Species and Transplant Size Influence Post-Transplant Survival, Growth and Root Regeneration of Three Oak Species

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ABSTRACT

Three oak species (swamp white oak [*Quercus bicolor* Willd.], scarlet oak [*Quercus coccinea* Münchh.], and bur oak [*Quercus macrocarpa* Michx.]) at three caliper sizes (small - 3.8 cm [1.5 in], medium - 6.4 cm [2.5 in], and large - 10.2 cm [4 in]) were transplanted balled and burlapped in spring within a nursery where they were subject to the same environmental conditions over three growing seasons. Nine treatments (the interaction of all species and size variables) were analyzed to determine the influence caliper size and species had on mortality, canopy dieback, canopy growth and root growth.

Caliper size had no influence on post-transplant leaf area for all species, while species influence on post-transplant leaf area was difficult to measure due to leaf morphology differences between these oak species. Shoot growth for all treatments was consistently well below that of the control trees over all three growing seasons, with only one exception. In this study, mortality and canopy dieback data provided better measures of post-transplant performance than canopy growth data.

Transplanted trees were considered successful if they not only survived but also thrived (had less than 20% canopy dieback). All three species transplanted equally well at the small caliper size. Species significantly influenced transplant survival and success rates for both the medium caliper and large caliper treatments. For both of these caliper size treatments swamp white oaks had higher survival and success rates than either other species, with the exception of the large caliper scarlet oaks that were equal in survival

alone to the large caliper swamp white oaks. Additionally, more medium and large caliper scarlet oak transplants survived and thrived than bur oaks at those sizes.

Caliper size only significantly influenced post-transplant performance of bur oaks, with smaller caliper trees transplanting with greater survival and success. Although caliper size did not significantly influence post-transplant performance for scarlet oaks and swamp white oaks, both species did trend toward fewer large caliper trees thriving than either other caliper size. This study suggests that the influence of caliper size on post-transplant performance strongly varies between species, even for species within the same genera, due at least in part to root system morphology. The species that had the most fibrous root system, swamp white oak, transplanted with the greatest success and the species with the coarsest root system, bur oaks, transplanted with the least success.

There was a strong positive relationship between the number of roots that are cut during the transplanting process and the number of new roots per tree that developed at the ends of those severed roots after transplanting. However, the influence that the number of cut roots had on the number of new roots per tree that were produced differed greatly by species. When the same number of roots per tree were cut, swamp white oaks generally produced more new roots per tree than either other species and scarlet oaks generally produced more new roots than bur oaks.

BIOGRAPHICAL SKETCH

Deanna F. Curtis received a Bachelor of Science degree in horticulture from Michigan State University in 2000.

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CHAPTER 1

LITERATURE REVIEW

1.1 CALIPER SIZE INFLUENCE ON TRANSPLANT SUCCESS

Urban trees are increasingly being transplanted at larger sizes to provide instant visual impact, with the expectation that they will fulfill their landscape design intent faster than smaller trees. A survey of current tree establishment practices in urban areas within 17 European countries concluded that the planting of larger trees (6.4-9.5 cm [2.5-3.7 in.], measured at 1.3m from the ground) was on the rise in Europe (Pauleit et al. 2002).

There is a common belief in the horticulture industry that smaller caliper balled and burlapped (B&B) trees may overcome the period of post-transplant stress more easily than larger ones, especially those species considered ‘difficult to transplant.’ Watson asserted that a transplanted tree requires one year for every 2.5 cm (or about 1 inch) of caliper to resume normal growth in its new site (Watson 1987). In reality, there are no real data to support this claim and only limited or theoretical data suggesting that smaller caliper trees may transplant with greater success than larger caliper trees.

Beyond simply surviving, trees are typically considered to have been transplanted successfully once they have become established in their new location. Establishment is equated with recovery from post-transplant stress, often referred to as transplant shock. Transplant shock describes the period of reduced growth that follows extreme root loss during harvest (Watson 1986);

specifically, a reduction in shoot extension, leaf area and leaf quantity compared with that of pre-transplant trees (Struve 1994). Establishment rates are often measured by comparing pre-transplant growth rates with post-transplant growth rates. Recovery from transplant shock implies a return to pre-transplant growth rates. Moreover, it is often argued that a tree will be unable to fully resume these healthy pre-transplant growth rates, and therefore will not be fully established, until the tree regains its natural balance between the growth below and above ground – its root to shoot ratio. (Borchert 1973; Geisler and Ferree 1984; Watson 1985).

1.1.1 Watson's Theoretical Model

Based on this idea that any root:shoot imbalance inhibits vigor, Watson created a model to illustrate his theory that smaller caliper trees 2.5-7.6 cm (1-3 in.), if given identical growing conditions, would eventually reach or exceed the size of larger caliper trees 10.2 cm (4 in. and above) over time, often before the larger trees have recovered from transplant shock (Watson 1985). In this paper, 'Tree size affects root regeneration and top growth after transplanting,' Watson contended that the smaller caliper trees would reach their pre-transplant root:shoot ratios sooner than large caliper trees of the same species. He asserted that despite the removal of a proportional amount of the root system when transplanted, larger trees leave behind a greater root mass and length, which will take longer to replace than that of smaller tree, assuming identical root growth rates among caliper sizes.

Early in his paper Watson referenced small caliper trees as 2.5-7.6 cm (1-3 in.) DBH (diameter measured at 1.37m [4.5'] above ground) and large caliper trees as 10.2 cm (4 in.) DBH and above. However, for the model described in the paper he used 10.2 cm (4 in.) DBH as the small caliper size and 25.4 cm (10 in.) DBH as the large caliper size – both arguably large by his own standards.

To create this model, Watson used an average regenerated root growth rate (for northern United States climates) of 45.7cm (18 in.) in length per year which radiated out from the severed roots of the transplanted root ball in all directions and resulted in the 91.4cm (3 ft.) yearly incremental increase in root system diameter shown in the model diagrams. This root growth rate is based on results from a previous study examining seasonal variation in root regeneration of transplanted trees for three species showing a root growth range of 4.7-10.6 cm (12-27 in.) per year (Watson and Himelick 1982). The author does concede that different species would have different root growth rates but he does not mention the possibility that two transplant sizes of the same species may regenerate roots at different rates. In addition, no study is referenced for the original size of the root system of either size tree used in the model.

The model predicted that after five years the smaller caliper tree would have replaced its original root system, while the larger caliper tree would have approximately 25 percent of its original root system. The model also predicted that it would take nearly 13 years for the larger tree to replace its original root system, by which point the smaller tree would have a similar size root spread and thereby a similar crown size to the larger tree. This model assumes an equal and constant yearly growth rate for roots and shoots for both species at both sizes but this is unlikely because, as Watson suggests, the smaller tree would have been growing more vigorously for a portion of those 13 years, having restored its root:shoot balance, and would potentially have surpassed the larger transplant in canopy size by that time. Due to the many assumptions made, this model may not accurately predict the time needed for two trees transplanted at different sizes to regenerate their existing root systems after transplanting nor the time needed to reach equal canopy size.

Following Watson's paper, three subsequent studies have examined, at least in part, the influence of transplant caliper size on transplant success.

1.1.2 Lauderdale et al. Study with Red Maples

In 1993 Lauderdale et al. examined the effect of transplant size on post-transplant growth, gas exchange and leaf water potential of balled and burlapped 'October Glory' red maple (*Acer rubrum* L.) at two transplant sizes, 3.8 cm (1.5 in.) and 7.6 cm (3 in.) (Lauderdale et al. 1995). In their study eight trees of each size were transplanted in May at two separate locations (a city park and a residential site) in Mobile, Alabama where they collected data from that growing season and the next. All trees were hand irrigated twice a week during the first summer after transplanting and were fertilized once in the spring of the second growing season.

Gas exchange and leaf water potential were measured in August 1993, June 1994 and August 1994. Gas exchange was measured for all trees by: net photosynthesis, to indicate general stress; transpiration, to indicate the potential for water and nutrient uptake by the roots; leaf stomatal conductance, to indicate moisture stress; and water-use efficiency. The smaller caliper trees had significantly higher net photosynthesis and transpiration rates, along with greater stomatal conductance rates, than those of the larger caliper trees for all three months measured. The calculated water-use efficiency observations indicated that the smaller trees used water more efficiently than the larger trees during both June and August of the second season. The smaller caliper trees had significantly higher (less negative) daily and pre-dawn leaf water potentials in the first growing season only. Lauderdale *et al*. asserted that gas exchange and leaf water potential data suggested that smaller caliper 'October Glory' red maple trees had a greater ability to overcome post-transplant moisture stresses than those transplanted at larger sizes. This ability to better overcome post-transplant stress may have accounted for the higher growth rates they found for the smaller trees.

Growth was quantified by three measurements: height increase, shoot elongation, and trunk diameter increase. While all three measurements showed greater average growth for the smaller trees than that of the larger trees, only shoot elongation proved to be significantly greater in the first year. However, this may be due to the fact that the authors only recorded growth measurements on trees that had less than 25% crown dieback in the first year. One small tree and six larger trees (out of sixteen trees total of each size) were excluded from the data set, as they experienced greater than 25% crown dieback. If the growth rates of all trees had been included, the results may also have shown significantly greater height and trunk diameter increases for the small trees during the first year. Further dieback information discussed in the study indicated that the smaller trees displayed fewer signs of transplant shock in the form of dieback the first year, as only one small tree had any amount of crown dieback and fifteen of the sixteen larger trees had varying levels of crown dieback.

The smaller caliper trees had significantly greater growth than the larger caliper trees for all three measurements in the second year of the study, in which two small and one large tree had more than 25% crown dieback and were excluded from the data set. Additionally, the authors noted that in the second year of the study fewer trees displayed dieback than the previous season, with only two small and three large trees exhibiting crown dieback. It is unclear as to whether this reduction in dieback from the first year to the second is due to regenerated new growth in the crown portions considered to have died back the first year or if the authors were only recording the change in dieback from the previous year.

