From Propagation to Field: Influence of Tray Design on Tree Seedling Quality and Performance[1]

Darby McGrath, Jason Henry, Ryan Munroe and Charlene Williams[2]

Abstract

This study evaluated the effects of low, moderate and high substrate exposure air-pruning propagation trays on eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall ssp. *deltoides*) and black cherry (*Prunus serotina* Ehrh.) seedling root system quality and overall performance. Root system quality was characterized primarily by proportion of coarse root defects within the container imprint. Seedlings were evaluated after a nearly four-month commercial greenhouse production phase and one year after transplanting into a nursery field. Above and below-ground growth were measured at both time points. Proportions of coarse root defects, indicating degree of root deflection in container production, were persistent between greenhouse and field production phases. The Open (high substrate exposure) tray produced seedlings with roughly three times less deflected coarse root weight compared to the Closed Wall (low substrate exposure) tray for both species in both production phases. At neither production phase were there significant differences in above-ground growth among trays. This corroborates findings from other research studies that have found that variable root system quality does not always result in above-ground growth differences; and that when it does, differences in growth may take several years to manifest.

Index words: tree seedling quality, root defects, transplant performance, above-ground growth.

Species used in this study: eastern cottonwood (*Populus deltoides* W. Bartram ex Marshall ssp. *deltoides*), black cherry (*Prunus serotina* Ehrh.).

Significance to the Horticulture Industry

The nature of root-constricting container growing has necessitated innovations in order to avoid producing permanently misdirected tree roots. One approach has been to use the growing substrate-air interface to naturally inhibit root growth. To that end, many iterations of propagation trays using various kinds of air-pruning features have been studied and used for decades. Air-pruning features have included different sized and shaped drainage holes, egress holes or slits on the sides of cell walls, and open, bounded substrate-using trays, which allow for air-pruning around the majority of the root ball with minimal plastic contact. Many container-propagated tree seedlings in the horticulture industry end up being upsized, either in the field or into larger containers. Still, seedlings may also be sold as plugs for naturalization plantings. Root systems with well-distributed structural roots, lateral root development and a lesser incidence of coarse root defects from an early age may perform better once transplanted or placed into a larger container. Additionally, reports that misdirected structural roots can reduce tree stability and, in some cases, reduce long-term vigor, highlight concerns about root system quality from the liner stage of production.

Introduction

Over the past several decades, forestry research has examined how different tree seedling propagation tray designs affect root system quality. Typically, studies have compared root systems produced among different tray cell designs or stock types, and have sometimes compared the results to naturally regenerated trees (Halter and Chanway 1993, Harrington et al. 1989, Lindström and Rune 1999, Nichols and Alm 1983, Ortega et al. 2006). This approach has contributed to an understanding of the types of root defects different propagation trays tend to produce, in addition to the influence of different planting methods. More recently, ornamental horticulture research has assessed root system quality coming out of different container designs and its influence on nursery stock quality (Allen et al. 2017, Amoroso et al. 2010, Appleton 1989, Gilman et al. 2010, Gilman et al. 2016). Research has focused on concerns around post-production longevity of container-grown trees with deformed root systems resultant from coarse roots being deflected by container walls (Gilman et al. 2003, Gilman and Paz 2014). Studies have centered on root system quality, tree stability and performance (survival and growth), and have provided the horticulture industry with important lessons, including methods to prevent and correct coarse root defects.

Previous research has found that propagation trays with reduced contact between the substrate and plastic structures tend to reduce the percentage of deformed roots (Gilman and Paz 2014, McGrath et al. 2017, Ortega et al. 2006, Rune 2003). Depending on the tree variety being propagated and its typical root system morphology, different cell designs will have varying results. For instance, aggressive tap rooting trees such as some oaks, pines and hickories will initiate the vast majority of their root growth early on to a large tap root, which, if not air-pruned effectively at the bottom of a container, can result in major defects, such as "L" or "J" roots (Miller and Bassuk 2018, Ortega et al. 2006). Not only do these deflected tap roots cause concern for future tree vitality, but

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[2]Vineland Research and Innovation Centre, 4890 Victoria Avenue North, Box 4000, Vineland Station, Ontario, L0R 2E0, Canada, Corresponding Author: darby.mcgrath@vinelandresearch.com.

the absence of effective air-pruning of tap roots can also reduce the amount of lateral root growth in propagation (Devine et al. 2009). Much of the research on tree seedling propagation and root morphology, in fact, has focused on commercial forestry species, many of which tend to produce single tap roots in propagation, for instance: radiata pine (*Pinus radiata* D. don) (Watson and Tombleson 2002), Scots pine (*Pinus sylvestris* L.) (Lindstrom and Rune 1999, Rune 2003), loblolly pine (*Pinus taeda* L.) and shortleaf pine (*Pinus echinata* Mill.) (Harrington et al. 1989), lodgepole pine (*Pinus contorta* Douglas ex. Loudon) (Halter and Chanway 1993), Italian stone pine (*Pinus pinea* L.) (Ortega et al. 2006), holly oak (*Quercus ilex* L.) and kermes oak (*Quercus coccifera* L.) (Tsakaldimi 2001).

