Root Medium Physical Properties

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SUMMARY. Acceptable physical properties are an integral part of root-media quality. However, there is no one growing medium that works best in all situations because root-media physical properties are not constant, but rather can be affected by the grower. Understanding the root environment under production conditions requires an understanding of the dynamic nature of air : water : solid ratio in the medium. The objective of this review is to consider key aspects of root-medium physical properties, which include bulk density and particle size, container capacity, media settling, water absorption, rewettability, moisture release characteristics, and water loss due to evaporation from the root-medium surface.

0ne of the most important aspects of transplant production is root-media quality (Biernbawn, 1992; Styer and Koranski, 1997). For proper shoot and root growth, a root medium must serve four functions: 1) provide water, 2) supply nutrients, 3) permit gas exchange to and from the roots. and 4) provide support for the plants (Nelson, 1991). Thus, acceptable physical properties are an integral part of media quality. However, there is no one growing medium that works best in all situations because root-medium physical properties are not constant, but rather can be affected by the grower (Fonteno et al., 1996). The objective of this review is to consider key aspects of medium physical properties which include air: water: solid space ratios, water absorption, rewettability, moisture release characteristics, and water loss due to evaporation from the root-medium surface.

Air: water: solid ratios

The distribution of air, water, and solid in a container medium depends on several factors including pore space, bulk density, particle size distribution, container height, and media settling.

PORE SPACE. The amount of total pore space (TPS) in a root medium is inversely proportional to the bulk density (BD) (Beardsell et al., 1979a; Bunt, 1983; Hanan et al., 1981). As the BD decreases, TPS increases linearly. For example, Bunt (1983) tested 32 combinations of peat and either vermiculite, calcined clay, or sand with BDs ranging from 90 to 1500 kg?m^{-3} and obtained the following relationship between the BD of the root media combination and the TPS:TPS (in % by volume) = 98.39 (±0.26) - 0.03655 (±0.00036) x BD (in kg?m^{-3}).

Sphagnum peat and vermiculite, components of the Cornell Peat-lite A mix, would have a BD of ˜125 kg?m^{-3}. Using the above equation, the calculated TPS (by volume) of the Peat-lite A mix would be ˜ 93%. In comparison, a loam based soil can have a BD of 1400 kg?m^{-3} and a calculated pore space of 47%.

It is commonly reported that mineral soils contain ˜50% solid and 50% pore space. In contrast, in a soilless peat-based root media, only 7% to 15% may be solid with the remaining 85% to 93% being occupied by pore space (Blom, 1983; De Boodt and Verdonck, 1971; Fonteno, 1988).

Pore space is occupied by either air or water. For a field soil, field capacity is the total amount of water present in the column (>1 m) after the soil has been saturated and allowed to drain. For an ideal field soil, pore space (50% of the total volume) after drainage is typically reported to be 50% air (25% of the total volume) and 50% water (25% of the total volume). For a container media, container capacity is the total amount of water present in the pot after the medium has been saturated and -allowed to drain. For an ideal container root medium in a 15-cm-tall (1.7-L) pot, the reported pore space (85% of the total volume) is 30% air (25% of the total volume) and 70% water (60% of the total volume) at container capacity (De Boodt and Verdonck, 1972). Fonteno (1988) found that the average air space in five commercially available root media was 21% (total volume) and the average water space was 65% (total volume) in 15-cm-tall pots at container capacity.

CONTAINER HEIGHT. Container height also affects the ratio between air and water in a given root medium. After saturation and drainage, a perched water table exists at the bottom of the pot (Spomer, 1975). For every 1cm increase in height above the bottom of the pot, there is a 0.1 kPa increase in moisture tension and less water held. Milks et al. (1989) demonstrated that the percent moisture held in a 17-cm-tall pot (by volume) decreased from 69% at the bottom of the pot to 32% at the top of the pot. The overall container capacity of the root media within the pot was the average water held by the root media throughout the column.

An illustration of how container height affects the water content of a root media is presented by Fonteno (1988). At container capacity, the average water content (by volume) of five different commercially available root media in a 15-cm-tall pot was

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64%, in a 10-cm-tall pot was 70%, a 48 cell bedding flat (8 cm tall) was 76%, and a 273 plug tray (5 cm tall) was 82% water by volume. The percentage of solid material in the root media remained constant in the different container sizes. It was the ratio of air space to water space that changed with the different container heights.

PARTICLE SIZE AND PORE SPACE DISTRIBUTION. Particle size and pore space distribution influence the ratio of water to air held in the root media after drainage. Two types of pores exist within a root medium: capillary and noncapillary. For the ideal container medium in a 15-cm-tall pot, capillary pores (<0.3 mm) will retain much of the water after an irrigation. Noncapillary pores (> 0. 3 mm) will retain only a small amount of water (held as a film along the side of the pore space) after an irrigation, thus providing the aeration for the roots. It is normally reported that the water held in a root media that is available to the plant is held at a tension between 1 and 10kPa (De Boodt and Verdonck, 1971) (see moisture release discussion). This range of moisture tensions correspond to pore space diameters of between 0.3 and 0.03 mm in a 15-cm-tall pot.