Potentially confounding factors in the Lauderdale et al. study include the pre-transplant history and handling of the trees, as well as their new planting sites. It is unclear if the trees came from the same nursery where they had been subject to the same growing condition or if they were dug on or near the same date. Lauderdale reported that both sites had very similar soil texture and that the soil pH ranged from 5.4-7.1 in the park and from 5.7-6.0 at the residential site. No mention is made of bulk density testing to compare compaction rates between each site. There was an attempt to control for any differences in site soil conditions by transplanting eight repetitions of each size at each location. However, despite seemingly similar soil conditions, urban and sub-urban landscapes can have extreme variable soil conditions even within very small areas due to human manipulations of these sites over time. Assuming these potentially confounding factors were accounted for, the authors showed that transplant size of red maples is an important variable in post-transplant performance. Lauderdale et al. concluded that smaller red maple transplants had greater growth rates and showed a greater ability to overcome post-transplant stress (specifically water stress) than larger transplants and, therefore, were able to establish themselves more quickly in the landscape.

1.1.3 Gilman et al. Study with Live Oaks.

Gilman et al. compared data from two related experiments with live oaks (*Quercus virigiana* Mill.) conducted from 1992 to 1995 in Gainesville, Florida that examined the influence of irrigation volume and frequency, in connection with various production methods, on post-transplant growth to investigate how size affects post-transplant establishment rates (Gilman et al. 1998). The first experiment utilized small caliper trees with trunk diameters ranging from 6.0 to 6.5 cm (2.5 to 2.7 in.) measured at 15 cm (6 in.) from the ground and the second experiment utilized large caliper trees with trunk diameters ranging from 8.9 to 9.9 cm (3.5 to 3.9 in.), also measured at 15cm from the ground. Trunk diameter and tree height growth data from these experiments were then used to compare the effects of tree caliper size on post-transplant growth and establishment.

The trees within each separate experiment had multiple pre-transplant production history differences, in addition to differences in post-transplant care. In the first experiment, 60 container-grown trees in #25 pots and 60 field-grown B&B trees dug in the fall of 1991 were transplanted in February 1992. All the trees in the second experiment were transplanted in May 1992 and included 10 nursery container- grown trees in 246L (65 gal) pots, 10 nursery field-grown B&B trees that were dug in late January 1992, then held over in a nursery and placed on drip irrigation until planting, and 10 wild-grown B&B dug trees which were not used in the caliper size comparisons. The field-grown B&B dug trees in the second experiment had been on drip irrigation, fertilized frequently and root pruned at least once a year since being planted in the field in November 1987. The first experiment used three irrigation volumes, each at two frequency intervals, but the second experiment examined only two frequency intervals which were not identical to those applied in the first experiment. Both studies provided irrigation only during the first year after transplanting and fertilized all trees each year with an ammonium nitrate surface application three times per year. Post transplant care in the second experiment also included mulch applications for all trees.

Three of the smaller caliper container-grown trees from the first experiment died in the first year, while all larger caliper trees of either production method survived. Gilman *et al*. showed that the smaller caliper live oaks increased in both trunk diameter and tree height faster than the larger caliper trees. However, any survival or growth data from these studies were not comparable due to many differing variables between these two experiments. Additionally, the authors concluded that ‘small nursery trees grew faster after transplanting than large ones because roots came into balance with shoots sooner,’ although no root growth was measured.

1.1.4 Struve et al. Study with Red Oaks

In the most recent study of the influence of caliper size on transplant success, Struve *et al.* compared the survival and post-transplant growth of two caliper sizes, 3.6 cm (1.4 in.) and 8.4 cm (3.3 in.), of red oak (*Quercus rubra* L.) over four growing seasons (Struve et al. 2000). They created two small caliper vigor treatments (low and high) in an attempt to control for pre-transplant growth vigor. The low vigor and high vigor designations were determined by the tree’s pre-transplant early liner growth: low vigor trees were approximately 1m (3 ft) tall and the high vigor trees were 2m (6ft) when lined out in 1993, three years prior to transplanting. The trees in the larger caliper treatment were not given a vigor-class designation and were all 1 to 1.3 m (3 to 4 ft.) tall when lined out in 1988, eight years prior to transplanting. Twelve trees of each small caliper treatment, along with twelve of the large caliper trees, were transplanted in spring of 1996. Five small caliper trees (3 low vigor, 2 high vigor) were not transplanted for use as controls.

The authors suggested that in typical nursery field production practices the trees sold at larger caliper sizes were generally harvested last from a given nursery block and were, therefore, genetically inferior due to the early removal and sale of the more vigorous trees at smaller caliper sizes. They proposed that the sale of these less vigorous trees at larger caliper sizes may have contributed to the poor performance often observed with larger caliper transplants. The low vigor trees in this study were meant to represent these slower-growing trees thought to be left behind in the nursery for harvest. However, over the four growing seasons, the low vigor small caliper trees performed as well as, if not better, than those designated as high vigor. Growth was measured by leaf area and shoot length for three growing seasons and by height and trunk caliper for four growing seasons. The small caliper trees showed no statistical difference between the low vigor and high vigor trees for all growth measurements each growing season, with the exception of the third growing season in which the lower vigor trees actually had significantly longer shoot length than the higher vigor trees.

The authors tried to account for other potentially confounding factors. They collected seed from the same mother tree to control for intraspecific genetic variability among non-clonal trees. They also adjusted their planting practices to provide nearly equal backfill to root-ball volume ratio for both caliper sizes. Lastly, they attempted to control for relative canopy to root-ball volume by raising the crowns of the larger trees from about 2m (6ft) to about 3m (8ft) immediately post-transplant. However, this removal of top growth on only one caliper size may have actually further confounded the examination of the effect of caliper size in this study.

No small caliper trees died over the course of the study, while seven out of the twelve larger caliper trees (58%) died during the second growing season. The authors attributed this high mortality rate in part to the tree's deep planting depth (a result of settling), as well as production history. They speculated that the lack of root pruning led to a lack of root regeneration for the larger trees. However, no roots were examined and no root measurements were taken in this study.

Despite the high mortality rates for the larger trees, Struve et al. concluded that large caliper red oaks can establish themselves equally well as small caliper red oaks after transplanting. This conclusion not only excluded mortality rates, but a portion of the growth data as well. Based on only two of the four growth measurements taken in this study (tree height and trunk caliper), the authors concluded that the surviving large caliper trees (five trees) actually had greater post-transplant growth than the smaller caliper trees. Exact height and trunk diameters were used for statistical analysis and did show the large caliper trees to be significantly taller and have significantly greater trunk diameters each year than the small caliper transplanted trees. However, due to the fact that the larger trees were not the same size when the experiment began, it may have been more useful to draw conclusions from the examination of the annual growth rates. While no statistical analysis was performed on the annual growth rate measurements, the authors did discuss portions of this data. Some of these results appear to contradict their above conclusions, showing the smaller trees to have had greater post-transplant growth than the larger trees. In the fourth growing season the smaller caliper trees of either vigor class still had more than double the annual height increase of the surviving larger caliper trees.

Similarly the leaf area measurements contradicted the conclusion that the surviving large caliper trees actually had greater post-transplant growth than the smaller caliper trees, though shoot growth data was inconsistent over the course of the study. Leaf area data showed the smaller caliper trees to have out performed the larger caliper trees after three years. The large caliper trees had significantly less leaf area than all other trees in the third year. In contrast, both the low vigor and high vigor small caliper transplants had similar leaf areas to the untransplanted controls, suggesting that they had recovered from post-transplant stress and were established.

Struve *et al.* attempted to determine establishment by comparing pre-transplant and post-transplant growth rates for both trunk caliper and tree height with incompatible results. The authors compared the three-year average increase in trunk caliper of each transplant treatment with that of untransplanted small caliper trees, as well as with the average pre-transplant growth rate of the larger trees (determined from growth ring measurements of seven randomly selected larger trees culled pre-transplant for the purpose of measuring pre-transplant vigor), and concluded that none of the transplanted trees could be considered established after comparing trunk caliper data. Alternately, they noted that in the third year of the study all transplanted trees exceeded their pre-transplant height growth rates. However, when the authors examined the three-year average height increase of transplant treatments they found only the small caliper low vigor transplants to have growth equal or greater to their pre-transplant growth rate and that the untransplanted small caliper trees actually had the smallest average height increase during those three years. Consequently, tree height may not be the most useful way to determine post-transplant success and establishment.

The authors also considered the establishment of the transplanted trees in another way. All trees in the study were irrigated three times during the first two growing seasons but no irrigation was provided in the third year. They noted that despite below average rainfall from May through October during the third growing season, none of the trees showed any visible signs of drought stress such as foliar discoloration, leaf scorch, early fall color or defoliation. The authors asserted that all surviving transplanted trees could be considered established after three years due to the lack of need for supplemental irrigation. Regardless of the establishment by any surviving large caliper trees, over half of them died. Consequently, the small caliper red oaks in this study transplanted far more successfully than did the large caliper red oaks.

Following these studies further research was needed regarding the influence of transplant size on post-transplant growth and establishment. Watson's model was only theoretical and not based on canopy or root growth data and Gilman et al. findings are negated by the fact that the study combined data from two separate experiments. Both Lauderdale et al. and Struve et al. did show caliper size to have influenced transplant success, despite Struve et al. conclusions to the contrary. Lauderdale et al. dieback observations and Struve et al. mortality data demonstrated the effect of caliper size on post-transplant performance, with the smaller trees in both studies clearly outperforming the larger trees. These two studies based their conclusions upon canopy growth measurements. Lauderdale et al. concluded that smaller caliper red maples had significantly greater post-transplant annual growth rates than larger caliper trees and attributed this to the smaller tree's greater ability to manage post-transplant moisture stress based upon gas exchange and leaf water potential data. However, Struve et al. misleadingly based their conclusions that surviving large caliper red oaks had greater post-transplant growth than smaller caliper trees by comparing the current year's growth measurements rather than yearly growth rates. None of these studies analyzed more than one species nor did they measure post-transplant root growth. This study was initiated to further investigate the influence of caliper size on transplant success by examining the influence of caliper size in connection with that of species and by examining post-transplant root growth.