In early stages of propagation, other problematic root defects arise as lateral roots develop. Deflections to lateral roots are most commonly oriented downwards, but can also spiral, kink or ascend (Gilman et al. 2010). Several studies have evaluated container-grown seedlings as they move through the nursery production system (Gilman and Paz 2014, Gilman and Harchick 2014, Gilman et al. 2016). These studies have found that root deflections from smaller containers, including propagation trays, were still evident in finished nursery trees. Similarly, research in forestry plantations has found that deflections occurring during nursery production in containers have a lasting impact on root morphology (Harrington et al. 1989, Nichols and Alm 1983). However, mixed results have been reported when evaluating the growth performance and wind firmness of tree seedlings years after out planting (Carlson et al. 1980, Halter et al. 1993, Halter and Chanway 1993, Lindström and Rune 1999, Preisig et al. 1979).

Longer-term effects of deformed coarse roots in large caliper transplanted trees have also been evaluated, with a particular interest in structural stability, which can sometimes be compromised (Gilman 2013). In scenarios where finishing nurseries purchase liners from specialized propagators, early stage production choices such as propagation trays may influence downstream nursery production, handling and the finished quality of trees. Therefore, a better understanding about the persistence of propagation tray effects in out-planted liners is needed. In general, the presence of multiple coarse, non-deflected lateral roots radiating outward from the root ball, with some roots located near the soil surface, especially for more shallow-rooting species (Watson and Tombleson 2002), are key features of 'high quality root systems'.

A variety of approaches have been utilized to reduce the incidence of deflected coarse roots, which if they occur, are often permanent. The main methods have included: chemical coatings of containers with root growth regulators (e.g. copper hydroxide), mechanical removal by shaving or pruning, modified container features (i.e. structural features of cells including a variety of shapes, ribs or grooves to guide roots to certain areas) and the use of air-pruning. Several studies have demonstrated that air-pruning is able to reduce the number of root deflections by influencing coarse root structural development (Frangi et al. 2016, Gilman and Paz 2014, Miller and Bassuk 2018, Ortega et al. 2006, Rune 2003). Many unique designs of propagation trays utilizing air-pruning have been commercialized in the last several decades. These have included designs that use enlarged drainage holes to better air-prune tap roots, vertically oriented slits of various sizes and circular holes placed around the container. Additionally, some cells are designed to hold Paperpot, Jiffy® or Ellepot™-bound substrates with minimal plastic contact, either along the sides of the substrate and/or at the bottom.

With the variety of commercial air-pruning products available, it is increasingly important for ornamental horticulture nursery producers to understand how the different designs influence seedling quality characteristics in the same way that forestry seedling producers have endeavoured to do (*sensu* Davis and Jacobs 2005). The purpose of the present study was to evaluate the influence of trays with differing levels of air-pruning available for use by commercial tree propagators in horticulture on select below and above-ground characteristics of seedling quality. Specifically, this study evaluates seed propagated eastern cottonwood and black cherry trees after a commercial greenhouse production phase of nearly four months (2017) and one year after transplanting seedlings into a nursery field (2018) to understand the persistence of propagation tray, root level effects on seedling quality.

Materials and Methods

Species selection. Eastern cottonwood and black cherry are fast-growing native species of southern Ontario and are commonly propagated from seed by the horticulture industry. Because these are early successional species (Taylor 2001, Uchytil 1991), they grow quickly under adequate environmental conditions, which makes them practical assessment species for examining root morphology in different propagation tray designs. Eastern cottonwood tends to produce a strong, single tap root (Schreiner 1971). Black cherry has a vigorous lateral and fibrous root system, as it is a shallow, surface-rooting species (Marquis 1990).