Puustjarvi and Robertson (1975) reported a relationship between particle size and water-holding capacity of peat. If the particle size is <0.01 mm, the pore space diameter is so narrow that the water is held at tensions that make the water unavailable to the plant. Particle sizes between 0.01 and 0.8 mm retain most of the water applied. As particle size increases from 0.8 to 6.0 mm, the proportion of large noncapillary pores increases thus increasing the amount of space occupied by air after an irrigation. Above 6.0 mm, large noncapillary pores predominate (Puustjarvi and Robertson, 1975). The type of peat used in a root medium will greatly affect the physical properties. In general, the more degraded the peat, the greater the BD and the smaller the particle size, both which reduce overall pore space (Puustjarvi and Robertson, 1975).

SHRINKAGE. Root-medium shrinkage affects the physical properties of a root media by decreasing column height and changing the distribution between capillary and noncapillary pores (Nash and Pokorny, 1990). Shrinkage occurs when the small particles settle into the large noncapillary pores located between the larger particles (Spomer, 1974). Nash and Pokorny (1990) found that excess shrinkage occurred in a two component root media when there was a large difference in the particle size of the two components. The greatest amount of settling occurred when the components were mixed in equal volumes. Bures et al. (1993) found that maximum shrinkage occurred when the proportion of coarse particles of pine bark and sand mixtures ranged from 50% to 70% of the volume. Settling could be reduced or eliminated by using similar size components in the root media (Nash and Pokorny, 1990).

SETTLING. The preparation and handling of peat-based root media can have a great effect the ratio of air: water contained in a root medium (Milks et al., 1989). For example, excess shredding or mixing can break down the structure of peat or any other component used in the medium by reducing the particle size. Excess compaction when the pot or flat is filled can push the particles closer together which decreases capillary pore space. Inadequate compaction when the pot or flat is filled can result in excess settling which reduces the column height. Argo and Biernbaumn (1993) and Blom and Piott (1992) found that most of the settling occurs with the first irrigation. A reduction in particle size, a decrease in capillary pore space, or a decrease in column height will all decrease the ratio of air: water contained in the medium after an irrigation.

Water absorption and rewettability

Some of the currently used laboratory methods of determining root media air and water space at container capacity (Fonteno, 1988; Milks et al., 1989; White and Mastalerz, 1966) have little relationship with a normal irrigation under commercial conditions (Argo and Biernbaum, 1994b). With laboratory methods, the root media remains submerged in water for 24 h. Following drainage, a perched water table is present at the bottom of the pot. Under production conditions, the root medium is typically dry at the start of an irrigation and may be irrigated for a period of one to five minutes. Lateral distribution of the water is slow and saturation often does not occur (Argo and Biernbaum, 1993; 1994b).

Organic materials such as peat tend to be hydrophobic and may be difficult to rewet if allowed to become too dry. Airhart et al. (1978) and Beardsell and Nichols (1982) found that when the water content (by volume) of pine bark was allowed to decrease below 35%, little of the water applied was retained. As moisture levels increased to 50%, the bark became progressively easier to rewet. Argo and Biernbaurn (1994b) found that peat-based media became more efficient at absorbing applied water as the moisture content of the medium increased before the irrigation.

The state of decomposition of the peat may also affect the ability to rewet after drying. Peats with a greater state of degradation also have a greater amount of humic acid. Humic acid plays an important role in cation exchange capacity of peat based root media. However, if peat is allowed to dry, the humic acid may form hard granules that have lost their initial capacity to absorb water and nutrients and may ultimately have an adverse effect on the structure of the peat (Puustjarvi and Robertson, 1975).

Other components can be added to a root medium to increase water absorption. Beardsell and Nichols (1982) found that water absorption by coarse sand did not depend on the moisture content before water being applied. This water absorption characteristic could be transferred to a root media in proportion to the amount of coarse sand used. Beardsell and Nichols concluded that a minimum of 30% of the volume of the root media be made up of coarse sand to achieve acceptable levels of rewettability (>80% of initial container capacity). However, the large percentage of sand reduced the water-holding capacity of the root media and, therefore, was less effective than preventing the root media from drying out (Beardsell and Nichols, 1982). Vermiculite and perlite may also improve the rewettability of root media (Bunt, 1988).

Irrigation method also can affect water absorption. Argo and Biernbaum (1994b) found that, with the same five media, an average of 0.5 L of water was absorbed with top watering, 0.38 L was absorbed with drip irrigation, and 0.19 L was absorbed with flood subirrigation. Under the conditions of the experiment, 0.60 L of water needed to be absorbed by the medium to reach the air:water ratio measured in the laboratory with a 24-h saturation period.

