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Exploring Water Movement through Stratified Substrates

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Summary

An increase in horticultural production requires a greater demand for more water use. Soilless substrates, particularly bark-based systems used in nursery production, can be inefficient with regards to resource utilization. Substrate stratification is an innovative substrate management technique that involves the layering or stacking two substrates of unique hydraulics properties within the container system. The objective of this study was to monitor how stratifying substrates influences substrate water potential between two different irrigation schedules. Stratified substrates allow for added water retention in the upper half of the container, whereas in the lower half, air-filled porosity was increased. Moreover, stratified substrates significantly reduced tension fluctuations that notoriously occur in the upper portion of the substrate profile. Oscillations were even further reduced when a cyclic irrigation schedule was implemented. Thus, stratified substrates have potential for improving water efficiency in nursery crop production.

INTRODUCTION

Agricultural production continues to be a primary consumer for natural resource withdrawals, specifically water, in the United States (Calzadilla et al., 2010). The nursery industry is a growing agricultural sector, where annual sales have increased $3 billion within the last decade according to the Census of Agriculture (USDA, 2019). Water scrutiny, availability, and local regulatory restrictions acknowledge the current challenges the nursery industry faces, especially with regards to horticultural substrates (Fulcher et al., 2016).

Nursery crops are conventionally produced in containers filled uniformly with a singular or multicomponent substrate, typically bark-based, and utilized for their suitable drainage and aeration properties (Pokorny, 1979). However, soilless substrates are inefficient in regard to resource use (water and mineral nutrients), requiring daily irrigation applications and continuous fertilization (Tyler et al., 1996). The need for constant irrigation is due to the limited container volume and the high porosity of bark-based substrates, which creates an undesirable moisture gradient (i.e. the upper portion of the pot is drier than the lower portion). Thus, resulting in an increase in water use to replenish the finite amount of available water (Owen and Altland, 2008). Therefore, engineering horticultural substrates to control water gradients within the container may result in more resource efficient production practices.

Substrate stratification, layering of unique substrates within the container to modify the air to water ratio for more desirable water retention and drainage properties, is a substrate management strategy that may improve plant nursery resource efficiency (Fields et al., 2021). Layering fine or fibrous substrate particles in the upper half of the container may increase substrate water holding capabilities in the initial plug or liner growing area, whereas the arrangement of coarse particles in the lower half can increase aeration and substrate drainage. This ability to engineer the hydraulic gradient within a container may be further benefited from precision irrigation scheduling, wherein water can be applied to supply the upper portion of the container.

Water availability which is associated with plant stress, quality, yield, and subsequent abilities for root systems to overcome drying periods can be estimated as a substrate tension (Shock et al., 2011). Substrate tension is a measure of how tightly water is held within a substrate and is commonly measured through use of tensiometers. A substrate that is able to withstand reaching low tensions would ensure plant roots can readily access water and nutrients. This in turn could not only improve crop quality, but may also lead to improved resource efficiency. Wallach (2008) discussed the use of tensiometers in the top and bottom portion of a nursery container filled with perlite under ‘moist’ and ‘dry’ conditions. It was observed that more frequent irrigations (moist) increased substrate water potentials (less negative) in the upper half of the substrate profile. Thus, improving water holding in the upper 50% of the container profile by placement of fine particles should further increase water potentials for more desirable substrate tensions.

Therefore, the objective of this study was to monitor and compare substrate water potentials throughout the container system of non-stratified and stratified profiles during daily water fluctuations and draw comparisons between two irrigation schedules (single application or cyclic).

MATERIALS AND METHODS

Aged loblolly pine (*Pinus taeda* L.) bark particles were fractioned via a continuous flow screen utilizing a 6.3 mm aperture screen. Conventional bark (unscreened), fine bark particles (< 6.3mm), and coarse bark particles (> 6.3 mm) were collected. Substrate physical properties were assessed on three replicates of each substrate utilizing a NCSU porometer to measure container capacity (CC), air space (AS), total porosity (TP) and bulk density (D_b; Fonteno and Harden, 2010). Substrate particle size distribution was measured by passing three 100 g dry replicates of each bark through a series of sieves while agitating for five min with a screen shaker (Ro-Tap Shaker; W.S. Tyler, Mentor, OH) and weighing the particles remaining on each screen. Substrate hydraulic properties were also assessed on three replicates of each material utilizing the evaporative method described Fields et al. (2016).