1.2 SPECIES INFLUENCE ON TRANSPLANT SUCCESS

Two of the three transplant size studies previously mentioned used oak species. Oaks were chosen for this study because, while they are very desirable urban trees, they are often underutilized due to their perception as relatively difficult to transplant. All three species of oaks used in this study (swamp white oak [*Quercus bicolor* Willd.], scarlet oak [*Quercus coccinea* Münchh.], and bur oak [*Quercus macrocarpa* Michx.]) are considered tolerant of urban conditions (Dirr 2009; Hightshoe 1988; Watson and Himelick 1997) while the reports of their transplantability vary. Existing information on the transplantability of swamp white oak is conflicting. Dirr states that the reports on transplantability from nurseryman are quite varied for swamp white oaks (Dirr 2009). Hightshoe noted that the species transplanted readily balled and burlapped (Hightshoe 1988); while Watson and Himelick only gave swamp white oak an intermediate ranking of #2-3 on their 'transplanting ease' scale in which the highest ranking of #1 equals 'plants most readily transplanted' and the lowest ranking of #4 equals 'plants most difficult to transplant' based upon the species ‘ability to generate new roots and tolerate stress following transplanting’ (Watson and Himelick 1997). Less information is available on the transplantability of scarlet oaks. Hightshoe states that they are difficult to transplant; while neither Dirr nor Watson and Himelick make any mention of their ease of transplant. All three sources consider bur oaks difficult to transplant; both Dirr and Hightshoe state as much and Watson and Himelick rank this species at a #3 for transplanting ease.

Transplant harvest method has been shown to influence the transplant success of these three species differently. Previous research done at Cornell on scarlet oaks indicated they have higher transplant survival rates when transplanted balled and burlapped vs. bare-root (Maguire 2004). However, when transplanted bare-root, scarlet oak transplanted well in early spring and mid fall but poorly in late spring and early fall (Harris and Bassuk 1994). Research on swamp white oak showed that it transplanted equally well balled and burlapped or bare-root (Buckstrup and Bassuk 2000). Observational data of Q. macrocarpa showed that it transplanted poorly bare-root, with only a 50 percent survival rate (Buckstrup and Bassuk 2009).

1.3 STUDY OBJECTIVE

Species that transplant unsuccessfully are frequently replaced with more commonly used species thought to be easier to transplant; this decreases tree diversity and promotes monocultures in our urban landscapes. Reducing the need to replace failed transplanted trees will reduce energy and cost and will benefit both landscape contractors and consumers. The objective of this study was to examine the effects of both species and caliper size on post-transplant survival, growth, and root regeneration of swamp white, scarlet, and bur oak to identify the most appropriate size to transplant each of these oak species successfully and aid in their greater use.

CHAPTER 2

MATERIALS AND METHODS

2.1 PLANT MATERIAL & PLANTING PROCEDURE

Three oak species (swamp white oak - *Quercus bicolor* [B], scarlet oak - *Q. coccinea* [C], and bur oak - *Q. macrocarpa* [M]) of three caliper sizes (small - 3.8 cm [1.5 in], medium - 6.4 cm [2.5 in], and large - 10.2 cm [4 in]) were transplanted at Schitchtel's Nursery in Springville, New York, on May 22, 2006. The combination of each species at each caliper size resulted in nine transplant treatments (B3.8, B6.4, B10.2, C3.8, C6.4, C10.2, M3.8, M6.4, and M10.2). Six repetitions per treatment resulted in 54 transplanted trees. An equal number of each species at each size were left undisturbed within the nursery as control trees for canopy growth comparison.

The transplanted oaks were harvested, transported to another field, and then planted – all within Schitchtel's Nursery. Weather conditions (cloudy with cool temperatures and light precipitation) were ideal for transplanting. The nursery environment provided the most uniform conditions possible, minimizing microclimate and soil variations, as well as post-transplant stress. All trees were originally planted at the nursery as lightly branched liners and had been established three or more years prior to transplanting.

Transplanted oaks were dug using a Vermeer tree spade (Vermeer Corporation – Pella, IA) and balled and burlapped (B&B) in wire baskets one day prior to transplanting. All tree specifications conformed to or exceeded the

American Nursery and Landscape Association's ANSI Z60.1-2004 standards for field-grown, shade tree nursery stock. Rootball dimensions were 61 cm (24 in), 71 cm (28 in), and 107 cm (42 in) for the respective trunk diameter sizes of 3.8 cm (1.5 in), 6.4 cm (2.5 in), and 10.2 cm (4 in).

Planting-holes were dug using a back-hoe and then backfilled without soil amendments after planting. There was no soil compaction or glazing of the holes from heavy equipment due to the soil structure. The nursery soil was a Chenango gravelly loam, with a ph range of 6.6-7.0. Planting-hole sizes were comparable to root-ball sizes due to the soil quality and compatibility from harvest site to planting site within the nursery. All rope was removed from root-balls, while only the upper one-third of the burlap and wire basket was removed, leaving remaining burlap and wire for stabilization. Trees were planted at the appropriate depth to allow for root flare visibility at grade. Tree species were randomly arranged within each caliper size group. Trees were spaced to allow for full canopy sun exposure.

Transplants were irrigated during the first growing season only. Each tree received a 20-gal (76-L) Treegator® slow release watering bag (Spectrum Products, Inc. – Youngsville, NC), which was filled with water when a week had passed without significant precipitation.

Rainfall from May to September in the Springville, NY area is shown below in *Table 1*. In the first growing season rainfall was below normal in May and June but then well above average July through September. Rainfall was consistently below normal for the entire second growing season. In the third growing season rainfall was below normal in May and Sept., normal in June, and then above normal in July and August.

Table 1: Precipitation Rates. Monthly rainfall data for Franklinville, NY during each growing season (Northeast Regional Climate Center).

	Rainfall - cm (in.)				
Year	**May**	**June**	**July**	**Aug**	**Sept.**
2006	7.9 (3.1)	6.9 (2.7)	18 (7.1)	13.2 (5.2)	15.5 (6.1)
2007	3.3 (1.3)	6.9 (2.7)	9.4 (3.7)	8.1 (3.2)	8.9 (3.5)
2008	8.4 (3.3)	11.4 (4.5)	13.2 (5.2)	10.4 (4.1)	9.4 (3.7)
Normal	9.1 (3.6)	11.4 (4.5)	10.2 (4.0)	9.7 (3.8)	11.2 (4.4)

2.2 DATA COLLECTION

Each spring tree mortality was determined for the previous growing season. Growth of transplants was measured over three seasons (2006-2008). All growth measurements were collected either in fall after the terminal bud had set or in spring before dormancy had broken. First season canopy growth data was collected on October 28, 2006, while root growth data was collected on May 7-8, 2007. Second season canopy growth data was collected on September 19, 2007, while root growth data was collected in November, 2007. All third season data was collected from August 11-14, 2008.

2.2.1 Canopy Dieback

Each transplanted tree was visually evaluated and given a dieback ranking of 0-6 at the end of the growing season in 2008. Each numerical ranking corresponded with an estimated percentage of canopy leaf density relative to branch density (0 = no dieback, 1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-99%, 6 = dead).

2.2.2 Canopy Growth Sample Measurements

Both leaf area and shoot growth samples were collected from terminal shoots located in full sun in the top one half of each tree. Ten fully expanded representative leaves were collected from each tree, leaf area was quantified (cm2) using a LI-COR® LI-3100 leaf area meter (LI-COR® Biosciences – Lincoln, NE), and the mean leaf area per tree was calculated. Three terminal shoots samples were collected, length was measured (cm) from the terminal bud scale scar to terminal bud, and the mean shoot length per tree was calculated.

Some control trees were sold after the first growing season, so measurements could not be taken on the same individual trees for all three growing seasons. When individual trees measured in the previous season were unavailable, samples were taken from similarly callipered trees of the same species found within one nursery block. Additionally no control data was available for two of the control treatments (medium caliper scarlet oaks and medium caliper bur oaks) in 2008. As a result, leaf area and shoot growth measurements for the control treatments were averaged each year by species. These averages represented normal growth rates of untransplanted trees for each species each year and were used for comparison with transplant treatments. Each growing season leaf area and shoot growth from surviving transplanted trees were calculated as a percentage of the control growth of each species to better examine establishment rates and to adjust for seasonal weather variations and leaf morphology differences between species.

2.2.3 Root Growth Sample Measurements

Root growth data was examined nondestructively for surviving transplanted trees in the first two years using a 90-100psi air excavation knife (Supersonic Air Knife Inc. - Allison Park, PA) to remove a section of soil (30.5 cm [1ft] wide by 30.5 cm [1ft] deep by 91.4 cm [3 ft] long) and expose the root system for data collection. An air excavation knife is a handheld tool that connects to an air compressor, funneling a high pressure stream of air out one end.

In 2006, trench excavation began on the same side of each tree and extended out from the edge of the root-ball. Lengths of all primary or secondary roots 2.5cm (1 in) or longer inside the trench were measured, allowing for the calculation of two separate measurements: total number of roots per tree excavated and total root length per tree. Markers were then placed at the end of the trench before any soil was backfilled, so as to identify the exact location to begin excavation the following season in 2007.

2.2.4 Post Root-Ball Harvest Root Growth Measurements

In 2008, the root-balls of all the surviving transplants were harvested in their entirety (using either a Vermeer tree spade or a 54” backhoe), as well as the root-balls of two dead large caliper bur oaks, to collect additional root measurements. Once the transplanted root-balls were extracted from the ground, any remaining burlap or portion of wire basket was removed by hand and then the air excavation knife was used to remove all soil from within the root-balls.

The ends of the severed roots from the original tree spade cut made during transplanting were examined. Four more root growth measurements were then measured: number of cut roots per tree; diameter (mm) of each cut root; number of primary new roots generated from each cut root after transplanting; and total number of primary new roots generated for each tree after transplanting.

2.3 STATISTICAL ANALYSIS

The unit for experimental analysis was a single-tree replicate. Data were randomized for variations within species, as specimens were not genetically identical clones. Significance of mortality and canopy dieback data was determined using a Chi-Square test at a 90% confidence interval using JMP-7 statistical software. Treatment differences for all growth data was determined after analysis of variance and treatment means separated using a t-test at a 90% confidence interval using JMP-7 statistical software. Growth data were transformed as needed to ensure normal distribution of residuals.

CHAPTER 3

RESULTS AND DISCUSSION

All transplanted trees were subject to the same growth limiting environmental factors; therefore, any differences in growth were the result of either main affect (species or size) or the interaction (treatment). However, these three oak species are not clonally propagated and some level of genetic difference exists within each species replicates.