Propagation tray selection. For this study, three commercially available propagation trays were selected, representing a gradient of trays with low, medium and high substrate exposure to air for air-pruning. The key features and dimensions of the trays tested are outlined in Table 1. The propagation tray with low air-pruning capacity had cells with closed walls with four vertically oriented ribs to direct roots downwards and a drainage hole on the bottom. Hereafter this tray will be referred to as the 'Closed Wall' tray. The propagation tray with moderate air-pruning capacity had 24 small semi-circular holes around each propagation cell, with a large open drainage hole on the bottom supported by four thin diameter plastic braces. Each cell was suspended above the ground. Hereafter this tray will be referred to as the 'Semi Open' tray. The propagation tray with high air-pruning capacity was designed to be wall-less and bottomless. Four plastic prongs suspend a paperpot-bounded substrate above the ground with minimal plastic contact on the sides near the bottom of each propagation cell. The bottom of the

Table 1. **Features of each tree propagation tray type used in the present study.**

	Tray features			Cells features				
Tray type	**No. of cells**	**Length**	**Width**	**Top diameter**	**Depth**	**Volume**	**Density**	**Description**
Closed Wall	25	346 mm (13.6 in)	346 mm (13.6 in)	65 mm (2.56 in)	121 mm (4.75 in)	310 cm^3 (18.3 in^3)	206/m^2	Cylindrical solid-walled with 4 vertical ribs extending down inside of the sidewalls. Drainage hole at the bottom.
Semi Open	32	686 mm (27 in)	343 mm (13.5 in)	76 mm (3 in)	102 mm (4 in)	240 cm^3 (14.6 in^3)	136/m^2	Cells raised off the floor, 8 columns by 3 rows of equally spaced small semi-circle air-pruning holes placed along the sidewalls. Open drainage hole at the bottom with 4 thin plastic diameter support structures.
Open	25	375 mm (14.8 in)	375 mm (14.8 in)	60 mm (2.36 in)	100 mm (3.94 in)	283 cm^3 (17.3 in^3)	178/m^2	Cells raised off the floor, completely open along the sides and at the bottom except for minimal contact with 4 prongs holding Ellepots^{TM} in place.

paperpot is also completely exposed to air. Hereafter this tray will be referred to as the 'Open' tray.

Nursery trial set-up and data collection. Seedlings were grown in an open-wall, closed roof greenhouse at a commercial nursery operation (Verbinnen's Nusery Ltd., Dundas, ON, Canada) for close to four months. Seedlings were seeded on June 13 (black cherry) and June 20 (eastern cottonwood), 2017. Black cherry seeds were cold stratified prior to seeding. Fresh eastern cottonwood seeds collected in June were used. Seedlings were grown blocked together by tray type for ease of management in the same greenhouse area under a boom irrigation system. Seven propagation trays were used for both the Open and Closed Wall trays, and six Semi-Open trays were used for each species. Each Open and Closed Wall tray contained 25 seedlings each for a total of 175 seedlings grown in each tray per species. Each Semi-Open tray contained 32 seedlings for a total of 192 seedlings grown per species.

For the Open tray, Ellepots^{TM} were used with proprietary growing media containing 60% sphagnum peat moss, 30% perlite and 10% coir dust by volume. Ellepots^{TM} used in the Open tray had a paper thickness of 0.127 mm (0.005 in; Ellegaard A/S, Esbjerg, DK). To ensure consistency within the study, this proprietary growing media was also used in the other two propagation trays.

On October 10, 2017, height and stem diameters (taken 2.5 cm [1 in] above the root collar) in two perpendicular orientations were measured on all seedlings using a digital caliper. A subset of 10 seedlings from each tray type were randomly selected for destructive harvest and data collection. On these seedlings, coarse root defects (determined on roots with diameters $>$ 2 mm), where present, were separated at the point of deflection and weighed separately. Total coarse root dry weights were recorded. Roots were oven-dried at 60 C (140 F) until a constant weight was observed.

Field tray set-up and data collection. Using a random number generator, 84 eastern cottonwood and 84 black cherry seedlings (28 seedlings per tray type of each species) were randomly selected to be planted into a nursery field in which trees would be maintained (e.g. irrigated, fertilized, weeded and pruned). The nursery field site located in Vineland Station, Ontario (43°19′ N, 79°40′ W) had a silt loam texture, an average bulk density of 1.32 g/cm^3 and a soil organic matter content of 4.03% based on loss-on-ignition samples collected at a 0 to 30 cm (0 to 12 in) depth. Seedlings were hand planted on October 19, 2017 at a 2 m (6 ft) spacing. A complete block design was used with 28 blocks in total and one seedling of each tray type represented per block. White plastic spiral trunk guards were installed for each seedling. The following spring (May 2018), each seedling was top dressed with 9 g (0.3 oz) of control release fertilizer [18-6-8 (with minor nutrients) Nutricote Total Plant Products Co. Ltd.] and a 20 cm (8 in) diameter coco mat [(TE Weed Prevention COCODISC®) Timm Enterprises Ltd.] was placed on top of the soil under each seedling.