Twenty containers (5.68 L) were filled with either of two substrates treatments 1) a conventional bark substrate or 2) a stratified substrate where coarse bark was utilized to fill to lower half the container and fine bark was utilized to fill the upper half of the container. Six replicates of each substrate treatment were fitted with calibrated elbow tensiometers (Soil Measurement Systems; Huntington Beach, CA, USA) at 25% and 75% below the substrate surface (Fig. 1). The replicates were randomly split into two irrigation treatments in a climate-controlled greenhouse. Irrigation treatments consisted of a single application irrigation schedule (SI; 1x/d, 600 mL) and cyclic application irrigation schedule (CI; 3x/d, 200 mL; 600 mL total). Data was collected for 6 d in fallow pots and recorded with a data logger (CR1000X; Campbell Scientific, Logan UT, US). Data was analysed using JMP Pro (15.1.0; SAS Institute, Inc.; Cary, NC, U.S.) utilizing Tukey's Honestly Significant Difference ($\alpha = 0.05$) to separate means across substrates (Table 1).

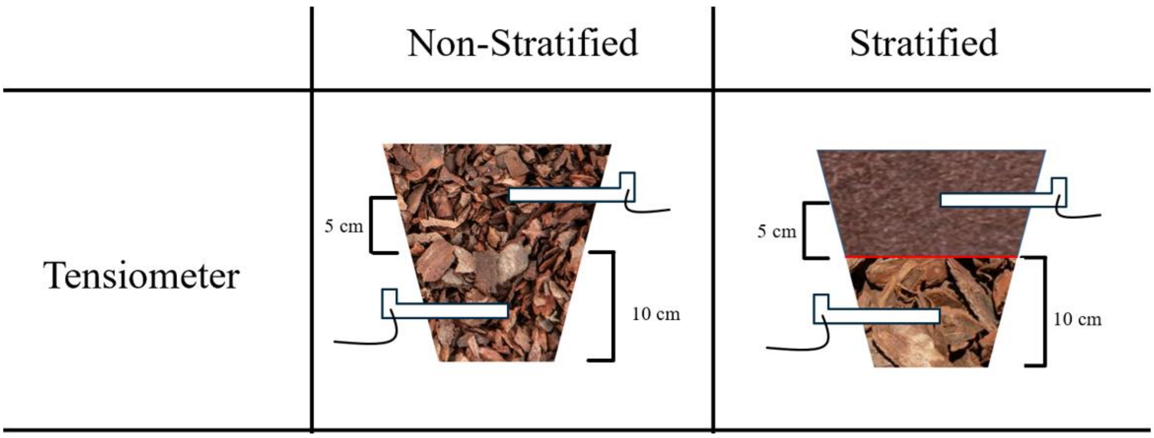

Figure 1. Fictitious depiction of tensiometer installation dimensions and placement.

RESULTS AND DISCUSSION

Physical Properties

Partitioning bark particles smaller than 6.3 mm significantly increased the substrate's ability to retain water (0.52 $cm^3\ cm^{-3}$) while increasing the majority of bark particle diameter greater than 6.3 mm reduced substrate CC (0.39 $cm^3\ cm^{-3}$), when compared to conventional bark (0.46 $cm^3\ cm^{-3}$; Table 1).

Bilderback et al. (2013) suggest that container capacity for horticultural substrates should range from 0.45-0.65 $cm^3\ cm^{-3}$. Increasing particle diameter from conventional bark also increases AS; however, reducing particle diameter did not influence AS (Table 1).

Table 1. Static physical properties and particle size distribution of pine bark substrates utilized in stratified substrate systems. Conventional bark was fractioned by passing through a 6.3 mm screen. The particles that remained on the screen were considered coarse bark, and the particles that passed through the screen were considered fine bark.