3.1 MORTALITY AND CANOPY DIEBACK

Mortality rates of transplanted trees were evaluated first by the main affects (species or size) and then as an interaction (treatment). None of the swamp white oaks died, two scarlet oaks died, and ten bur oaks died out of eighteen transplanted trees of each species. Two small caliper trees, four medium caliper trees, and six large caliper trees died out of eighteen transplanted trees of each caliper size. Of the six transplanted trees within each treatment: no swamp white oaks of any size died; one small, one medium, and no large caliper scarlet oaks died; one small, three medium, and all six large caliper bur oaks died. All dead trees died during the first growing season with the exception of one small bur oak that died during the second growing season. No additional trees died in the third growing season. All control trees lived. For the binomial mortality ranking (0=Dead, 1=Alive) for individual trees, see *Table 9* in the appendix. The percentage of trees that were living was calculated for comparison with the percentage of trees that were thriving.

At the end of the third growing season a canopy dieback ranking was used to determine which trees were thriving. Trees were given a numerical ranking that corresponded with an estimated percentage of canopy leaf density relative to branch density (0 = no dieback, 1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-99%, 6 = dead). For the canopy dieback rankings of each individual tree, see *Table 9* in the appendix. Only trees with a dieback ranking of either 0 or 1 were considered to be thriving. There was no treatment in which 100% of the trees were thriving. At the end of the third growing season, fourteen swamp white oaks, ten scarlet oaks, and five bur oaks were thriving out of eighteen total transplanted trees of each species, while thirteen small caliper trees, ten medium caliper trees, and six large caliper trees were thriving out of eighteen total transplanted trees of each caliper size. Of the six transplanted trees within each treatment: five small, five medium, and four large caliper swamp white oaks were thriving; four small, four medium, and two large caliper scarlet oaks were thriving; four small, one medium, and no large caliper bur oaks were thriving. The percentage of trees living and those thriving, first by species and size separately, and then by treatment are shown, respectively, in *Figure 1*, *Figure 2* and *Figure 3.*

Post-transplant survival is not a meaningful measure of a tree's transplant success, as survival alone does not prove a tree to be thriving in its new environment nor guarantee that it will not require removal and replacement. Post-transplant performance was determined by both mortality rates and canopy dieback data. Transplanted trees were considered successful if they not only survived but also thrived (had less than 20% canopy dieback).

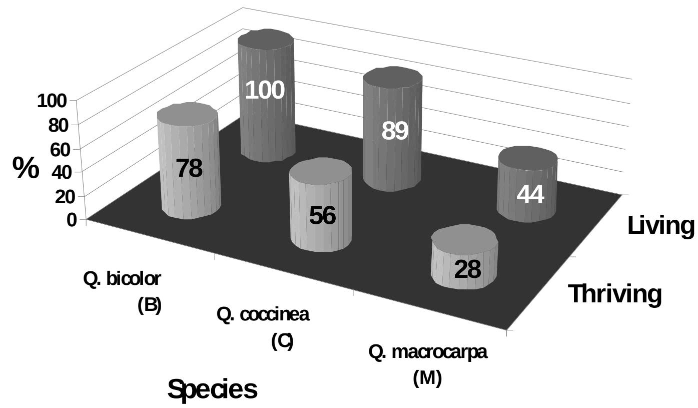

Figure 1: Percentage of Trees Living and Thriving by Species. Percentage of transplanted trees from each species (n=18) that were living and those that were thriving at the end of the third growing season. (chi-square test significant at: Living P<0.0001; Thriving p=0.0087.)

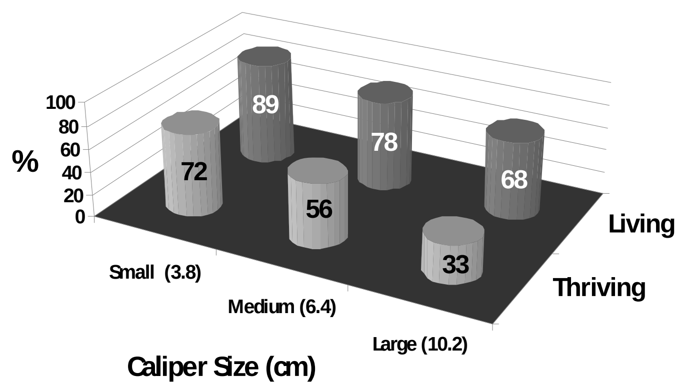

Figure 2: Percentage of Trees Living and Thriving by Caliper Size. Percentage of transplanted trees from each caliper size (n=18) that were living and those that were thriving at the end of the third growing season. (chi-square test significant at:: Living p=0.2636; Thriving p=0.0594.)

Species significantly influenced the amount of trees living and those thriving, while caliper size only significantly influenced the number of transplants that were thriving but did not significantly influence their survival (using a Chi-Square test, significant at a 90% confidence interval, p<0.10). Swamp white

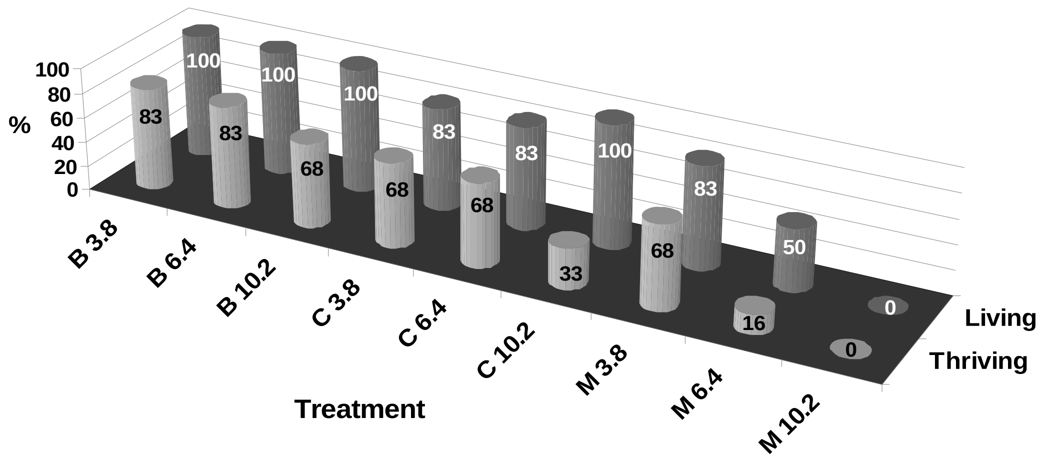

Figure 3: Percentage of Trees Living and Thriving by Treatment. Percentage of transplanted trees from each treatment (n=6) that were living and those that were thriving at the end of the third growing season. Treatments are an interaction of three species (B - Swamp White Oak [*Quercus bicolor*], C - Scarlet Oak [*Q. coccinea*], and M - Bur Oak [*Q. macrocarpa*]) and three caliper sizes (small - 3.8 cm [1.5 in], medium - 6.4 cm [2.5 in], and large - 10.2 cm [4 in]). (chi-square test significant at: Living p<0.0001; Thriving p=0.0098)

oaks were the only species in which all trees survived and transplanted with significantly greater success than either other species. Bur oaks had the poorest post-transplant performance, as both swamp white oaks and scarlet oaks had at least double the transplant survival and success rates of bur oaks. Significantly fewer trees thrived as caliper size increased and there was a trend towards lower survival rates as caliper size increased.

The treatments (the interaction of all species and size variables) significantly influenced both the number of trees living and thriving. Treatment results for post-transplant performance, as well as all subsequent growth data, were analyzed to determine the influence caliper size had on each species and the influence species had at each caliper size.

Caliper size was only shown to have significantly influenced the number of bur oaks living or thriving (*Table 2*). As caliper size increased, the number of bur oaks that survived or thrived significantly decreased. All swamp white oaks of each caliper size survived, while the large caliper scarlet oaks actually displayed a trend of higher survival rates than the small or medium caliper trees. Despite these survival rates, both species trended toward fewer large caliper trees thriving than smaller caliper sizes. This data suggests that the influence of caliper size on post-transplant performance strongly varies between species, even for species within the same genera.

Table 2: Significance of Caliper Size Influence by Species. Chi-square significance listed for the analysis of caliper size influence within each species. (n=18)

Species	Significance of Caliper Size Influence (P>ChiSq)	
	Living	Living
B	.	0.7343
C	0.4180	0.4033
M	0.0041	0.0164

Species only significantly influenced the number of medium and large caliper trees living or thriving (*Table 3*). All three species transplanted equally well at small caliper sizes. For both the medium and large caliper size treatments swamp white oaks had higher survival and success rates than either other species, with the exception of the large caliper scarlet oaks that were equal in survival alone to the large caliper swamp white oaks. Additionally, more medium and large caliper scarlet oak transplants survived and thrived than bur

Table 3: Significance of Species Influence by Caliper Size. Chi-square significance listed for the analysis of species influence within each caliper size. (n=18)

Caliper Size	Significance of Species Influence (P>ChiSq)	
	Living	Living
3.8	0.4180	0.7456
6.4	0.0691	0.0433
10.2	< 0.0001	0.0219

oaks at those sizes.

Examination of the treatments affects showed that species and size are not independent variables. This data showed the influence of caliper size on post-transplant performance to vary by species, just as it showed the influence of species on post-transplant performance to vary by caliper size.

Survival and success rates for both scarlet and bur oak may have benefited from earlier spring digging and planting. Harris and Bassuk (1994) found that scarlet oaks transplanted with much greater success in early spring than later spring and noted that the later spring transplanting date coincided with a period of maximum shoot growth.

3.2 CANOPY GROWTH SAMPLE MEASUREMENTS

Treatment least square means and related significant differences for leaf area sample measurements area listed in *Table 4*, with those for shoot growth sample measurements listed in *Table 5*. Leaf area and shoot growth measurements for the large caliper bur oaks were not included for all three years, as all trees in the transplant treatment died during the first growing season. For individual tree leaf area and shoot growth means, see *Table 10* for transplant data and *Table 11* for control date in the appendix.

Table 4: Leaf Area Sample Measurements. Treatment least square means and related significant differences for leaf area sample measurements. Means followed by different lowercase letters represent significant differences (t-test, p<0.10) among treatments for a given growth measurement. Reduction of replicates (N < 60) or absence of data set for transplants is due to death of individual trees. Significance refers to F-value of treatment effects following analysis of variance.

