Extreme Arboriculture: Lessons from Moving Mature Trees

Abstract

A research study was conducted on 535 commercial tree transplanting operations in Hong Kong involving nine common subtropical species (*Bombax ceiba, Celtis sinensis, Crateva unilocularis, Ficus benjamina, Ficus microcarpa, Melaleuca quinquenervia, Peltophorum pterocarpum, Pongamia pinnata, Syzygium cumini*). The study sought to investigate the possible relationships between different transplant factors for each species, including the characteristics of the tree (height, trunk diameter, health, form and original soil environment) and the specific transplant operation (time of year of pruning and transplanting, pruning interval, root ball depth and ratio, extent of canopy pruning and handling), with transplant outcome (success or failure). The study demonstrated that the transplant factors that influenced transplant outcome were highly dependent on species. Tree height, soil quality and root pruning timing had a strong relationship with transplant outcome for several species. The findings also indicated that specific characteristics (e.g., a fast growth habit) and morphological adaptations (e.g., shallow, highly compact root systems) that allow trees to survive in street environments are associated with tolerance to transplanting.

Introduction

Keywords:

tree transplanting,
street trees,
transplant shock,
transplant factors,
transplant success.

Transplanting mature trees from urban street locations has become a common part of Hong Kong's ongoing development. Where there is considered to be a high chance of survival, trees affected by construction projects are often transplanted to other sites within the territory, or taken to temporary holding nurseries and returned later to a final position within the project site. Although a costly practice, many hundreds of street trees are transplanted annually this way under Hong Kong public works projects, as a way of preserving the city's green heritage.

Each transplanting operation is unique, but collectively they offer a chance to understand the response of mature trees to the massive disruption to root and canopy systems that occurs during transplanting, as well as to understand how the characteristics of the tree, planting site and specific transplanting process can influence the outcome (success or failure) of such operations.

Trees' Responses to Transplanting

Much of what is understood regarding trees' responses to transplantation is derived from the study of field grown nursery trees (<150 mm calliper).

Transplant Shock

Transplanting is typically considered to be successful when the tree survives and regains normal patterns of shoot and root growth, without any significant impact on its future growth potential and life expectancy.

The extensive loss of the root system and reduction in canopy volume that occurs during transplanting has a significant impact on tree biology, which can result in

Mathew Pryor[1]

[1] Division of Landscape Architecture, The University of Hong Kong, Hong Kong

an extended period of slow growth. In this period of 'transplant shock' trees can display morphological symptoms such as shorter twig and root elongation, stunting and canopy dieback, as well as physiological symptoms such as a low shoot water potential, reduced photosynthesis, tissue inelasticity and desiccation (South and Zwolinski, 1997).

Transplant shock is a response to water stress arising from the sudden water imbalance within the tree that occurs as a result of a change in the shoot-root ratio, that is, the significant loss of water-absorbing roots without a corresponding reduction in the capacity to lose water by transpiration through the leaves. The degree of change in the shoot-root ratio influences the severity of symptoms and period over which symptoms occur (Watson, 1985; Watson, 2010). Water stress continues until roots have re-grown sufficiently to re-establish water balance.

The time required for a tree to overcome transplant shock and re-establish itself depends on species and morphological characteristics (Harris and Gilman, 1991), and is influenced by the physiological impact of the transplant process with respect to the proportion of root biomass and canopy volume retained, the extent of disruption (Struve *et al*., 2000), transplant timing, environmental conditions and cultural practices after replanting (Gilman, 1990). In addition, tree species with a higher shoot-root ratio have less chance of surviving transplanting than species with a lower shoot-root ratio (Harris and Gilman, 1991). Likewise species with a greater capacity to regenerate roots and withstand water stress have been observed to have a higher chance of surviving transplanting.

For field grown nursery trees, a large percentage of the root system can be lost in forming the root ball before transplanting. In general, the proportion of roots retained in root balls decreases as the trunk diameter increases (Watson and Himelick, 2013). Some species may lose >98% of their roots (measured by length) (Gilman, 1988). Preparatory root pruning may reduce the extent of this loss to 92-95%.