On September 4, 2018, height and stem diameter measurements [taken at 2.5 cm (1 in) above the soil line in one direction] were recorded for all trees using a digital caliper. A subset of seven trees per species produced in each of the three tray types was selected for destructive harvest from the first seven blocks (1 tree from each block) of the 28-block field. However, due to some tree mortality, between five and six trees were analyzed per species for each tray type. Trees were dug using a rear-mounted backhoe bucket attachment on a tractor. Following this, all roots [$>$ 3 mm (0.12 in) diameter] of these trees were pruned at the 10 cm (3.9 in) mark away from the center of the stem at the soil line and above-ground growth was discarded. The 10 cm (3.9 in) radius was chosen as a root ball size in order to examine the coarse root system directly associated with coarse roots produced in the propagation trays. It effectively excluded the influence of sinker roots and other coarse root branching that occurred in the field during the 2018 growing season. Any stem wood above the soil line, in addition to all roots with diameters smaller than 3 mm (0.12 in), were also cut off and discarded. Roots were then pruned at their point of exit from the propagation container imprint [$\sim$2.5 cm (1 in) from the stem] to obtain root weight outside the container imprint (all root growth between 2.5 cm and 10 cm from the stem). Dimensions of container imprints were determined either by visual inspection or by using the known dimensions of the

Table 2. **Below-ground growth of eastern cottonwood and black cherry seedlings after greenhouse nursery production in October 2017 and September 2018 on the nursery field site, one year after out planting. Different letters represent significant differences at p < 0.05.**

Species	Tray	~4 months in Greenhouse	One year in Field	
		Total coarse root dry weight (g)	Total coarse root dry weight (g)z	Coarse root dry weight outside container imprint (%)y
Eastern cottonwood	Closed Wall	1.70 a	115.1 a	45 a
	Semi Open	2.36 b	65.7 a	69 b
	Open	1.51 a	109.2 a	65 ab
Black cherry	Closed Wall	2.66 a	36.9 a	43 a
	Semi Open	2.50 a	38.4 a	56 a
	Open	3.02 a	41.4 a	49 a

zRefers to the total coarse root weight measured 10 cm [3.9 in] in all directions from the stem at the soil line.

yRefers to the percentage of the coarse root weight from the total coarse root weight measured between the container imprint (~2.5 cm [1 in] from the stem) and 10 cm [3.94 in] in all directions from the stem at the soil line.

propagation cell in which the tree was grown. Because of the influence of the cell features in each tray, it was frequently visually apparent where the container imprint was located after one year in the field. Deflected roots within the container imprint were pruned at their first point of deflection and those sections of roots were weighed to obtain a percentage of coarse root dry weight associated with defects within the container imprint. This measure is therefore comparable to the coarse root defect dry weight obtained in 2017. The percentage of coarse root weight outside the container imprint was analyzed in order to provide an indirect measure of the efficiency of coarse root exploration of field soil and the potential influence of root defects on root egression. All roots were oven-dried at 60 C until constant weight was observed.

Data analysis. Data presented in Tables 2 and 3 were analyzed using GraphPad Prism version 8.3.0 (GraphPad Software Inc., La Jolla, CA). Outlier data points were assessed using the ROUT Method with $Q = 1\%$. The analysis presented in Figures 1, 2, 4 and 5 was conducted in R 3.6.3 (R Core Team). For Tables 2 and 3, and Figures 1 and 2, one-way analysis of variance (ANOVA) and Kruskal-Wallis tests were administered after data were analyzed for normality and homogeneity of variance. Transformations of response variable data were attempted when appropriate to try to normalize data. The Tukey's or Dunn's Multiple Comparison post-hoc tests were used where necessary ($p < 0.05$). Percentage of coarse root dry weight associated with root defects between greenhouse and field production phases (Figures 4 and 5) was evaluated using Students t-tests and Mann-Whitney tests ($p < 0.05$).

