in the potted substrate at the nursery, 75 pots (25/substrate) were taken randomly from the field and were brought to a greenhouse. In the greenhouse, air temperature was maintained at about 18 ± 2 °C during the night and 23 ± 2 °C during the day; relative humidity oscillated from 60% to 80%. Light transmittance into the greenhouse was $\approx$ 50% to 70% of the outdoor value. Four pots per substrate were set aside for physical analysis.

The remaining 21 pots/substrate were split into three blocks (seven pots of the same substrate in each block). All nine blocks (three blocks $\times$ three substrates) were placed in a Latin square design with substrates occupying different positions in the lateral and longitudinal dimensions. Within each block, soil water was

depleted at different levels in six different pots while one pot was kept well watered (brought back to container capacity, -0.8 kPa, of water potential, twice a day) as control. Differential soil water depletion was obtained by staggering in time the removal of the pots from irrigation, so that after 3 d of drying for the driest treatment, the bulk soil water potential in the droughted pots ranged from -0.8 to -50.0 kPa. The experiment was repeated in the fall of 1993, using 3-year-old plants grown in the potted substrate at the nursery and brought to the greenhouse to be treated in an identical manner as in 1992.

SOIL AND PLANT WATER POTENTIAL MEASUREMENTS. Soil water potential, xylem water potential, transpiration rate, and leaf conductance were measured on these plants in different soil water conditions. Soil water potential was monitored directly using tensiometers (Tensimeter, Soil Measurement Systems, Tucson, Ariz.) placed at mid-substrate height within each pot (one tensiometer per pot). Measurements of xylem water potential (ψ_x) were performed on three branches (one from the top, middle and lower portions of the canopy) using a pressure chamber. The excised branches were immediately put into a polyvinyl bag and placed in the pressure chamber (model 3000; Soilmoisture Equipment Corp., Santa Barbara, Calif.). Measurements were carried out following Turner's (1988) recommendations.

Transpiration rate (Tr) and leaf conductance (g) were measured simultaneously using a transpiration measurement system (LI-1600; LI-COR, Lincoln, Nebr.) in the greenhouse. Measurements were made on five single leaves from the upper, middle and lower portions of the canopy to approximate the average transpiration rate and stomatal conductance. The leaf area contained in the leaf chamber was 2 cm 2 . Light intensity, expressed as photosynthetic photon flux density, was 700 to 1000 μ mol $\cdot$ m $^{-2}$ $\cdot$ s $^{-1}$, and relative humidity in the leaf chamber was set to ambient greenhouse level. After the measurements, all plant leaves were detached and total plant leaf areas were measured using a leaf area meter (LI-3000A).

Soil water potential at the soil-root interface (ψ_r) was computed according to Eq. 1 (Jones, 1983)

$$\psi_r = \psi_x^d - \psi_x^i \times (g_i^d \times A^d) / (g_i^i \times A^i) \quad [1]$$

where ψ_r is the soil water potential at the soil-root interface, ψ_x is the xylem water potential and g_i the stomatal conductance in the plant under some degree of soil water deprivation (d), and in a similar, well-watered control plant (i). The ratio of leaf areas (A) from the two plants is used to account for the differences in plant size (Jones, 1983). Within each block, a value of ψ_r was calculated for each of the six droughted pots using the value of ψ_x^i and g_i^i measured on the plant growing in the well-watered control pot.

This methodology implicitly incorporates a number of assumptions. Because of abundant watering prior to the measurement, ψ_r is assumed to be very close to 0 kPa in the well-watered pots. It is also assumed that there is a linear relation between Tr and g_i as well as between ψ_r and ψ_x .

To determine the threshold value under which water availability drops in a substrate, the two types of measurements of soil water status are subsequently linked to bulk soil water potential. The link to bulk soil water potential is necessary because bulk water potential measured with tensiometers will be the parameter used to control irrigation, rather than xylem, bagged leaf or soil-root interface water potential, which are impractical for routine monitoring. Therefore, empirical relationships between indices of plant and soil bulk water status are developed to determine the threshold value for water availability in the different substrates tested.