The proportion of root biomass retained in the root ball is much higher due to the greater concentration of root biomass near the base of the tree. Around 53-100% of the root biomass was found to be have been retained in trees up to 60 mm (DBH) and 29%-83% in trees of 60-200 mm (DBH) (Gerhold and Johnson, 2003).

Larger diameter roots within the zone of rapid root taper (Henwood, 1973), which store significant carbohydrate reserves required for re-growth in young trees, may be captured in the root ball. However, only 5%–18% of the fine, water-absorbing roots (< 2 mm) are retained (Gilman *et al*., 1992; Gilman and Beeson, 1996b), resulting in high levels of water stress and transplant shock.

Root Pruning

Root pruning before transplanting can reduce the impact of root loss by stimulating the generation of new fibrous water-absorbing roots from the callus tissue around the severed ends of roots at the edge of the root ball. These roots can then rapidly move out into the surrounding soil (Watson, 1998) and restore water and nutrient uptake capability. Repeated pruning can increase the proportion of fine roots (Gilman and Anderson, 2006) and promote a more branched and dense root system (Gilman *et al*., 2002). New roots can also increase carbohydrate reserves within the tree.

Although roots can be initiated immediately given suitable growing conditions, the longer the period between root pruning operations and transplanting, the greater the mass of new roots that is likely to be formed and potentially retained in the root ball. The effectiveness of root pruning is related to season, in particular to periods of active root growth. The regeneration of heavily pruned root systems tends to be most rapid when canopy growth is least rapid, that is, outside periods of active shoot growth (Watson and Himelick, 1982).

Root pruning for mature tree transplanting in Hong Kong is typically conducted in three stages with intervening rest periods: (i) dig and backfill root pruning trenches on two sides; (ii) repeat for the other two sides; and (iii) undercut and lift. This process is intended to minimise the effects of root loss while maximising the period for new root growth before transplanting.

The optimum time for transplanting in temperate climates is considered to be autumn and spring, coinciding with periods of active root elongation, and when soil moisture and temperature are favourable for root regeneration (Richardson-Calfee and Harris, 2005).

After transplanting, soil that has been backfilled around the root ball is generally of a higher quality than at the original site. This can promote rapid rooting outside the root ball and the absorption of water required for a tree to re-establish an appropriate water balance and recover from transplant shock (Watson, 1992).

Recent studies of nursery stock production transplanting have demonstrated the effectiveness of soil injections of carbohydrates (Percival and Fraser, 2005), the addition of auxins into the growing media (Percival and Gerritsen, 1998) and the use of arbuscular mycorrhizal fungi in increasing post-transplanting root growth and tree survival. These treatments have not yet found their way into standard practices in Hong Kong.

Root Ball Size

The size of the root ball represents a balance between the practicalities of moving a tree and attempts to maximise the volume of the original root system to support the tree after transplanting. Standard root ball sizes for field grown nursery trees are expressed as ratios of root ball diameter to stem diameter. For larger sizes (20 cm DBH) the ratio is 10:1 in the USA (American Nursery and Landscape Association, 2004) and 8:1 in Europe (European Nursery Stock Association, 2010).

Root ball depth for small transplants is suggested to be 60% of the root ball diameter. Although tree root density with respect to depth is dependent on species characteristics and soil environment, in general a larger proportion of root biomass is concentrated in the upper soils layers, 0-45 cm deep (Toky and Bisht, 1992). There may be a diminishing benefit (volume of roots captured in the root ball) of adopting the 60% figure for larger size trees. The HKSAR government (2008) recommends a maximum root ball depth of 90 cm for street trees in Hong Kong due to underground physical constraints.

Canopy Pruning

Canopy pruning is undertaken in tandem with root pruning to reduce water stress by balancing the loss of water uptake capacity with the corresponding reduction in the capacity to lose water through leaf transpiration. Percival (2007) showed that shoot pruning can significantly increase transplant survival and subsequent tree growth.