Results and Discussion

Below-ground characteristics of seedling quality. During propagation, Open tray seedlings had significantly less coarse root weight associated with root defects (approximately three times less) compared to the Closed Wall tray-produced seedlings for both species (Fig. 1 and 2, $p < 0.01$). This finding is consistent with other studies (Gilman and Paz 2014, McGrath et al. 2017). McGrath et al. 2017 found that red maple (*Acer rubrum* L.), red oak (*Quercus rubra* L.) and trembling aspen (*Populus tremuloides* Michx.) seedlings grown in Ellepot^{TM}-bound substrate in an earlier pre-commercial version of the same Open tray used in the present study had a lower proportion of deformed roots as compared to a closed-wall tray. Gilman and Paz (2014) found that West Indian mahogany [*Swietenia mahagoni* (L.) Jacq.] seedlings grown in propagation trays also using Ellepot^{TM}-bound substrate, which were almost fully exposed to air, similar to the Open tray, had few root deflections. This was in contrast to a much higher incidence of deflected roots in a solid-walled plastic container, similar to the Closed Wall tray in the present study.

The maximum percentage of deflected coarse root weight did not rise above an average of 22% in eastern cottonwood seedlings or 15% in black cherries seedlings, in the Closed Wall tray (Fig. 1 and 2). These relatively low percentages occurred even though deflected lateral roots were commonly produced in this tray (Fig. 3). Most

Table 3. **Above-ground growth of eastern cottonwood and black cherry seedlings after greenhouse nursery production in October 2017 and in September 2018 on the nursery field site, one year after out planting. Different letters represent significant differences at p < 0.05.**

Species	Tray	~4 months in Greenhouse		One year in Field	
		Height (cm)	Average stem diameter (mm)	Height growth increment during 2018 (cm)	Trunk diameter growth increment (mm)
Eastern cottonwood	Closed Wall	62 a	4.47 a	146 a	27.4 a
	Semi Open	55 a	4.56 a	140 a	25.8 a
	Open	58 a	4.23 a	140 a	27.0 a
Black cherry	Closed Wall	50 a	4.74 a	72 a	10.9 a
	Semi Open	42 a	4.85 a	82 a	11.9 a
	Open	44 a	4.78 a	80 a	12.5 a

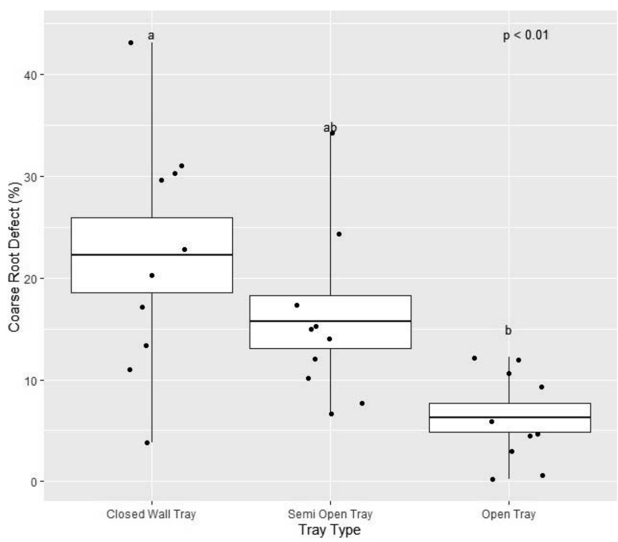

Fig. 1. Box and whisker plots depicting the percentage of coarse root dry weight associated with root defects in eastern cottonwood seedlings after completion of the greenhouse production phase. Different letters represent significant differences at $p < 0.05$. Each dot represents an individual tree root system.

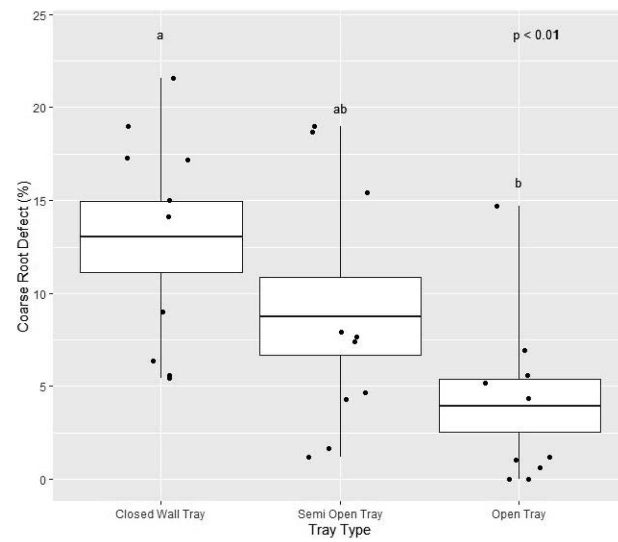

Fig. 2. Box and whisker plots depicting the percentage of coarse root dry weight associated with root defects in black cherry seedlings after completion of the greenhouse production phase. Different letters represent significant differences at $p < 0.05$. Each dot represents an individual tree root system.