	Static Physical Properties [a]			
Substrate	Container capacity $cm^3\ cm^{-3}$	Air space $cm^3\ cm^{-3}$	Total porosity $cm^3\ cm^{-3}$	Bulk density $g\ cm^{-3}$
Conventional bark	0.46 b [c]	0.33 b	0.79 a	0.17 a
Fine bark	0.52 a	0.30 b	0.82 a	0.17 a
Coarse bark	0.39 c	0.43 a	0.83 a	0.16 a
P-value [d]	<0.0001	0.0098	0.4252	0.0956
	Particle Size Distribution [b]			
	Extra Large (>6.3 mm) $g\ g^{-1}$	Large (6.3–2.00 mm) $g\ g^{-1}$	Medium (2.00-0.71 mm) $g\ g^{-1}$	Fines (<0.71 mm) $g\ g^{-1}$
Conventional bark	0.36 b	0.43 b	0.13 b	0.08 b
Fine bark	0.01 c	0.50 a	0.36 a	0.14 a
Coarse bark	0.56 a	0.36 c	0.04 c	0.04 c
P-value [d]	<0.0001	<0.00021	0.0001	0.0019

[a] Measured via porometer analysis. Total porosity = air space (minimum air-filled porosity after free drainage) + container capacity (maximum water holding capacity after free drainage).
[b] Percent of total sample dry mass within the particle size range.
[c] Letters denote detected differences among means of three substrates (conventional bark, fine bark, and coarse bark) utilizing Tukey's HSD (α = 0.05).
[d] Measures of overall treatment effects utilizing ANOVA analysis with a significance value of (α = 0.05).

Again, coarse bark was the only substrate that was not within recommended guidelines for CC and AS (0.10-0.30 $cm^3\ cm^{-3}$; Bilderback et al., 2013). Total porosity and bulk density were unaffected by fractionating bark particles (Table 1).

Concentrating the majority of bark particles greater than 6.3 mm resulted in the greatest proportion of extra-large particles and alternatively, reducing particle size significantly decreased the percentage of extra-large particles relative to conventional bark (Table 1). Inversely, fine bark particles had the greatest proportions of large, medium, and fine particles (i.e. <6.3 mm), whereas coarse particles had the least (Table 1).

Hydraulic Properties

Substrate hydraulic properties were utilized to develop moisture characteristic curves, which were subsequently fit to a constrained soil water retention model (van Genuchten, 1985). The porosity of conventional pine bark is heterogeneous, which results in a non-uniform pore size distribution. Thus, a myriad of pore sizes exists throughout a nursery container filled with conventional bark (Drzal et al., 1999). However, the bark screening process creates a more uniform pore size distribution due to the bulk of the bark particle sizes consisting of semi-identical diameters (Fields et al., 2018). A gradual decline in volumetric water content (VWC) with decreasing tension was observed in conventional bark (Fig. 2A), which confirms heterogeneous porosity. Moreover, the conventional bark retains more water at lower tensions than the other substrates do (Fig. 2). This is likely due to water being restrictively held through hysteretic porosity throughout the profile. Conversely, fine and coarse bark have a rapid decline in VWC below tensions considered readily available water (-10 and -50 hPa; de Boodt and Verdonck, 1972), likely due to the uniform pore size distribution, indicative of the screening process (Fields et al., 2021; Fig. 2B).