Canopy pruning needs to be carefully judged. Pruning has the potential to reduce photosynthate production, slow potential root re-growth and create competition with roots for stored carbohydrates (Harris *et al*., 2004). Hagen (2001) noted that removing live branches could have a negative impact on trees by depleting energy reserves. If undertaken in spring, pruning may inhibit cambial activation in established trees, and possibly the movement of auxin from the buds to the root tips that is required for transplant recovery (Hamilton, 1988).

Physical Impacts During Transplanting

Besides pruning cuts, trees can suffer physical damage during lifting and transportation. Accidental impact wounds (cuts, abrasions, bark torsion and compression) can occur to stems, branches and surface roots, while impacts from changes in environmental conditions, such as sun and wind exposure in transit and at the planting site, can affect the whole tree. Desiccation can occur within days if root balls are not fully hydrated (Gilbertson *et al*., 1985). Transplant wounds increase vulnerability to disease and pest attack (notably, in Hong Kong, fungal rots and termites), which may compound the effects of water stress (Peltier and Watson, 2000).

Transplant shock can also be exacerbated by the disturbance of root-soil contact during the mechanical lifting and moving process (Sands, 1984). Disruption in the rhizosphere interaction between roots and the surrounding soil may result from weight re-distribution in the root ball during lifting, and vibration and percussive impacts during handling and transportation. While trees are tolerant of low levels of disruption, above a certain level disruption can significantly affect the potential for root re-growth and survival (Koeser and Stewart, 2009).

Difference between Street and Field Grown Nursery Trees

The morphology of street trees can differ from trees of a comparable age that have grown in open field environments as a result of the poor quality above and below ground conditions found in a typical streetscape. These differences can affect the survival of newly planted trees (Gilbertson *et al*., 1985) and their tolerance of transplanting.

Street tree soils in Hong Kong are typically heterogeneous, nutrient poor and heavily compacted (Jim, 1998). Soils have little organic matter or soil organisms, and are subject to high levels of salt and other contaminants. Although soils are poorly drained, urban street trees often experience drought as a result of the poor infiltration of water through paved surfaces. High levels of compaction are common, and a high penetration resistance and limited macro pore space restrict root establishment and growth (Day *et al*., 2000; Reichwein, 2002). Soil quality is a significant inhibitor of tree root growth and a constraint on tree growth generally (Coder, 1998).

A number of studies have indicated that root depth depends heavily on species and soil conditions (Day *et al*., 2010). Crow (2005) and Wang *et al*. (2006) found that the roots of urban street trees were largely concentrated in the upper soil zones due to the increasingly poor soil conditions at depth. The high incidence of surface roots on street trees also reflects this finding. The root system architecture of street trees is more complex and asymmetric than that of trees growing in open field conditions, and root biomass, in particular fine water-absorbing roots, is likely to be more concentrated immediately around the trunk. Estimating a tree's root spread in urban soils is especially difficult due to the variable conditions below ground. Tree height, spread and trunk diameter have not been found to be good predictors of root spread (Day *et al*., 2010).

Highly constrained root systems have been repeatedly observed on street trees in Hong Kong (Urbis, 2013), with roots confining themselves within the volume of the original planting pits, even where the surrounding soil appears suitable for root growth. This is possibly a consequence of differential soil moisture and oxygen levels between the area of the open tree pit and surrounding closed pavement surfaces. A notable morphological effect of this discrepancy is the formation of very dense root systems close to the tree (Photo 1), and a high frequency of girdling roots.

Street tree canopy space is also restricted by the presence of adjacent structures and buildings, the passage of vehicles and allowance for sightlines. Canopies are frequently pruned and lifted to avoid such impacts. High levels of airborne pollutants can also stunt the growth of roadside trees (Sjöman and Nielsen, 2010).

Photo 1: Morphological response of trees in Hong Kong to growing in confined pavement pits

These poor growing environments often result in short average life expectancies for street trees (Nowak *et al*., 2004). In essence, only those species that are tolerant of the environmental conditions present within a streetscape and that have the ability to respond rapidly to environmental change will survive.