SUBSTRATE PHYSICAL PROPERTIES. Particle size distribution was measured before planting and chemical characteristics of the

media were measured at harvest time, on disturbed samples. These data have been presented elsewhere (Allaire et al., 1996). Substrate PSS was initially dominated by particle sizes <1 mm and 1 to 4 mm. It had a mean weighted diameter (a value of the mean diameter of particles in the substrate calculated according to Kemper and Rosenau (1986)) of 1.15 mm. After 2 years of production, it had an electrical conductivity of 3.3 dS·m⁻¹, a pH of 4.3, a C to N ratio of 22, and a total porosity of 0.74 cm³·cm⁻³. Substrate PBSC was initially dominated by fractions <1 mm and 1 to 4 mm. It also had some coarser fractions ranging from 4 to 25 mm for a mean weighted diameter of 1.65 mm. It had, after 2 years of use, an electrical conductivity of 2.5 dS·m⁻¹, a pH of 5.0, a C to N ratio of 24 and a total porosity of 0.77 cm³·cm⁻³. Finally, the substrate PBS was mainly composed of fractions <1 mm and 1 to 4 mm. It initially had fractions ranging from 4 to 16 mm in diameter for an intermediate mean weighted diameter of 1.47 mm. Two years later, an electrical conductivity of 9.2 dS·m⁻¹, a pH of 4.5, a C to N ratio of 21, and a total porosity of 0.73 cm³·cm⁻³ were measured.

The remaining physical properties were measured in situ in four pots per substrate in the greenhouse. Water desorption curves were determined using two vertically inserted tensiometers (one at the top of the substrate and a second at the bottom of the substrate) and time domain reflectometry (TDR) probes of length equal to substrate depth (13.5 cm). The probes were placed close (within 4 cm) to the centre of the pot, at the bottom of the plant. Dielectric constant (K_a) readings of TDR were converted into volumetric water contents using Paquet's equation for pooled substrates (Table 5 in Paquet et al., 1993). Air-filled porosity was calculated from the difference between the volumetric water content at saturation (θ_s) and that after saturation and drainage of the potted medium for 2 h (θ_c). After that period, the substrate had reached equilibrium and the average potential corresponded to half the substrate height (-8 cm head or -0.8 kPa potential). The corresponding volumetric water content (θ_c) therefore represents the maximum volumetric water content that can be stored in a substrate potted into a 5-L container and is often referred to as the container capacity.

Available water was calculated from the difference between θ_c and the volumetric water content measured when the substrates were equilibrated at -10 kPa on a tension table (θ_{-10}) (DeBodt and Verdonck, 1972). Saturated hydraulic conductivity (K_s) was measured directly in the pot, using a constant head permeameter and taking into account the effect of pot drainage hole location on flow measurement (Allaire et al., 1994).

Unsaturated hydraulic conductivity ($k(\psi_s)$) measurements were obtained from the instantaneous profile methods (Hillel et al.,

1972) using two vertically installed tensiometers (one at the top and one at the bottom of the substrate) in a pot filled with saturated medium. The pots had their bottom part cut and removed and were then put on a tension table (Paquet et al., 1993) under a potential of -15 kPa. Removal of the plastic bottom was necessary to ensure a good contact between the substrate and the tension table, to use the theoretical approach of Hillel et al. (1972) for the calculation of the unsaturated hydraulic conductivity. Water content was monitored from the TDR readings. Water potentials at the top and bottom of the pot, calculated from the tensiometers readings, were recorded simultaneously with TDR readings for 36 h. The relationship between k_s and $k(\psi_s)$ was described using Eq. 2:

$$k(\psi_s) = k_s e^{(\alpha \psi_s)} \quad [2]$$

where ψ_s is the bulk soil water potential and α is a fitted parameter. This function was found to provide the best description of the unsaturated-saturated hydraulic conductivity among all other published models reported by Mualem (1986).

DESIGN AND ANALYSIS. Comparisons of the substrate physical properties were performed according to a completely randomized block design (Snedecor and Cochran, 1989) with four replications. Statistical and regression analyses were performed with SAS/STAT Package Release 6.03 (SAS Institute, Cary, N.C.). Least squares methods were used to fit Eq. 2 to measured unsaturated hydraulic conductivity data using Mathcad Software package version 4.0 (Mathsoft, Cambridge, Mass.).

The threshold value for water availability for the different substrates was calculated by fitting segmented regression lines to data of the xylem and soil-root interface relationships with bulk soil water potential, using the procedures described by Hudson (1966) and Mathcad software version 4.0 to fit the regressions. Data weighting was applied so that each regression had a contribution to the residual sum of squares that was independent of the number of observations used for its calculations (Hudson, 1966). Two curves were used because the fitting of two curves had the capacity to adjust to a theoretical maximum between the two suboptimal states: a state of saturation where plants do not show any potential decrease or a small increase with decreasing bulk soil water potential and a state of dry-down where important drops in either xylem or soil-root interface water potentials are observed.