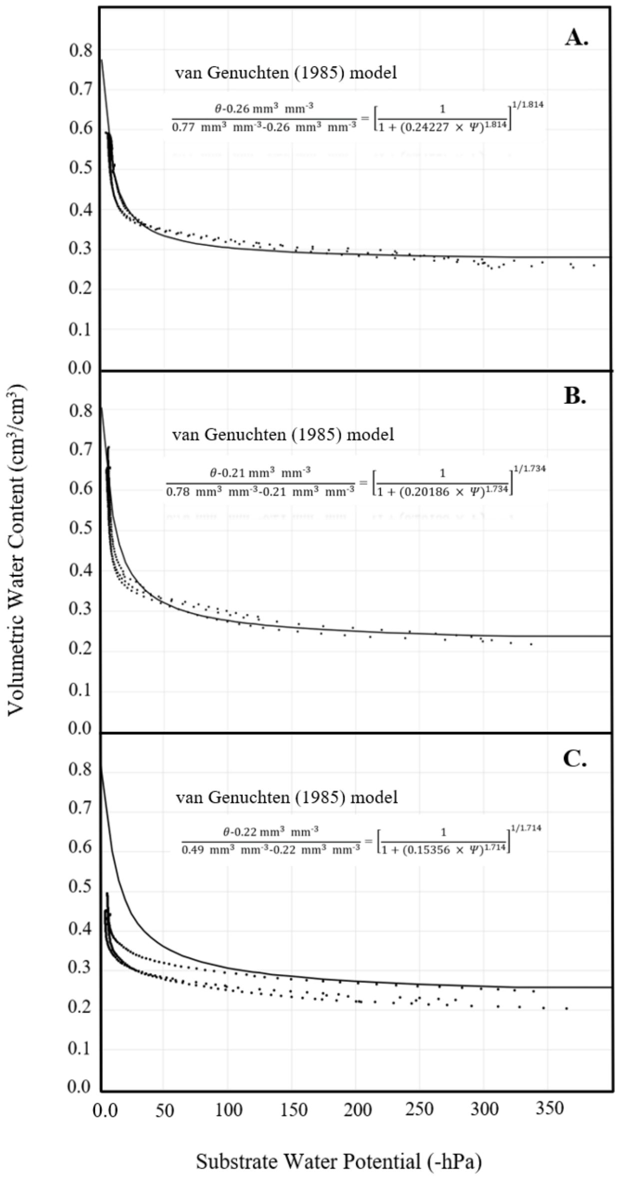

Figure 2. Substrate moisture characteristic data (points) fit to a constrained van Genuchten (1985) hydraulic model (solid line). The data was measured via evaporative measurement and porometers on three replicates of each substrate. Substrates include A) conventional bark, B) fine bark (<6.3 mm) and C) coarse bark (>6.3 mm). Volumetric water content ($cm^3\ cm^{-3}$; Y-axis) was plotted against substrate water potential (-hPa; X-axis).

The fine bark also had the greatest initial CC when compared to other substrates (Table 1). The coarse bark had greater particle diameters, resulting in an increased percentage of macropores (Drzal et al., 1999). Thus, the rate of water loss in the coarse bark diminished at relatively high tensions as there was little remaining free water, where small reductions in VWC continued to result in large reductions in water potential in at higher tensions than the other barks leaving the remainder of water tightly surface bound (Fig. 2C).

Monitoring Substrate Water Potential Non-stratified substrates experienced large fluctuations in daily substrate tensions when receiving a single irrigation event (Fig. 3A).