The ability to adapt rapidly to environmental conditions should facilitate the transplanting of street trees. The restricted root system should result in a larger proportion of the original root mass captured within the root ball. The density of the root system should result in more cohesive root balls that are able to withstand more disruption during transportation. Smaller, narrower canopies should also reduce the amount of canopy pruning required to transport trees, and less canopy and root pruning reduces potential imbalances in the shoot-root ratio.

Methods

Case Study of Transplanting Street Trees in Hong Kong

The objectives of the research study were (a) to determine whether any of the characteristics of the individual trees or specific details of the transplanting operation (transplant factors) influenced the outcome (success or failure) of that operation, and (b) to assess whether physiological tree adaptations that allow trees to survive in poor quality street environments in Hong Kong induce tolerance of transplantation.

Controlled experiments are not possible when transplanting mature street trees due to the wide variance in site conditions and cultivation history.

The research study was based on the observation and measurement of the commercial transplanting of 535 mature street trees that were relocated from urban street locations in various parts of Hong Kong to offsite planting locations within a 12-month period (2010 to 2011). All of the trees had been growing in pavement pits (typically 1.0 x 1.0 m) (Photo 1), narrow raised planters (typically 1.0 m wide) (Photo 2) or larger open planting beds. The trees were of nine common broadleaved species (Table 1), and ranged in height from 3.0 to 14.0 m, with trunk diameters (DBH) ranging from 0.1 m to 0.67 m and canopy spreads from 2.5 m to 8.0 m.

Photo 2: Excavating trees from roadside locations in Hong Kong

Data regarding the size and condition of each tree was obtained from tree surveys that had been prepared for the transplanting works approval process, and was verified by physical measurements of sample specimens by the research team. Information on the condition of the original and receptor sites and the transplanting operations was obtained from the contractor's works records, photographs and observation of the transplanting operations.

Transplanting works were undertaken within a single tree transplanting works contract, following a prescribed specification and method statement. The timing of the transplanting operations was dictated by site and project constraints. Each tree was root pruned in advance of transplanting using a three-stage process. The root pruning interval varied between specimens in relation to trunk diameter (from <1 to 6 months). Digging and shaping of the root ball was performed by hand. Root balls were typically 0.8-1.2 m deep and wrapped and wired to protect them during transportation (Peltier and Watson, 2000).

Canopy pruning was specified with the intention of balancing root loss while leaving sufficient foliage for regrowth. As trees had to be transported on public roads, road traffic regulations (Transport Department, 1997) meant that the root ball, trunk and canopy had to be physically reduced (by pruning or tying) to fit within a box with the dimensions 2.5 x 3.5 x 12.0 m (Photo 3). The rigid (mature) branching structure of many trees resulted in a significant proportion of the canopy (average 38.5%) having to be removed to facilitate road transportation. The branching structure of some species, such as *Bombax ceiba*, was severely compromised during this process, and the large-sized pruning cuts (up to 250 mm in diameter) subsequently made them vulnerable to termite attack and fungal infection.

Photo 3: Limitation of transporting trees by road

Trees were lifted by straps wrapped around the root ball, with a further guide strap attached at the mid trunk (Photo 4 (over)). Canopies were wrapped, laid horizontally on the trucks and securely tied. Trees were transported 20 km by road to temporary receptor sites, where they were held for up to

Photo 4: Lifting and handling mature street trees

Photo 5: *Melaleuca quinquenervia*: original roadside location and after transplanting to the receptor site

42 months. Trees were set at 5.0 m spacing in specially constructed aboveground, geo-fabric lined wire mesh planter boxes 1.0-1.4 m high and 20-30% wider than the root ball (Photo 5).

This form of the planter box facilitated the monitoring of the trees' responses to transplanting, allowed easier access to the canopy and provided opportunities to examine root growth at the planter edge and beneath the planter without disturbing the tree. Free drainage of the root ball was ensured, mulch was retained over the root ball and competition from weeds was minimised. The planter also allowed soil volume and irrigation water to be measured for individual trees, and permitted the targeted application of fertilisers and pest control measures.