Much of the research on the rewettability of peat has dealt with the effect of wetting agents or surfactants. Many surfactants exist but relatively few are not phytotoxic to plants (Sheldrake and Matkin, 1969). Wetting agents are nonionic materials that bind to the surface of the root media particle and decrease the surface tension of the water, thus increasing the penetration of water into the root media (Valoras et al., 1976; Templeton, 1987). Wetting agents are commonly added to commercial peat based root media to aid in rewetting (Templeton, 1987).

The effect of a wetting agent can be relatively long lasting. Valoras et al. (1976) found that a nonionic surfactant did not degrade quickly in sphagnum peat. After 270 d, only 30% of the surfactant had decomposed in the peat compared to 70% degradation in a water repellent sandy loam soil. Argo and Biernbaum (1993) found no increase in water absorption by reapplying a wetting agent to 6-month-old hybrid impatiens (*Impatiens Wallerna* Hook F.) hanging baskets grown using long-fibered peat-based media compared to that of the same media not given the wetting agent. In all cases, a wetting agent was added to the medium at mixing (6 months prior). However, in media containing more degraded peats, the reapplication of a wetting agent was necessary to increase the rewetting of the medium 6 months after planting.

Moisture release characteristics

The water held in the root medium after an irrigation can be divided into water available to the plant (available water) and water that remains in the root medium even when the plant is wilted (unavailable water). The available water is reportedly held at moisture tensions of between 1 and 1467 kPa, 1 kPa would be the average tension in a root medium contained in a 20-cm-tall pot at container capacity and 1467 kPa would be the same root media at permanent wilt (Bunt, 1988; Milks et al., 1989) (1 kPa = 10 mbars x 10 cm water).

A reduction in plant growth is observed long before the moisture tension reaches 1467 kPa (Bunt, 1988). For example, Spomer and Langhans (1975) measured an increase in the growth of chrysanthemums (*Dendranthema grandiflora* Ramat) as the water content of the root media was increased to ~90% of pore saturation (by volume). Kiehl et al. (1992) also found that chrysanthemum fresh and dry weight decreased as the constant moisture tension the plants were grown at increased from 0.8 to 16 kPa. However, if the moisture tension were allowed to cycle between 0.8 and 16 kPa (medium was allowed to dry between irrigations), then the growth of the chrysanthemums was similar to the 0.8-kPa treatment.

The water content of container root media that is easily available to the plant is often reported to be held at tensions between 1 and 5 kPa. The water content of media held at moisture tensions between 5 and 10 kPa is termed water buffering capacity (De Boodt and Verdonck, 1972). Milks et al. (1989) termed the water held at moisture tensions above 30 kPa as being unavailable water. Verdonck et al. (1983) recommended that for optimal growth conditions, 30% to 45% (by volume) of the water held in a root media after an irrigation should be easily available water. Fonteno and Nelson (1990) found that two commercial root media had available water contents of ~35% by volume.

Peat type and particle size also affect moisture release. As with water holding capacity, the more degraded the peat, the greater the percentage of water held at higher moisture tensions (Puustjarvi and Robertson, 1975). The higher moisture tensions are due to the greater percentage of fine particles (<0.1 mm) and capillary pores small enough to retain water even at the high moisture tensions.

The difference between available water-holding capacity (AWHC) and water release from a root medium to the plant was illustrated by Beardsell et al. (1979b). Different organic and inorganic root media components were evaluated for both water holding capacity and days to wilt (water release). French marigold seedlings (*Tagetes patula* L.) were transplanted into the different components and allowed to acclimate. The components were then saturated with water and allowed to dry until wilt was observed. Of the organic materials, peat held the greatest amount of water after an irrigation, but plants grown in peat took the shortest period of time to wilt. Pine bark held 30% less available water than that of peat. However, plants grown in pine bark went 80% longer than that of plants grown in peat before wilt was observed. Transpiration rates (measured gravimetrically) for plants grown in peat were higher than that of plants grown in any other material tested. In all other materials besides peat, transpiration rates of the plants gradually decreased as water became limiting. This would indicate that for materials such as pine bark or sandy loam, there was a relatively small percentage of easily available water, but a large percentage of less available water (water buffering capacity) that could be absorbed by the plant, but not as quickly as easily available water. In comparison, peat contained a large percent-age of easily available water but once used up, there was relatively little water buffering capacity and the plants quickly wilted (Beardsell et al., 1979b).

Evaporation of water from the surface of the root media

Laurie (1950) commented on the large amount of water lost by peat due to surface evaporation. Peat fibers act as a wick, moving the internal moisture by capillarity to the surface where evaporation is most rapid. The more fibrous the peat, the greater the wicking effect and the greater amount of water lost due to surface evaporation.