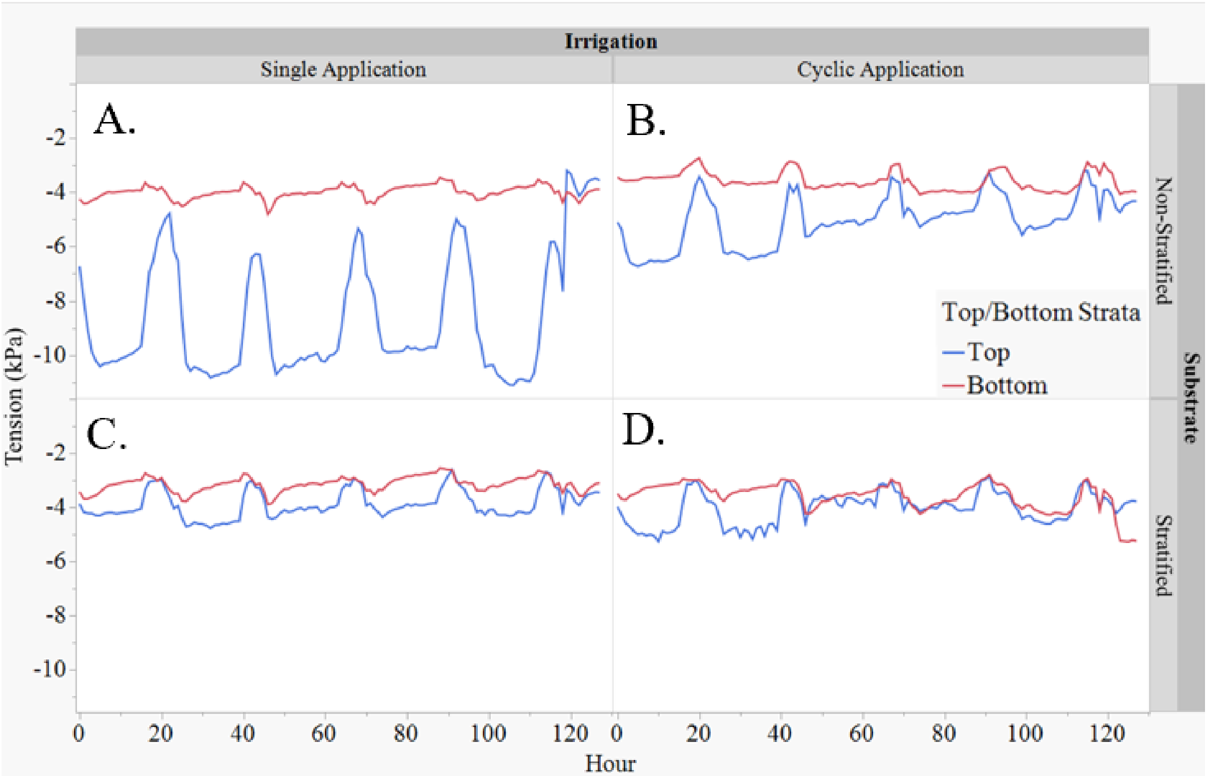

Figure 3. Substrate water potentials calculated via elbow tensiometers in the upper and lower portions of the container under single or cyclic irrigation application scheduling over 6 d. Treatments include A) Non-stratified substrates within a single application irrigation B) Non-stratified substrates within a cyclic irrigation application C) Stratified substrates in a single application and D) Stratified substrates within a cyclic irrigation application.

The lowest tension reached (below -10 kPa) was in the upper portion of the non-stratified substrate under a single application. This is indicative of a traditional container substrate system, where the upper proportion of the substrate dries rapidly due to gravitational drainage and evaporation (Fonteno, 1989). The stratified system reached tensions only half of that in the same irrigation schedule (-5 kPa; Fig. 3C). Stratifying the substrate reduced the water loss from gravitational drainage through increased upper strata water retention, maintaining a more continual moisture profile, while the greater proportion of extra-large particles in the coarse bark resulted in rapid water loss in the lower 50% of the substrate profile (Fig. 3A). Hillel (2004) stated that VWC and tension are inversely related; hence, more water holding capabilities ensured tensions remained within the range of readily available water, possibly reducing energy required for root uptake (Fields, 2016).

Cyclic application scheduling effectively increased substrate tensions to more desirable water potentials in the control substrate (Fig. 3B). The more frequent and shallow irrigations increased the VWC in the upper half of the container for longer durations where it was observed to have dried to a greater magnitude in a single, large irrigation application (Fig. 3A-B). To a greater extent, when stratified substrates consist of fine bark particles on the top, an optimal substrate tension was maintained throughout the day (Fig. 3D). Moreover, in the stratified system under cyclic irrigation, the tension in the upper half followed parallel trends with the tension in the lower half during and between irrigation events. This is evidence of the uniform water gradient within the container system that was hypothesized to result from the stratifying process (Fig. 3D).

Through most of the monitoring, the upper portion of the container experienced the greatest daily fluctuation in water potential. All lower strata water potentials were relatively stable with minimal deviations (± -2 kPa; Fig. 3). This indicates that incorporation of coarse bark materials in the lower portion of the container system did not adversely affect moisture content, instead they provided relatively stable water potentials through production. Thus, stratifying substrates were able to optimize upper container water balance where the initial plant rooting zone occurs (i.e. from initial liner or plug growth) while maintaining optimal lower container VWC.

It is important to develop and engineer more resource efficient production practices as the horticultural industry continues to increase in production. Stratifying the substrate through layering fine bark on top of coarse bark has been shown as a method to effectively reduce daily water fluctuations within the container while maintaining optimal water tensions throughout the container system. Furthermore, pairing stratified substrates with more efficient and targeted irrigation strategies (i.e. cyclic irrigation) can further stabilize substrate moisture tensions during and between irrigation events. Traditional nursery substrates irrigated daily will experience large changes in in water potential in the profile. Stratified substrates greatly reduce the tension fluctuations through strategic modified substrate hydraulic modifications.

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