Comparisons of the threshold obtained for each parameter were performed by analysis of variance, with substrates considered as fixed effects and years considered as replications.

Results and Discussion

Data from 1992 and 1993 show that stomatal conductance dropped with decreasing bulk soil water potential, with the diminution being more pronounced in the higher range of water potential (Fig. 1). Decreased bulk soil water potential did not necessarily result in a drop in xylem water potential since the plants restricted water loss by closing their stomata. Indeed, despite a decrease in the bulk soil water potential, xylem water potential was maintained at a constant level within the higher range of potentials (Fig. 2 a-c). Beyond a certain threshold bulk soil water potential, xylem water potential showed a rapid decrease.

Water potential at the soil-root interface showed a relationship with bulk

Fig. 1. Relationship of stomatal conductance with varying bulk soil water potential for substrates PSS (a), PBSC (b), and PBS (c).

Fig. 2. Relationship of xylem (a–c), and soil–root interface water potential (d–f) with varying bulk soil water potential for substrates PSS (a and d), PBSC (b and e), and PBS (c and f).

soil water potential similar to that described above for xylem water potential (Fig. 2 d–f). Such similarity is to be expected since ψ_x is one of the variables used to compute ψ_r (Eq. 1). Plateaus in soil–root interface water potential values were also observed and were followed by a rapid decrease beyond a threshold bulk water potential. The calculated threshold bulk soil water potentials for xylem and soil–root interface are given in Table 1.

For xylem or soil–root interface water potential, differences in the threshold were nonsignificant at $P = 0.05$. For all substrates, decreasing bulk soil water potential did not create any drop in xylem water potential when the bulk soil water potential was maintained at about -3 to -14 kPa, according to xylem, and -3 to -11 according to the potential at the soil–root interface. As the potential decreased further from these threshold values, plant water status was affected. The threshold values determined using the soil–root interface water potential were in agreement with previously published data on crop yield, where different water potentials were maintained over long periods of growth. Indeed, our observations support the findings of Röber and Hafez (1981) and of Spomer and Langhans (1975) for *Chrysanthemum* growth, and of Frenz and Lechl (1981) and of Goodman (1983) for tomato fruit yield.

The absence of differences in the threshold were somewhat expected since very few differences were observed between factors possibly affecting this threshold. Indeed, as a root extracts a given volume of water from its surrounding soil, the water content drops, causing a corresponding drop in soil water potential of that near-root zone. The drop of water potential in the near-root zone depends on the water demand by the plant, on the volume of water present in the vicinity of the root, and on the ability of the soil further away from the root to replenish the soil water around the root (Reicosky and Ritchie, 1976). The latter is controlled by the $k(\psi_r)$ of the rhizospheric soil, by the disruption of the hydraulic continuity between soil and the root (Nye, 1994), and by the

specific water capacity (the derivative of the soil water characteristic curve at a particular water potential, Hillel, 1980). Finally, the drop in potential can be exacerbated by the accumulation of solutes at the external boundary of the root, therefore increasing osmotic potential (Duval, 1992; Hamza and Aylmore, 1992).

As expected, substrates showed no significant differences in the stored water volume, the specific water capacity (through water desorption characteristics) and the increasing soil hydraulic resistance with decreasing potentials (through determination of unsaturated hydraulic conductivities). The shapes of the water desorption curves were similar (Fig. 3) for all three substrates. There were no significant ($P \leq 0.05$) differences among substrates in either air-filled porosity or available water (Table 2).

The same conclusions were drawn for the $k(\psi_r)$ values of substrates at different potentials (Fig. 3b). Values of $k(\psi_r)$ decreased rapidly with decreasing ψ_r . Comparison among substrates was made by fitting Eq. 2 to the observed values of k_s , ψ_s and $k(\psi_s)$ for each of

the four replicates within each substrate, and by comparing the value of the α parameter by analysis of variance (Table 2). R squared values of individual regressions were all between 0.70 and 0.95. No significant differences were found between substrates.