The environmental conditions (temperature, wind exposure) across the receptor sites were broadly identical, and trees were guyed to ensure stability in typhoon winds. The same works team provided all of the arboricultural aftercare, including daily irrigation, weeding, mulching, fertilising, and disease and pest control.

Transplant Factors

Thirteen transplant factors were selected for this study, as follows.

Characteristics of the individual tree and its existing growing condition:

- species
- tree height
- trunk diameter
- original health (good, fair, poor)
- original form (good, fair, poor)
- original location (pavement pits, raised planter, open ground).

Specific details of the transplanting operation:

- time of year of first root pruning (categorised into two-month intervals)
- pruning interval (in months from 0 to 6 months)
- time of year of transplanting (categorised into 2 month intervals)
- root ball depth
- root ball ratio (trunk diameter (DBH):root ball diameter)
- extent of canopy pruning (% reduction in canopy volume estimated from before and after photographic images)
- handling (identifying trees that had/had not suffered damage to the trunk or roots during transplanting).

Transplant Outcomes

For the purpose of analysis, the outcome of the transplanting operations was defined as either 'success', where the tree overcame transplant shock and made a complete return to normal growth, or 'failure', where the tree died or displayed clear symptoms of terminal decline.

Transplant shock was measured with respect to annual twig elongation. Reference specimens for each species were identified in the surrounding landscape of the original sites and compared with the transplanted trees. As twig elongation occurs at different rates in different parts of the canopy, measurements of twig growth were taken at ten points on the canopy and then averaged.

Other symptoms of transplant shock were noted to include average shoot length, leaf size, volume of new foliage, extent of canopy dieback, root growth and elongation (on sample specimens), flowering and fruiting patterns.

Results

The majority of the trees experienced some form of transplant shock. Less than 2% of the trees displayed no signs of transplant shock and grew at a normal rate directly after replanting. With some specimens, transplant shock was intense but short lived; for others the intensity was less severe but extended over a longer period.

A few trees died within days of being moved. Others died more slowly, enduring a period of transplant shock before entering terminal decline. Symptoms of terminal decline included reduced vigour, no new foliage growth, increasing canopy dieback, bark cracking and no root growth. These symptoms were often accompanied by incidents of insect attack and fungal infection for which pest and fungal control measures were generally ineffective.

By the end of the third year after transplanting it was possible to determine the outcome (success or failure) of the transplanting operations for all of the trees (Table 1).

For each of the nine tree species, statistical correlation analysis was undertaken to identify which of the transplant factors were significant ($P \leq 0.01$) in determining a success or failure outcome (Table 2). As the research data was based on commercial practice rather than generated under controlled conditions, values of more than 0.3 (less than -0.3) were considered to indicate a strong linear relationship and values between 0.2 and 0.3 (-0.2 and -0.3) to indicate a moderate linear relationship.

Some of the datasets were skewed, with a large majority of specimens having one particular result (e.g., 54 out of 57 *Bombax ceiba* were successful), consequently the failures in the set provided limited data for statistical analysis.

Correlation analysis showed that there was a strong relationship between original location and transplant outcome for *Ficus microcarpa* and *Melaleuca*

Table 1: Transplant success/failure for nine tree species commonly planted in Hong Kong

	Number	Success (no/%)	Failure (no/%)
Bombax ceiba, Cotton tree	57	54/94.9	3/5.1
Celtis sinensis, Chinese hackberry	43	33/76.7	10/23.3
Crateva unilocularis, Spider tree	37	31/83.8	6/16.2
Ficus benjamina, Weeping fig	59	38/64.4	21/33.6
Ficus microcarpa, Chinese banyan	129	100/77.5	29/22.5
Melaleuca quinquenervia, Paper bark tree	117	87/74.4	30/25.6
Peltophorum pterocarpum, Yellow poinciana	42	27/64.3	15/35.7
Pongamia pinnata, Wild bean	25	20/80.0	5/20.0
Syzygium cumini, Jambolan plum	26	20/76.9	6/23.1
Total	**535**	**410 / 76.7**	**125 / 23.3**