Treatment	Transplant N value	2006 Leaf Area			2007 Leaf Area			2008 Leaf Area		
		Transplant (cm2)	Control (cm2)	% of Control	Transplant (cm2)	Control (cm2)	% of Control	Transplant (cm2)	Control (cm2)	% of Control
B 3.8	60	35 a		42	42 a		78	51 a		82
B 6.4	60	31 ab	83	37	42 a	54	78	52 a	62	84
B 10.2	60	33 ab	(n=180)	39	48 a	(n=180)	89	56 a	(n=170)	90
C 3.8	50	19 d		37	31 b		66	37 b		93
C 6.4	50	30 abc	51	59	24 b	47	51	40 b	40	100
C 10.2	60	22 cd	(n=180)	43	29 b	(n=180)	62	34 b	(n=180)	85
M 3.8	50*	17 d		19	31 b		76	37 b		54
M 6.4	30	23 bcd	120	26	29 b	41	71	33 b	69	48
M 10.2	X	X	(n=180)	X	X	(n=180)	X	X	(n=90)	X
Significance		0.0108			< 0.0001			0.0007		
Transformation		Sqrt			Sqrt			Sqrt		

X = *absent data set*
* 30 in 2006

Leaf area measurements for all treatments increased from each growing season to the next, with only one exception. Leaf area for the medium caliper scarlet oaks decreased slightly from 2006 to 2007 due to a high treatment average in 2006. This high treatment average resulted in significantly greater leaf area for the medium caliper scarlet oaks than the small caliper scarlet oaks. However, there were no other significant differences in leaf area

Table 5: Shoot Growth Sample Measurements. Treatment least square means and related significant differences for shoot growth sample measurements. Means followed by different lowercase letters represent significant differences (t-test, p<0.10) among treatments for a given growth measurement. Reduction of replicates (N < 18) or absence of data set for transplants is due to death of individual trees. Significance refers to F-value of treatment effects following analysis of variance.

Treatment	Transplant N value	2006 Shoot Growth			2007 Shoot Growth			2008 Shoot Growth		
		Transplant (cm)	Control (cm)	% of Control	Transplant (cm)	Control (cm)	% of Control	Transplant (cm)	Control (cm)	% of Control
B 3.8	18	11 a		55	3 de		14	8 bc		25
B 6.4	18	5 bc	20	25	5 cd	22	23	5 cde	32	16
B 10.2	18	6 b	(n=54)	30	3 e	(n=54)	14	4 de	(n=51)	13
C 3.8	15	5 bc		25	8 ab		24	9 ab		35
C 6.4	15	17 a	20	85	7 abc	34	21	9 ab	26	35
C 10.2	18	5 bc	(n=51)	25	11 a	(n=54)	32	12 a	(n=36)	46
M 3.8	15*	5 bc		28	7 bcd		50	8 bcd		38
M 6.4	9	3 c	18	17	3 de	14	21	2 e	21	10
M 10.2	X	X	(n=54)	X	X	(n=54)	X	X	(n=27)	X
Significance		< 0.0001			< 0.0001			0.0012		
Transformation		log			log			log		

X = *absent data set*
** 18 in 2006*

between caliper sizes within each species over all three years.

Leaf area measurements between caliper sizes within the same species are more directly comparable than those between species of the same caliper size due to species differences in leaf morphology. Swamp white oaks and bur oaks, due in part to their inclusion within the white oak group, have more similar leaf morphology and, therefore, have somewhat comparable leaf areas. Scarlet oak leaves, while still lobed, are generally finer and more deeply sinused than either other species, resulting in a smaller leaf area than either other species. Leaf area measurements were taken on control trees (non-transplanted trees) to determine normal growth for each species each year and account for any seasonal environmental differences.

For all three years, the swamp white oaks had significantly greater leaf area than scarlet oaks and bur oaks at each caliper size, with the exception of the medium caliper trees in 2006 in which there were no significant difference between any of the three species. However, if leaf area is expressed as a percentage of the control, the relationship between the species becomes more complex. In 2006, the percentages for swamp white oaks and scarlet oaks were both much higher than those for bur oaks. By the third year both swamp white oaks and scarlet oaks of each treatment size had leaf area percentages of 80% or higher, again much higher than that of bur oaks. Although in 2007, bur oaks had much higher leaf area percentages than in the previous or the following season due to a low control average that year, resulting in higher percentages than the scarlet oaks. Generally the percentages of controls increased as leaf areas increased each year for all species with the exception of the bur oaks from 2007 to 2008, as well as with the medium caliper scarlet oaks from 2006 to 2007.

The genetic variation in leaf morphology that exists within each of these wind pollinated, freely hybridizing oak species may have further confounded the comparison of leaf area. The control trees showed much variation in leaf area from one year to the next. This may have been due in part to the fact that the control trees available for this study each year were not always physically the same trees located in the same field as a result of their harvest and sale. Bur oaks appeared to have the greatest variability in leaf area. Dirr noted that he found describing species characteristics, such as leaf morphology, for bur oak to be difficult because of the extreme variability among the species. (Dirr 2009).

There was not a pattern of yearly increase in shoot elongation for most of the treatments, as there was for leaf area. Although there were some significant differences between species for each caliper size and between caliper sizes for each species, shoot growth for all treatments was poor and far less than that of the controls for all three growing seasons, with the exception of one treatment during the first growing season. In 2006 shoot growth for the medium caliper scarlet oaks was 85% of the control average, while all other treatments that year and all treatments in 2007 and 2008 had shoot growths generally far below 55% of the control average. It is unclear why this one treatment had such high shoot growth and high leaf area measurements in the first season or why that trend did not continue for the next two seasons. Harris and Bassuk (1994) found that scarlet oak had the fastest shoot extension when compared with three other species, although none of which were oaks.

Shoot growth for all treatments was consistently well below that of the controls over all three growing seasons, with the exception of one scarlet oak treatment during the first growing season. In the last two growing seasons all treatments had much higher percentages of control growth for leaf area than for shoot growth. This pattern indicated that the trees may have utilized all of their available resources for greater leaf area expansion rather than shoot extension, in an attempt to increase their photosynthetic potential. A similar trend appeared in Struve et al. data for red oaks (Struve et al. 2000). In the third growing season of their study both small caliper treatments had equal leaf area with the control trees but one of the treatments still had less than half the shoot growth of the controls. Additionally, while the leaf area and shoot growth for the large caliper trees were both below that of the control trees in the third year, the percentage of leaf area when compared to the controls was triple that of the shoot growth.

Surprisingly, the canopy dieback rankings did not correspond with leaf area and shoot growth measurements for individual trees. Higher leaf area and/or longer shoot growth (within each treatment or within each species) were not consistent with lower percentages of canopy dieback. In this study, the percentage of trees that were thriving provided greater insight into the transplant success of each treatment and was a more directly applicable measure of establishment in the landscape than leaf area or shoot growth.

3.3 ROOT GROWTH SAMPLE MEASUREMENTS

During the initial root excavations in 2006 for the sample root growth measurements, a clear difference in root morphology among these three species was observed. The swamp white oaks had a very fibrous root system with extensive branching patterns and the bur oaks had a very simple root structure, while the scarlet oaks appeared to be an intermediate between the other two species. These observations did not conflict with any previously reported information on root system morphology of each oak species.

Scarlet oak's root system was described as 'relatively coarse and unbranched' in a study intended, in part, to characterize the species' roots system (Struve and Moser 1984). In that study the authors speculated that the nature of scarlet oak's root system may relate to the species transplant difficulty. Additionally, Harris and Bassuk (1994) speculated that it was scarlet oak's coarse root system, reduced from transplanting, which negatively impacted the tree's ability to supply sufficient water during the high evaporative conditions and contributed to the species poor survival rate in late spring in their study. Swamp white oak and bur oak root systems have not been as documented as that of scarlet oak. Hightshoe listed the root system of swamp white oak as shallow and fibrous (Hightshoe 1988). Struve et al. categorized bur oak as a deep-rooted species (Struve *et al.* 2006).

Both root growth sample measurements, the number of roots per tree and the total root length per tree, were calculated for all surviving transplanted trees at the end of the first and second growing seasons in 2006 and 2007. All sample root growth data for the large caliper bur oaks were excluded for both years, as all trees in the treatment died during the first growing season. Treatment least square means and related significant differences for root growth sample measurements are listed in *Table 6*. See *Table 12* in the appendix for root growth sample data for individual trees.

The small caliper swamp white oaks had significantly more roots per tree than the large caliper swamp white oaks and significantly greater total root length per tree than both the medium and large caliper swamp white oaks. There were no significant differences in the number of roots per tree or the total root

Table 6: Root Growth Sample Measurements – Number of Roots per Tree and Total Root Length per Tree. Treatment least square means and related significant differences for root growth sample measurements. Means followed by different lowercase letters represent significant differences (t-test, p<0.10) among treatments for a given growth measurement. Reduction of replicates (N < 6) or absence of data set is due to death of individual trees. Significance refers to F-value of treatment effects following analysis of variance.

Treatment	N value	Number of Roots per Tree		Total Root Length per Tree (cm)	
		2006	2007	2006	2007
B 3.8	6	18 a	24	486 a	280
B 6.4	6	15 ab	18	220 bc	227
B 10.2	6	12 bc	43	268 b	536
C 3.8	5	8 cd	20	167 bcd	192
C 6.4	5	8 cd	17	110 cde	240
C 10.2	6	5 de	22	82 de	261
M 3.8	5	4 e	17	45 e	208
M 6.4	3	6 cde	19	81 cde	261
M 10.2	X	X	X	X	X
Significance		0.0004	0.2829	< 0.0001	0.4144
Transformation		Sqrt	Sqrt	Sqrt	Sqrt

X = *absent data set*

length per tree between the medium caliper and large caliper swamp white oaks. Scarlet oak and bur oak showed no significant difference between the caliper sizes for either root growth measurement. However, the scarlet oaks trended toward an increase in root length per tree as caliper size decreased and bur oaks trended in the opposite direction.

Within the small caliper treatments, the swamp white oaks had significantly more roots per tree and greater total root length per tree than either other species and scarlet oaks had significantly more roots and greater total root length than bur oaks. The medium caliper swamp white oaks had significantly more roots per tree than either other species and trended toward greater total root length per tree than either other species. The medium caliper scarlet oaks showed a slight trend toward greater total root length per tree than the bur oaks at that caliper size. The large caliper swamp white oaks had significantly more roots per tree and significantly greater total root length per tree than the large caliper scarlet oaks.

Although there were no statistical differences between treatments for either root growth sample measurements in 2007, there were some trends due to high treatment averages for the large caliper swamp white oaks. As opposed to the small caliper swamp white oaks in 2006, it was the large caliper swamp white oaks that strongly trended toward both more roots per tree and greater total root length than either other caliper size of swamp white oaks or any other treatments. Both the scarlet oaks and the bur oaks trended slightly toward an increase in total root length per tree as caliper size increased, following the same trend as the previous year for the bur oaks but the opposite trend for the scarlet oaks.