incidences of root deflection only occurred on smaller, laterally initiated root growth, or on oblique roots, many of which may have formed in the later stages of seedling development in the greenhouse. The relatively low incidence of deflected tap roots of black cherry in the Closed Wall tray is likely a result of the presence of a drainage hole that, at least some of the time, served to air-prune the tap root as they extended. There was comparatively more effective water capture and greater moisture retention in the Closed Wall tray (personal communication, Alex Verbinnen, Verbinnen's Nursery, Ontario, Canada). Eastern cottonwood seedlings are reported to have relatively slow early stage root growth, which can be overcome with continuous access to moisture (Schreiner 1971). Therefore, the high levels of moisture in the Closed Wall tray may have promoted more rapid extension of the tap root. This would have allowed it to reach the drainage hole relatively rapidly, stimulating branching earlier than in the other trays. The pruning of tap roots at the drainage hole is known to initiate lateral branching (Hankin et al. 2019). Additionally, the late spring seeding ensured that excessive time in the trays did not occur. Black cherry seeds would typically have been sown in early April and eastern cottonwood in June (personal communication, Alex Verbinnen). Reduced time in propagation trays is known to help avoid formation and worsening of root defects (Balisky et al. 1995), which may otherwise have been more pronounced in the Closed Wall tray (McGrath et al. 2017).

After one year in the field, the eastern cottonwood trees grown in the Closed Wall tray, which had the highest percentage of coarse root defects, had the lowest percentage of root weight outside the container imprint. (Table 2). This indicates that a higher incidence of coarse root defects that persisted from propagation may have reduced the effectiveness of root extension into field soil one year after out planting. When comparing the root systems of all three trays from the greenhouse propagation phase with root systems after one year in the nursery field, there were no significant differences between the percentages of coarse root defects by tray type when comparing the trays to themselves in the greenhouse to the field phases (Fig. 4 and 5, $p > 0.05$). This indicates that the deflections that occurred in the propagation trays were persistent after planting, and may contribute to problems in later stages of production and the landscape (Harrington et al. 1989). Problems with tree health and performance have been linked to root deformities, even many years after out planting (Gilman et al. 2016). Although the long-term effects of included bark from entangled roots within the root ball are still not fully understood, studies have suggested they may be deleterious to future tree stability (Lindström and Rune 1999). For these reasons, coarse root defects are critical for nursery producers to consider when producing trees in propagation trays or purchasing them from propagation suppliers (Gilman et al. 2012).

After a production period of nearly four months after seeding, eastern cottonwood seedlings grown in the Semi Open tray had greater coarse root weight compared to the other two trays as measured inside the container imprint (Table 2). No significant differences in coarse root dry weight were observed among black cherry seedlings. However, after one growing season in the field, no total root weight differences were observed among trees grown in any of the tray types in either species (Table 2).

Above-ground characteristics of seedling quality. There were no significant above-ground growth differences between the three different tray designs for eastern cottonwood or black cherry seedlings after one growing season in the greenhouse (Table 3). Differences in cell volume, spacing (Landis et al. 2014) and capture of irrigation and fertilizer water are factors that would most directly influence above-ground growth. The Closed Wall