Significant differences in salt concentrations were found between PBS ($EC = 9.2 \text{ dS} \cdot \text{m}^{-1}$) and the two other substrates in 1992 ($EC = 2.5$ to $3.3 \text{ dS} \cdot \text{m}^{-1}$), although no salinity measurements were made in 1993 (Allaire et al., 1996). This difference appeared despite a same initial salinity level for all substrates and the same weekly fertilization and leaching schedule applied to all substrates. The absence of a significant effect of salt levels on the threshold value may be due to the fact that additional fertilizers were top-dressed and fertilizer grains were observed to stay at the top surface of the substrate. Consequently, the rhizosphere may not have high solute concentrations at the external boundary that may cause a change in the threshold value. Also, it is observed that the trends in the threshold values (higher values in the threshold for PBS relative to the two others for xylem and soil–root interface water potentials) are consistent with this higher salinity, despite the lack

Table 1. Threshold bulk soil water potential values estimates from segmented regression analysis (Fig. 2) based on xylem water potential or soil–root interface water potential observed during 2 different years.

Substrate	Year		Mean of both years
	92	93	
Xylem potential (kPa)			
PSS	-17.9	-10.7	-14.3
PBSC	-7.6	-15.0	-11.3
PBS	-0.9	-5.2	-3.1
LSD(0.05)			14.5
Soil-root interface water potential (kPa)			
PSS	-16.7	-5.6	-11.2
PBSC	-15.4	-4.9	-10.2
PBS	-0.9	-5.0	-3.0
LSD(0.05) ^c			20.5

^cLeast significant difference at $P \leq 0.05$, 3 df.

Fig. 3. Water desorption characteristics (a) and natural logarithm (ln) of the unsaturated hydraulic conductivities (b) of the three different substrates used.

of significant differences at $P = 0.05$ ($P = 0.17$ for xylem and 0.47 for soil-root interface with 3 df).

Two major practical implications may result from these findings. The first one implies the existence of thresholds, which are observed in all three substrates. Using two indicators, we have shown that signs of plant water stress begin at threshold values ranging from -14 kPa to -3 , averaged for 2 years, depending on the indicator used. This has implications for irrigation since the frequency of watering may be diminished to a fixed threshold without affecting yield. The average threshold value of water availability appears to be close to the generally used values of -10 kPa (Verdonck and Gabriels, 1991) for xylem (-9.6 kPa) and for the soil-root interface (-8.1).

Table 2. Physical properties of the different substrates.

Substrate	k_s^z (cm·s ⁻¹)	α^y value (kPa ⁻¹)	Air-filled porosity ^x (cm ³ ·cm ⁻³)	Available water ^w (cm ³ ·cm ⁻³)
PSS	0.035 ^v	0.69	0.08	0.32
PBSC	0.036	0.67	0.09	0.31
PBS	0.020	0.70	0.08	0.30
P	0.24	0.86	0.89	0.60

^zSaturated hydraulic conductivity.

^yCurve fitting parameter, calculated using Eq. 2.

^xDifference in volumetric water content between saturation and drainage (-0.8 kPa of water potential).

^wVolumetric water content of -0.8 to -10 kPa of water potential.

^vEach number represents the average of four replicates.

The second implication deals with the variability of the threshold itself, which has consequences on the assessment of plant water status as well as the analysis of the physical properties of artificial mixes. The important variability observed in the threshold xylem water potential value (-7.6 to -15.0 kPa for PBSC, -10.7 to -17.9 for PSS, -0.9 and -5.2 for PBS) questions the accuracy of a unique threshold bulk soil water potential value of -10 kPa as an irrigation start point and as a limit of water availability in artificial mixes. Since xylem water potential has been linked to crop yield for a large range of tree species (Shackel et al., 1997), important yield decreases may be expected if irrigation is started slightly below the threshold and therefore, small differences in the threshold may result in large yield decreases. Monitoring xylem water potential is then more likely to be accurate to assess water availability to the plant than trying to use a unique bulk water potential threshold value for different substrates to start up irrigation. From this consideration, the analysis of available water in substrate as the volumetric water content from container capacity to -10 kPa appears a misleading generalization of the relationship between crop growth and container water status. Consequently, when evaluating substrate properties, plant based measures appear more promising than soil based measures to monitor plant water status. These statements remain speculative and further work should be conducted to determine if this variability has a real impact on plant growth or if it is simply a reflection of the accuracy of the methodology used in determining the thresholds themselves.

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