In the second growing season the small caliper swamp white oaks again trended toward greater root growth than either other species for both growth measurements, as they had the previous year. However, the small caliper scarlet oaks only followed the previous year's pattern of greater root growth than bur oaks for one of the two root growth measurements, with more roots per tree than bur oaks but a similar total root length. The medium caliper treatments displayed a subtle trend in the total root length per tree that was a reversal of the previous year's. The swamp white oaks went from having the greatest total root length in 2006 per tree to the lowest in 2007, while the bur oaks went from the lowest total root length per tree to the greatest. Species differences among large caliper treatments in 2007 trended toward the previous year's pattern, with swamp white oaks showing more roots and greater root length than scarlet oaks.

Lack of significant differences in the second growing season were due to data variability that was the results of the data collection process. In the first year root measurement began uniformly from the root ball; however, the second year's excavation began from a marker that indicated the extent of the previous years roots growth for each individual tree.

Species differences in sample root growth in 2006 paralleled species differences in above ground post-transplant performance, with greater root growth resulting in greater transplant survival and success. Swamp white oaks had higher survival and transplant success rates than either other species and they showed much greater root growth than either other species in 2006. Swamp white oaks had significantly more roots per tree at each caliper size and significantly, or at least displaying a strong trend towards, greater total root length per tree at each caliper size. Bur oak had the lowest transplant survival and success rates and also had the least amount of root growth. Scarlet oaks had intermediary root growth between swamp white oak and bur oak, just as their survival and success rates had been intermediary. Scarlet oaks had significantly more new roots and greater total root length than bur oaks for the small caliper trees and trended toward greater root growth for the medium caliper trees.

3.4 POST ROOT-BALL HARVEST ROOT GROWTH MEASUREMENTS

Post root-ball harvest root growth measurements (number of cut roots per tree, number of new roots per tree, diameter of cut roots, and number of new roots per root) were collected from surviving transplanted trees only for all treatments, with the exception of the large caliper bur oak treatment. All of the large caliper bur oaks died and data was collected from two dead trees in that treatment. This impacted the statistical analysis for both the number of cut roots and the number of new roots per tree. However, for both large caliper bur oaks sampled, the number of cut roots per tree were nearly identical. Data from the large caliper bur oaks was excluded from the diameter of cut roots data set, as the trees in this treatment were not comparable to those of other treatments that had been living for three growing seasons.

Treatment least square means and related significant differences for the post root-ball harvest root growth measurements, the number of cut roots per tree and the number of new roots per tree are listed in *Table 7*, while those for the diameter of cut roots and the number of new roots per root are listed in *Table 8*. See *Table 13* in the appendix for post root-ball harvest root growth data for individual trees.

3.4.1 Number of Cut Roots per Tree and Number of New Roots per Tree

Scarlet oak was the only species that displayed the logically anticipated trend of progressively more cut roots within the root-ball as caliper size increased. Although, the number of cut roots per tree for the small and medium caliper

Table 7: Post Root-ball Harvest Root Growth Measurements – Number of Cut Roots per Tree and Number of New Roots per Tree. Treatment least square means and related significant differences for post root-ball harvest root growth measurements, Number of Cut Roots per Tree and Number of New Roots per Tree. Means followed by different lowercase letters represent significant differences (t-test, p<0.10) among treatments for a given growth measurement. Reduction of replicates (N < 6) is due to death of individual trees. Significance refers to F-value of treatment effects following analysis of variance.

Treatment	N value	Number of Cut Roots per Tree	Number of New Roots per Tree
B 3.8	6	44 d	246 de
B 6.4	6	68 b	404 bc
B 10.2	6	68 b	525 ab
C 3.8	5	55 bcd	232 de
C 6.4	5	70 b	305 cd
C 10.2	6	108 a	552 a
M 3.8	5	49 cd	169 ef
M 6.4	3	41 d	149 ef
M 10.2	2	68 bc	108 f
	Significance	< 0.0001	< 0.0001
	Transformation	Log	Sqrt

scarlet oaks were not actually significantly different. The medium caliper and large calipers swamp white oaks had identical treatment means and had significantly more cut roots per tree than the small caliper swamp white oaks. There was no significant difference in the number of cut roots per tree between the small and medium caliper bur oaks. The large caliper bur oaks showed a trend toward the more cut roots per tree than medium or small caliper bur oaks; however, they only had significantly more cut roots than the medium caliper trees.

Scarlet oaks and swamp white oaks had progressively, although not always significantly, more new roots per tree as caliper size increased. Significant

Table 8: Post Root-Ball Harvest Root Growth Measurements – Diameter of Cut Roots and Number of New Roots per Root. Treatment least square means and related significant differences for post root-ball harvest root growth measurements, Diameter of Cut Roots and Number of New Roots per Root. Means followed by different lowercase letters represent significant differences (t-test, p<0.10) among treatments for a given growth measurement. Significance refers to F-value of treatment effects following analysis of variance.

Treatment	N value	Diameter of Cut Roots (mm)	Number of New Roots per Root
B 3.8	261	11 b	6 ab
B 6.4	406	12 b	6 ab
B 10.2	409	18 a	8 a
C 3.8	275	12 b	4 cd
C 6.4	352	11 b	4 cd
C 10.2	647	17 a	5 bc
M 3.8	247	9 c	3 d
M 6.4	123	12 b	4 cd
M 10.2	134	X	2 e
	Significance	< 0.0001	< 0.0001
	Transformation	Log	Sqrt

X = *absent data set*

differences among caliper sizes for the number of new roots per tree followed those for the number of cut roots per tree. While there were no significant differences between the caliper size treatments for bur oaks, they displayed a slight trend in the opposite direction of the other two species, with fewer new roots as caliper size increases. Large caliper bur oaks had the highest number of cut roots per tree but the lowest number of new roots per tree.

For the small caliper treatments, all three species had a similar number of cut roots and produced a similar number of new roots, just as all three species transplanted equally well at the small caliper size. However, both swamp white oaks and scarlet oaks trended toward producing more new roots per tree than bur oaks. For the medium caliper treatments both the swamp white oaks and scarlet oaks had significantly more new roots per tree than bur oaks, as they had significantly more cut roots per tree than bur oaks, and swamp white oaks trended towards producing more new roots than scarlet oaks. Within the large caliper treatments, although scarlet oaks had significantly more cut roots per tree than either swamp white oaks or the bur oaks, swamp white oaks produced similar amounts of new roots per tree as scarlet oaks, resulting in both the scarlet oaks and swamp white oaks producing significantly more new roots per tree than bur oaks.

Watson conceded that his model did not account for difference in root growth rate (Watson 1985). His model used the same yearly rate of growth for each caliper size transplant of the same species. However, both the sample root growth data and the post-harvest measurement of the number of new roots per tree showed that different transplant sizes of the same species will not necessarily produce root at the same rate.

There was a strong positive relationship between the number of roots that are cut during the transplanting process and the number of primary roots per tree that developed at the ends of those severed roots after transplanting, as shown in *Figure 4*. When the data set was viewed in its entirety, it showed that including more cut roots inside the ball when the root-ball was created, resulted in the production of more new roots per tree. However, the influence that the number of cut roots had on the number of new roots per tree that were produced differed greatly by species. When the same number of roots per tree were cut, swamp white oaks generally produced more new roots per tree than

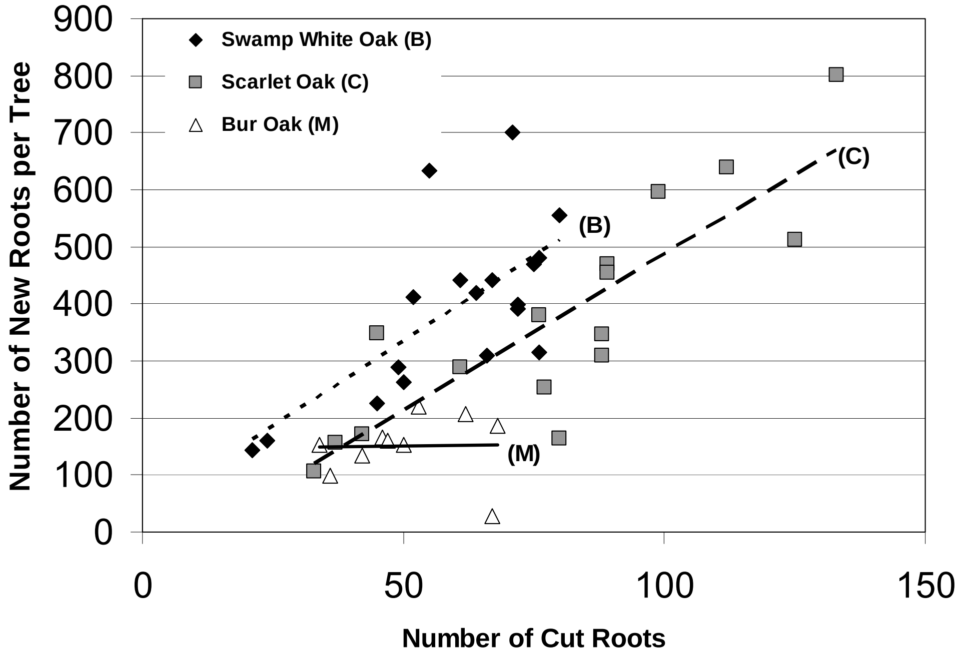

Figure 4: Relationship between the Number of Cut Roots per Tree and the Number of New Roots per Tree. Relationship between the number of roots that are cut during the transplanting process and the number of primary roots per tree that developed at the ends of those severed roots after transplanting. The number of roots per tree that will develop was predicted by the following equations for each species, where N was the number of new roots per tree and C was the number of cut roots: swamp white oak (B), N = 36.78 + 5.93C (R2 = 0.46) and scarlet oak (C), N = - 62.88 + 5.5C (R2 = 0.72). These equations are significant at F< 0.0001 for swamp white oak and F=0.002 for scarlet oak following analysis of variance. The prediction equation for bur oak (M) was not significant with all data points included. However, when both data points from the large caliper bur oak treatment were removed, the prediction equation (N = 7.92+ 3.32 C [R2 = 0.62]) was significant at F= 0.0198.

either other species and scarlet oaks generally produced more new roots than bur oaks.