In a experiment by Beardsell et al. (1979b), different materials were placed in 13-cm-tall pots and saturated with water. After draining, the pots were weighed to determine the amount of total water held in the pot. Weights were taken daily for the first 5 d and every other day for the remaining 8 d to determine the amount of water lost by evaporation from the surface of the media. Peat took 7 d to loose 0.25 L or 50% (by volume) the water held at container capacity by evaporation. In comparison, pine bark lost 0.10 L or 22% (by volume) of the total water held at container capacity over the same time period. Thus, the high water holding capacity of peat compared that of other material used in container media is offset in part by the large amount of water lost because of evaporation from the surface (Beardsell et al., 1979b).

Various researchers have estimated the amount of water lost from the pot due to evaporation from the surface of the root media during plant production to be 25% to 30% of the total amount of applied irrigation water (Argo and Biern baum, 1994a; Argo and Biernbaum, 1995b; Furuta et al., 1977; Van de Werken, 1989;Yelanich, 1995). Evapotranspiration can be reduced by simply placing a barrier over the surface of the root medium to block evaporation. Furuta (1976) reduced evapotranspira tion of Monterey pines (*Pinus radiata* D. Don) grown in 3.8-L pots by 26% with the use of a plastic disk placed over the surface of the root medium. Argo and Biernbaum (1994a) reduced evapotranspiration of Easter lilies (*Lilium longiflorum* Thunb.) grown in 15-cm-tall pots by 35% in the greenhouse and 56% in the post-production environment by placing a saran cover on the surface of the root medium. Argo and Biernbaum (1995b) reduced evapotranspiration of poin-settias (*Euphorbia pulcherrima* Willd.) grown in 15-cm-tall pots by 46% by placing a polystyrene disk on the surface of the root medium.

Conclusion

In transplant production media, water often is not a limitation because it can be applied at any frequency needed for growth (i.e., flotation trays, automated boom irrigation). Instead, aeration is the primary concern. There are at least three ways to increase aeration in transplant production media. The first is to use a coarser medium (increase the particle size). However, most transplant production medium has a very fine particle size in order to uniformly fill the production tray. The second is to increase the depth of the cell in the production tray (increase the container height). However, growers prefer shallower transplant production trays (personal communication, F. Blackmore, Black-more Co.). Increasing the depth of the cell also increases the volume of medium and water contained in the cell. Since water management often is used as a plant-growth regulator, increasing the volume of water contained in the production tray is thought to decrease the effectiveness of water management in controlling height. The third way to increase aeration is not to maintain the medium at container capacity. In bedding and potted plant production, water often is not applied in sufficient volumes for the medium to reach container capacity. In transplant production, sufficient water may be applied to reach container capacity, but the time spent at container capacity is low. The rate of media drying is increased with the use of horizontal airflow fans, under bench heating, and ventilated plug trays.

In the laboratory and the green-house, root-medium physical proper-ties are influenced by bulk density (Bunt, 1983; Beardsell et al., 1979a; Hanan et al., 1981), particle size (Puustjarvi and Robertson, 1975), and container height (Fonteno, 1988; Milks et al., 1989). In the greenhouse, physical properties also are influenced by irrigation method, applied water volume, and media mois ture content (Airhart et al., 1978; Argo and Biernbaum, 1994b; Beardsell and Nichols, 1982; Bunt, 1988). Finally, the amount of time the media is at or near container capacity may be relatively small because of plant transpiration and evaporation from the root medium surface (Argo and Biernbaum, 1994a, 1995b; Furuta, 1976). Understanding the root environment under production conditions requires an understanding of the dynamic nature of air: water ratio in the medium and the limitations of static laboratory physical property measurements.

Many experiments have been con-ducted to determine plant responses to root media with different physical properties. Often, the different root media are watered and fertilized identically (Bilderback et al., 1982; Brown and Emino, 1981; Fonteno and Nelson, 1990; Fonteno et al., 1981). The conclusions of these experiments could have been unintentionally biased because the experimental methods may have been optimized for a single medium or container size. To compare root media with different water-holding capacities or the same root media in different size containers, the total water-holding capacity and the amount of available water must be determined for each root medium or pot size individually. Irrigation scheduling should be based on loss of a specific volume of water from the medium and should be quantified either gravimetrically (Argo and Biernbaum, 1994a; 1995a; Yelanich, 1991;1995; Yelanich and Biernbaum, 1993) or with tensiometers (Kiehl et al., 1992) to ensure that specific treatments are not over- or underwatered. The volume of water leached from a pot should be quantified using container capacities leached (CCL) rather than leaching fraction (Yelanich, 1991) because CCL is based on a fixed volume of water (the container capacity of the medium) while leaching fraction is based on the volume of water applied which can change with each irrigation.

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