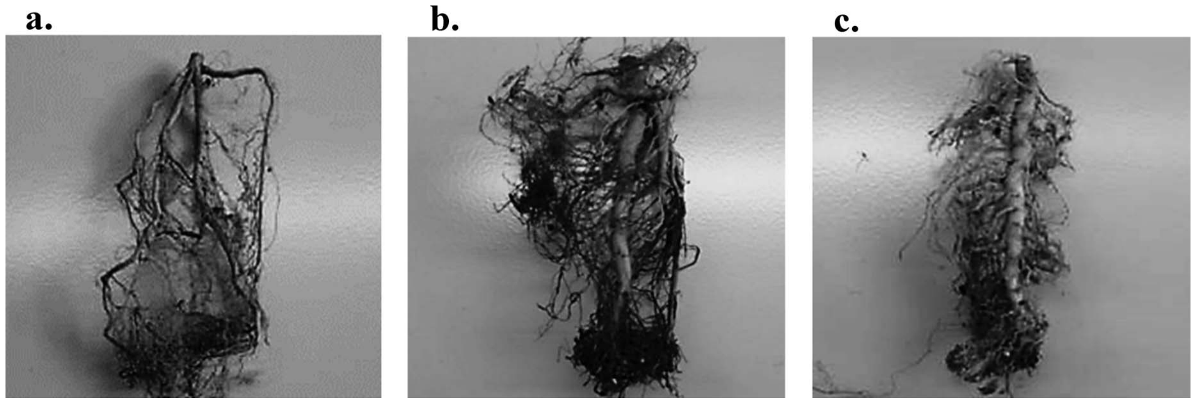

Fig. 3. Photographs of root-washed eastern cottonwood seedlings produced in the Closed Wall (a), Semi Open (b) and Open (c) tray in the commercial greenhouse in 2017. Photographs depict key coarse root features representative of what was observed in the three trays. Note the downward deflected surface lateral and root tips terminating at the bottom of the plug (a), the relatively greater incidence of undeflected lateral roots and effective air-pruning of the tap root (b), and the non-deflected lateral roots branching outward along the entire length of the air-pruned tap root (c).

tray had the largest cell volume of 310 cm^3 (19 in^3), followed by the Open tray at 283 cm^3 (17 in^3) and then the Semi Open tray at 240 cm^3 (15 in^3) (Table 1). Additionally, due to the design of the Open tray, for which the distributor recommends using frequent, cyclic irrigation, the Open tray captured the least amount of water during irrigation of the three trays, followed by the Semi Open tray and then the Closed Wall tray, which captured water most effectively from the boom irrigation system (personal communication, A. Verbinnen). These combined factors would suggest that the Closed Wall tray should have produced the largest seedlings. However, these differences were likely compensated for in the greenhouse as the nursery began monitoring seedlings more carefully and increasing water and fertigation as needed, thereby mitigating differences in growth that may have occurred otherwise.

After one growing season in the field, no height or stem diameter differences were observed among trees grown in any of the tray types in either species (Table 3). In forestry research, variable findings have been reported for above-ground growth differences as a result of propagation in different tray types. For instance, Rune (2003) did not find growth differences when measuring Scots pine six years after out planting seedlings from two different tray types (a closed wall design versus an air-pruning slit wall design). Lindström and Persson (1996) found that severe root deformation caused by solid-walled trays used for seedling propagation resulted in reduced above-ground growth in trees after six years (Rune 2003). Ortega et al. (2006) did observe some differences in growth among seedlings produced in trays with different degrees of air-pruning, but pointed to issues with nursery rearing and out planting techniques as stronger factors than container design and volume.

Other studies have found that container effects may take longer to impact above-ground growth. Marshall and Gilman (1998) reported no differences in root or canopy growth of red maples produced in seven different #15 container types five months after planting, but after five years Gilman et al. (2003), in a follow-up paper, noticed large, significant differences in the trunk cross-sectional area between several of the container types. The study reported differences in root weight and number of deflected roots in different container types after nursery production (Gilman et al. 2003). Halter et al. (1993) found the retention of vertically oriented roots, and the presence of kinked, coiled or constricted roots in container-grown

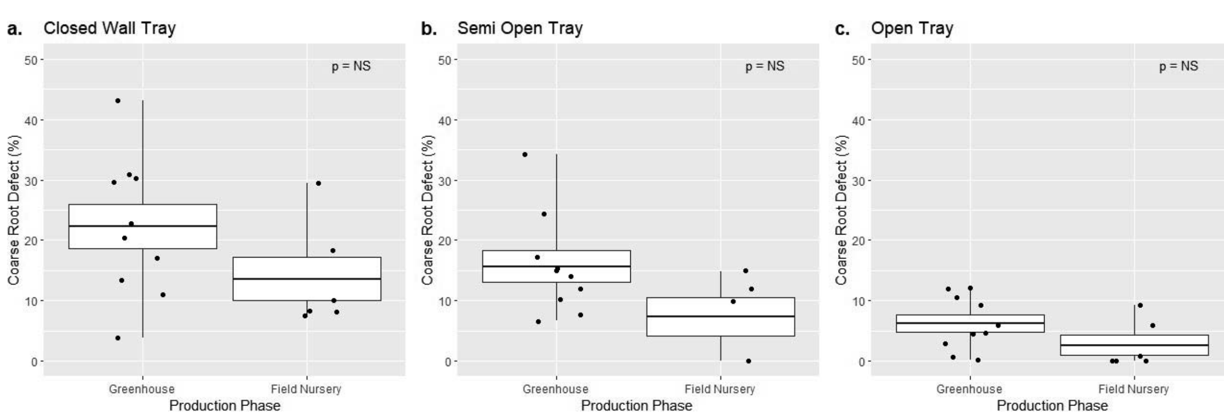

Fig. 4. Box and whisker plots depicting the percentage of coarse root dry weight within the container imprint associated with root defects in eastern cottonwood trees after completion of the greenhouse production phase and one year in the field nursery. Different letters represent significant differences at $p < 0.05$. Each dot represents an individual tree root system.