Transplant success is likely influenced not just by a species ability to produce new roots, but by the structure of those roots that are produced. Examination of post root-ball harvest root growth showed that both swamp white oaks and scarlet oaks produced similar numbers of new roots per tree for the large caliper treatments, suggesting that they would likely transplant with similar success. While both species had a 100% survival rate for their large caliper treatments, 68% of swamp white oaks and only 33% scarlet oaks were thriving. Difference in post-transplant root growth between species may be even more exaggerated than shown by this root data due to root morphology. In post root-ball harvest data the number of new roots produced at the cut ends were measured, but this data does not reflect the level of branching that occurred on these roots that formed after transplanting. Production of greater root mass and surface area may have contributed to greater transplant success of swamp white oaks by increasing their ability to absorb more water. Alternately bur oak's post-transplant performance likely suffered due to not only the production of fewer roots but also a lack of root branching. Additionally the greater branching by the roots measured after post root-ball harvest may explain why swamp white oak sample root growth measurements showed generally greater root growth than either other species.

3.4.2 Diameter of Cut Roots and the Number of New Roots per Root

The large caliper treatments for both swamp white oaks and scarlet oaks had significantly larger diameter roots and trended toward producing more new roots per root than either other caliper size treatments. However, small and medium caliper treatments for swamp white oaks and scarlet oaks showed no significant differences in root diameter and both sizes had equal treatment means for each of these species. Medium caliper bur oaks had significantly larger diameter roots than small caliper bur oaks. While the diameter of the large caliper bur oaks could not be compared to that of the other species, they produced significantly fewer new roots per root than either other bur oak treatment, as well as significantly fewer new roots per root than all other treatments.

Both swamp white oak and scarlet oak had significantly larger diameter roots than bur oak in the small caliper treatments. No one species had significantly larger diameter roots than another for the medium caliper treatments or either large caliper treatment measured. However swamp white oaks produced significantly more new roots per root than either other species at each caliper size and large caliper scarlet oaks produced more new roots per root than large caliper bur oaks.

There is a positive relationship between the diameter of the roots cut during the transplanting process and the number of primary new roots per root that developed at the ends of those severed roots after transplanting. When the entire data set was viewed, it showed that the greater the caliper of the cut root, the greater number of new roots per root developed from that cut root. However, the strength of that relationship and the influence that the diameter of cut roots has on the number of new roots per root that are produced differs greatly by species. The number of roots per root that will develop is predicted by the following equations for each species, where R is the number of new roots per root and D is the diameter of the cut root: swamp white oak, R = 2.50

+ 0.29D (R2 = 0.43); scarlet oak, R = 1.64 + 0.21D (R2 = 0.33); and bur oak, R = 2.50 + 0.10D (R2 = 0.10). All three equations were significant at F < 0.0001 following analysis of variance. Swamp white oak has a slightly higher slope than scarlet oak (indicating a greater influence of the caliper of cut roots on the number of new roots per root) and a slightly higher RSq than scarlet oak (indicating a stronger relationship between the two variables). Bur oak showed a weak relationship between these two variables.

Root morphology appeared to greatly influence the survival and success rates of these three species, as the species that had the most fibrous root system, swamp white oak, transplanted with the greatest success and the species with the coarsest root system, bur oaks, transplanted with the least success.

Another factor that may have attributed to root growth differences between species is the amount of time a tree has to produce new roots in a given season. Research on green ash seedlings (*Fraxinus pennsylvanica* Marsh.) found that trees that broke bud earlier had greater root growth over the same amount of time as those trees that broke bud later (Arnold and Struve 1989). Additionally in their study they found that new roots initiated at pruned root surfaces 10 to 19 days after intact lateral roots had begun to elongate. In our study the time between bud break and root regeneration was unknown. Oaks, in general, break bud later in the season when compared to other genera of trees; however, there may be some variation between time of bud-break for different oak species. For trees that already have a reduced time frame with which to grow new roots after transplanting, such as oaks, a long delay between bud-break and root regeneration would hinder their transplant success, particularly for those species with fewer intact lateral roots.

Trees with more fibrous roots would logically have more intact roots within the root-ball that had not been severed during transplanting. One study found that an increase in lateral roots indicated an increase in performance after planting for sweetgum (*Liquidamber styraciflua* L.) seedlings (Kormanik 1986). The existence of a greater number of intact lateral roots which could begin growing immediately after transplanting may explain why, when the same number of roots per tree were cut, swamp white oaks generally produced more new roots per tree than either other species and scarlet oaks generally produced more new roots than bur oaks. Further studies should examine the relationship between post-transplant performance and the number of roots left intact within the root-ball during transplanting for various species of landscape sized tree.

APPENDIX

Table 9: Individual Tree Mortality and Canopy Dieback Rankings. For mortality (0 = Died and 1 = Survived). For canopy dieback (0 = no dieback, 1 = 1-20%, 2 = 21-40%, 3 = 41-60%, 4 = 61-80%, 5 = 81-99%, 6 = dead).

Tree #	Species	Caliper	Mortality	Dieback
B1	B	3.8	1	0
B2	B	3.8	1	0
B3	B	3.8	1	0
B4	B	3.8	1	1
B5	B	3.8	1	1
B6	B	3.8	1	2
B7	B	6.4	1	1
B8	B	6.4	1	3
B9	B	6.4	1	1
B10	B	6.4	1	1
B11	B	6.4	1	1
B12	B	6.4	1	1
B13	B	10.2	1	1
B14	B	10.2	1	0
B15	B	10.2	1	2
B16	B	10.2	1	2
B17	B	10.2	1	1
B18	B	10.2	1	1
C1	C	3.8	1	0
C2	C	3.8	1	0
C3	C	3.8	0	6
C4	C	3.8	1	2
C5	C	3.8	1	0
C6	C	3.8	1	0
C7	C	6.4	1	1
C8	C	6.4	1	5
C9	C	6.4	1	1
C10	C	6.4	1	0
C11	C	6.4	1	1
C12	C	6.4	0	6
C13	C	10.2	1	1
C14	C	10.2	1	0
C15	C	10.2	1	2
C16	C	10.2	1	3
C17	C	10.2	1	2
C18	C	10.2	1	3
M1	M	3.8	1	0
M2	M	3.8	0	6
M3	M	3.8	1	0
M4	M	3.8	1	2
M5	M	3.8	1	0
M6	M	3.8	1	0

Table 9 (Continued)

Tree #	Species	Caliper	Mortality	Dieback
M7	M	6.4	0	6
M8	M	6.4	1	2
M9	M	6.4	0	6
M10	M	6.4	1	0
M11	M	6.4	1	3
M12	M	6.4	1	6
M13	M	10.2	0	6
M14	M	10.2	0	6
M15	M	10.2	0	6
M16	M	10.2	0	6
M17	M	10.2	0	6
M18	M	10.2	0	6

Table 10: Individual Transplant Tree Means for Canopy Growth Sample Measurements.

Tree #	Species	Caliper	Leaf Area			Shoot Growth		
			2006	2007	2008	2006	2007	2008
B1	B	3.8	30.71	37.77	51	7.8	3.5	11.7
B2	B	3.8	44.42	64.26	71.66	18.3	2.6	8.4
B3	B	3.8	32.25	32.82	41.64	13.8	4.5	10.6
B4	B	3.8	38.4	36.54	52.14	8.0	2.8	4.4
B5	B	3.8	31.31	38.89	41.83	8.8	4.0	3.7
B6	B	3.8	35.2	43.45	49.97	8.2	2.7	6.4
B7	B	6.4	19.22	41.35	33.24	5.8	5.0	3.0
B8	B	6.4	33.75	37.09	58.61	5.1	6.0	5.0
B9	B	6.4	37.23	41.9	55.95	8.0	4.8	4.9
B10	B	6.4	27.43	48.27	56.36	1.6	2.9	7.3
B11	B	6.4	42.95	40.4	58.93	2.1	3.2	3.5
B12	B	6.4	28.15	43.16	51.67	4.3	5.0	3.1
B13	B	10.2	28.18	53.16	68.61	6.7	1.8	2.3
B14	B	10.2	30.75	47.9	60.76	7.1	5.8	3.3
B15	B	10.2	31.47	33.29	50.91	6.5	3.1	3.3
B16	B	10.2	49.37	53.06	69.11	7.5	1.4	9.0
B17	B	10.2	25.72	48.42	48.78	6.3	2.5	1.6
B18	B	10.2	29.53	51.19	35.65	2.9	3.0	2.8
C1	C	3.8	19.55	29.72	31.99	8.9	9.5	5.4
C2	C	3.8	17.66	36.43	37.97	5.8	7.7	16.2
C3	C	3.8	.	.	.	.	.	.
C4	C	3.8	25.1	17.13	34.08	1.7	3.6	8.1
C5	C	3.8	21.83	26.92	44.01	2.1	10.6	9.8
C6	C	3.8	12.69	43.09	37.56	7.5	8.6	7.0
C7	C	6.4	30.3	26.41	53.8	25.0	5.2	11.8
C8	C	6.4	36.55	18.98	41.56	18.9	3.0	5.2
C9	C	6.4	32.91	24	40.11	15.5	10.6	6.0
C10	C	6.4	37.8	22.56	38.3	18.0	6.9	10.2
C11	C	6.4	13.3	25.66	28.62	6.6	6.7	11.9

Table 10 (Continued)

Tree #	Species	Caliper	Leaf Area			Shoot Growth		
			2006	2007	2008	2006	2007	2008
C12	C	6.4	.	.	.	.	.	.
C13	C	10.2	16.93	24.17	35.14	3.2	9.7	6.9
C14	C	10.2	43.73	38.47	41.98	9.3	11.8	13.2
C15	C	10.2	24.61	36.41	38.32	3.8	15.0	14.5
C16	C	10.2	15.27	25.72	31.66	2.4	11.5	14.9
C17	C	10.2	17.62	22.18	24.1	3.9	11.0	11.7
C18	C	10.2	14.91	29.64	30.28	4.2	7.3	8.9
M1	M	3.8	.	22.44	20.61	7.1	2.1	1.1
M2	M	3.8	12.23	.	.	5.1	.	.
M3	M	3.8	.	37.26	42.9	3.4	7.1	11.7
M4	M	3.8	16.48	28.7	50.26	4.7	4.7	19.5
M5	M	3.8	21.63	20.5	33.3	3.6	2.6	1.8
M6	M	3.8	.	44.96	37.34	5.0	15.9	7.2
M7	M	6.4	.	.	.	.	.	.
M8	M	6.4	.	29.74	35.54	1.6	3.9	2.6
M9	M	6.4	16.56	.	.	.	.	.
M10	M	6.4	.	28.03	26.07	3.8	2.8	2.0
M11	M	6.4	32.2	30.09	37.1	3.2	2.7	2.0
M12	M	6.4	20.63	.	.	.	.	.
M13	M	10.2	16.72		.	.	.	.
M14	M	10.2	14.98	.	.	.	.	.
M15	M	10.2	.	.	.	.	.	.
M16	M	10.2	21.24	.	.	.	.	.
M17	M	10.2	.	.	.	.	.	.
M18	M	10.2	15.48		.	.	.	.

Table 11: Individual Control Tree Means for Canopy Growth Sample Measurements.

Species	Caliper	LeafArea			Shoot Growth		
		2006	2007	2008	2006	2007	2008
B	3.8	81.56	53.17	65.72	31.1	23.0	26.5
B	3.8	77.3	50.96	67.22	17.6	22.3	40.0
B	3.8	100.63	44.47	90.93	31.4	16.3	26.3
B	3.8	86.28	63.19	89.74	23.5	22.7	23.8
B	3.8	88.8	55.42	67.82	26.7	11.8	22.9
B	3.8	64.86	46.61	45.49	18.8	24.0	11.9
B	6.4	88.55	50.15	52.63	8.2	25.6	23.3
B	6.4	77.9	51.55	42.4	7.6	14.6	35.3
B	6.4	88.87	44.68	71.98	29.3	29.6	27.2
B	6.4	57.25	67.56	66.01	12.4	22.9	22.4
B	6.4	71.18	42.73	77.3	14.0	11.7	30.6
B	6.4	89.8	58.21	47.75	16.2	31.8	26.5
B	10.2	81.44	49.47	.	11.5	24.0	40.4
B	10.2	86.52	56.52	38.7	16.6	27.0	48.6
B	10.2	87.33	55	54.9	22.4	25.0	44.7

Table 11 (Continued)

Species	Caliper	LeafArea			Shoot Growth		
		2006	2007	2008	2006	2007	2008
B	10.2	107.6	66.57	49.86	23.3	21.3	40.4
B	10.2	71.36	59.04	62.71	24.1	13.8	49.0
B	10.2	92.21	57.35	56.02	22.5	31.1	.
C	3.8	24.87	36.86	35.05	24.0	23.7	16.5
C	3.8	56.59	38.08	43.79	16.9	21.3	7.6
C	3.8	50.53	47.29	38.64	21.1	8.1	22.6
C	3.8	47.36	45.4	31.81	19.9	26.1	32.4
C	3.8	49.43	40.12	44.62	14.8	26.5	34.6
C	3.8	57.38	43.87	53.96	17.9	18.8	25.6
C	6.4	32.38	35.19	35.9	20.1	31.9	38.6
C	6.4	36.43	46.81	32	18.0	35.6	21.1
C	6.4	36.47	28.81	36.27	18.3	41.3	28.1
C	6.4	38.64	50.05	45.65	16.5	30.8	36.2
C	6.4	43.13	62.43	40	6.6	34.0	24.8
C	6.4	46.34	70.61	40.34	23.2	39.4	22.2
C	10.2	61.3	51.06	.	15.3	36.9	.
C	10.2	77.09	38.89	.	11.1	57.3	.
C	10.2	45.79	47.67	.	22.8	56.2	.
C	10.2	55.05	68.93	.	40.7	51.1	.
C	10.2	77.82	37.1	.	34.0	45.0	.
C	10.2	72.42	59.1	.	.	22.0	.
M	3.8	97.99	29.34	46.2	13.3	15.1	26.6
M	3.8	109.96	34.9	34.15	10.1	12.1	11.8
M	3.8	82.34	37.42	54.83	8.4	16.6	20.3
M	3.8	.	35.59	66.61	16.6	26.5	4.4
M	3.8	.	38.87	44.73	11.0	29.9	13.7
M	3.8	.	27.99	45.26	10.9	20.8	11.8
M	6.4	88.59	29.57	.	15.8	10.6	.
M	6.4	78.21	33.73	.	16.4	9.5	.
M	6.4	108.15	29.8	.	35.3	6.2	.
M	6.4	.	34.72	.	18.8	4.2	.
M	6.4	.	28.96	.	19.6	8.3	.
M	6.4	.	33.99	.	33.3	12.0	.
M	10.2	88.22	43.03	.	30.0	15.3	25.7
M	10.2	118	62.59	131.51	24.0	15.1	34.6
M	10.2	94.15	58.95	110.73	15.6	11.7	37.2
M	10.2	76.31	65.36	84.98	23.0	7.9	.
M	10.2	54.62	58.38	.	6.7	16.8	.
M	10.2	88.87	59.59	.	11.5	13.0	.

Table 12: Individual Transplant Tree Means for Root Growth Sample Measurements.

Tree #	Species	Caliper	2006 # of Roots	2006 Total Root Length (cm)	2007 # of Roots	2007 Total Root Length (cm)
B1	B	3.8	17	554	21	239
B2	B	3.8	10	437	15	99
B3	B	3.8	24	818	27	338
B4	B	3.8	12	272	12	140
B5	B	3.8	27	497	62	785
B6	B	3.8	20	340	6	81
B7	B	6.4	13	224	48	584
B8	B	6.4	3	18	1	15
B9	B	6.4	21	107	14	201
B10	B	6.4	20	297	5	30
B11	B	6.4	16	193	16	196
B12	B	6.4	19	478	25	335
B13	B	10.2	8	318	29	498
B14	B	10.2	15	508	79	1041
B15	B	10.2	14	241	47	599
B16	B	10.2	4	71	27	163
B17	B	10.2	12	68	64	782
B18	B	10.2	18	404	13	135
C1	C	3.8	11	152	13	109
C2	C	3.8	3	79	16	170
C3	C	3.8	.	.	.	.
C4	C	3.8	2	28	23	292
C5	C	3.8	6	69	6	66
C6	C	3.8	20	505	41	323
C7	C	6.4	4	81	0	0
C8	C	6.4	6	64	3	66
C9	C	6.4	8	69	16	231
C10	C	6.4	13	229	35	457
C11	C	6.4	8	109	32	447
C12	C	6.4	.	.	.	.
C13	C	10.2	2	64	19	163
C14	C	10.2	7	66	41	460
C15	C	10.2	8	112	25	231
C16	C	10.2	4	104	11	267
C17	C	10.2	1	18	15	267
C18	C	10.2	7	130	18	178
M1	M	3.8	1	15	9	91
M2	M	3.8	0	0	.	.
M3	M	3.8	6	84	15	183
M4	M	3.8	6	56	25	284
M5	M	3.8	2	20	22	262
M6	M	3.8	8	94	14	221
M7	M	6.4	.	.	.	.
M8	M	6.4	5	48	18	292
M9	M	6.4	.	.	.	.

Table 12 (Continued)

Tree #	Species	Caliper	2006		2007	
			# of Roots	Total Root Length (cm)	# of Roots	Total Root Length (cm)
M10	M	6.4	7	150	38	483
M11	M	6.4	7	46	1	8
M12	M	6.4	.	.	.	.
M13	M	10.2	.	.	.	.
M14	M	10.2	.	.	.	.
M15	M	10.2		.	.	.
M16	M	10.2	.	.	.	.
M17	M	10.2	.	.	.	.
M18	M	10.2	.	.	.	.

Table 13: Individual Transplant Tree Means for Post Root-Ball Harvest Root Growth Measurements.

Tree ID #	Species	Size (cm)	Number of # Cut Roots per Tree	Number of New Roots per Tree	Diameter of Cut Roots (cm)	Number of New Roots per Root
B1	B	3.8	72	391	10	5
B2	B	3.8	49	289	10	6
B3	B	3.8	45	226	12	5
B4	B	3.8	50	263	8	5
B5	B	3.8	21	144	16	7
B6	B	3.8	24	160	15	7
B7	B	6.4	75	470	12	6
B8	B	6.4	61	441	13	7
B9	B	6.4	76	314	10	4
B10	B	6.4	76	481	13	6
B11	B	6.4	52	411	15	8
B12	B	6.4	66	309	11	5
B13	B	10.2	72	398	18	6
B14	B	10.2	80	556	16	7
B15	B	10.2	55	633	21	12
B16	B	10.2	64	420	18	7
B17	B	10.2	71	701	20	10
B18	B	10.2	67	441	18	7
C1	C	3.8	88	346	10	4
C2	C	3.8	42	171	13	4
C3	C	3.8	.	.	.	.
C4	C	3.8	33	106	12	3
C5	C	3.8	37	157	4	4
C6	C	3.8	76	381	12	5
C7	C	6.4	61	289	12	5
C8	C	6.4	80	164	9	2
C9	C	6.4	77	253	9	3
C10	C	6.4	89	470	13	5

Table 13 (Continued)

Tree ID #	Species	Size (cm)	Number of # Cut Roots per Tree	Number of New Roots per Tree	Diameter of Cut Roots (cm)	Number of New Roots per Root
C11	C	6.4	45	349	16	8
C12	C	6.4	.	.	.	.
C13	C	10.2	133	801	17	6
C14	C	10.2	89	455	15	6
C15	C	10.2	88	310	17	4
C16	C	10.2	125	512	15	4
C17	C	10.2	99	596	20	6
C18	C	10.2	112	640	18	6
M1	M	3.8	53	220	8	4
M2	M	3.8	.	.	.	.
M3	M	3.8	62	207	8	3
M4	M	3.8	50	152	8	3
M5	M	3.8	36	99	10	3
M6	M	3.8	46	166	9	4
M7	M	6.4	.	.	.	.
M8	M	6.4	34	153	14	5
M9	M	6.4	.	.	.	.
M10	M	6.4	42	135	12	3
M11	M	6.4	47	160	11	3
M12	M	6.4	.	.	.	.
M13	M	10.2	.	.	.	.
M14	M	10.2	67	28	10	< 1
M15	M	10.2	.	.	.	.
M16	M	10.2	.	.	.	.
M17	M	10.2	.	.	.	.
M18	M	10.2	.	.	.	.
.	M	10.2	68	187	11	3

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