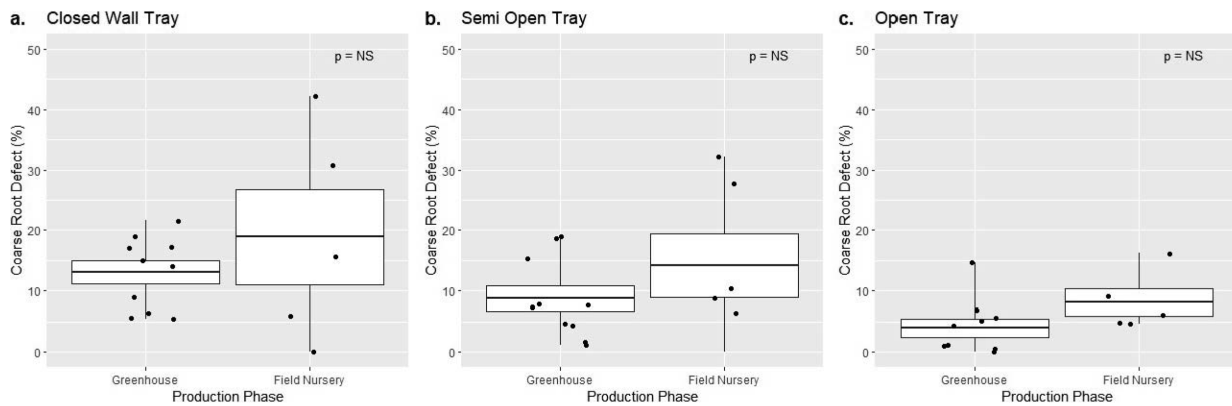

Fig. 5. Box and whisker plots depicting the percentage of coarse root dry weight within the container imprint associated with root defects in black cherry trees after completion of the greenhouse production phase and one year in the field nursery. Different letters represent significant differences at $p < 0.05$. Each dot represents an individual tree root system.

lodgepole pine saplings. These defects were tied to reduced height, poor root distribution (symmetry) of laterals, fewer first order laterals and greater distance from the ground line to the first structural lateral root compared to naturally regenerated trees of the same age (twelve-years old). Differences in above-ground growth therefore may only manifest after several years, highlighting the shortcomings of using mainly above-ground metrics as measures of seedling quality.

Although more recent versions of nursery stock standards include more information on assessing root morphology, e.g., the Florida Grades and Standards for Nursery Plants 2015 (Anonymous 1998), Canadian Nursery Stock Standard 9th Edition (Heuver and Lumis 2017), to-date seedling and tree quality are still primarily assessed using above-ground characteristics in ornamental nursery stock production. Height and stem diameter are the most commonly evaluated traits used during seedling quality assessment. Forestry research, and the studies discussed above, have demonstrated that above-ground qualities alone do not represent overall seedling quality and are not necessarily reflective of below-ground qualities. Forestry research has long called for the consideration of root morphology for assessing quality because it is a good predictor of seedling performance potential (Davis and Jacobs 2005). Below ground measures may be more indicative of potential developmental concerns such as poor root distribution, altered rooting depth and restricted root growth in early growth stages in nursery production. The present study finds that root defects from propagation persisted in the field one year after planting. This was not reflected in above-ground growth. Additional metrics for characterizing root systems are needed for nursery production that can effectively demonstrate the influence of root system morphology on overall nursery stock quality and transplantability.

After assessing eastern cottonwood and black cherry seedlings grown in three different commercially available propagation trays with different levels of air-pruning at two time points, the findings suggest that the more open walls and bottoms of the air-pruning tray cells resulted in fewer occurrences of deflections during propagation. The study also demonstrates that deflections of coarse roots that occurred in propagation persisted in the nursery field one-year after transplanting. Neither during propagation nor after planting in the nursery field was above-ground growth impacted by variable root system quality.

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