Table 2: Correlation between each transplant factor and outcome (success or failure) for nine tree species

Variables / Success/ Failure of Species	Height	Trunk diameter	Form	Health	Original location	Pruning time	Pruning interval	Transplanting time	Root ball depth	Root ball ratio	Extent of canopy pruning	Handing
Bombax ceiba	-0.181	-0.292	0.134	0.109	0.146	-0.329*	-0.032	-0.293	-0.167	0.181	-0.147	-0.243
Ficus benjamina	-0.466*	0.154	0.245	-0.250	0.450*	-0.316*	0.455*	0.155	-0.348*	-0.252	-0.059	-0.056
Ficus microcarpa	-0.098	0.118	0.157	-0.001	-0.336*	0.332*	0.004	-0.150	0.381*	0.138	-0.049	-0.122
Melaleuca quinquenervia	-0.353*	-0.242	0.463*	0.150	-0.442*	0.500*	-0.577*	-0.389*	-0.299	0.005	-0.130	0.055
Celtis sinensis	-0.100	-0.152	0.205	0.038	0.165	-0.109	0.296	-0.337*	-0.007	0.188	-0.021	-0.203
Crateva unilocularis	-0.269	-0.131	0.181	0.153	-0.281	0.079	-0.155	0.025	-0.075	0.154	0.033	-0.041
Peltophorum pterocarpum	0.229	0.497*	0.136	-0.043	-0.092	-0.559*	0.085	0.185	0.382*	-0.206	-0.103	0.085
Pongamia pinnata	0.059	-0.205	0.169	0.000	--	--	0.102	--	-0.248	0.129	-0.329*	0.185
Syzygium cumini	-0.559*	-0.175	-0.455*	-0.455*	-0.272	-0.252	0.252	-0.110	0.041	0.146	0.127	0.234

quinquenervia, with specimens from pavement pits more likely to survive than those that had been moved from raised planters or open ground. The converse was observed for *Ficus benjamina*, where trees from open ground locations had a higher chance of survival.

The height of the tree was strongly related to transplant outcome for *Ficus benjamina, Melaleuca quinquenervia* and *Syzygium cumini,* where shorter specimens had a much greater chance of transplant success than taller specimens.

Trunk diameter also had a strong relationship with outcome for *Melaleuca quinquenervia*, where smaller diameter trees had a higher chance of survival, and for *Peltophorum pterocarpum*, where larger diameter trees had a higher chance of survival.

The original form of the tree had a strong relationship with outcome for *Melaleuca quinquenervia*, with trees of good original form having a much higher chance of survival. Original health had a strong negative correlation with outcome for *Syzygium cumini* specimens, where trees in poor original health had a higher chance of survival. The results for original form and original health, however, may have been influenced by the skewed distribution in these datasets, with a large majority of specimens originally having 'good' form and 'good' health due to the process by which specimens were selected for transplanting.

There was a strong correlation between root pruning time and outcome. *Ficus microcarpa* and *Melaleuca quinquenervia* were more successful if root pruned in the autumn than at other times of the year. *Peltophorum pterocarpum*, *Bombax ceiba* and *Ficus benjamina* were more likely to survive transplanting if pruned in early spring. Similarly, *Melaleuca quinquenervia* and *Celtis sinensis* had a higher chance of success if transplanted in the autumn.

The length of the root pruning interval had a strong relationship with outcome for *Ficus benjamina*, where specimens that experienced longer intervals between pruning operations were more successfully transplanted, and for *Melaleuca quinquenervia*, where specimens with shorter pruning intervals were more successful.

There was a strong relationship between root ball depth and outcome for *Ficus benjamina*, which had a significantly higher chance of transplant success with a shallower root ball, and for *Peltophorum pterocarpum* and *Ficus microcarpa*, where specimens with deeper root balls had a significantly higher chance of transplant success.

No significant relationship was found between root ball ratio, operational handling and transplant outcome, although the data was unevenly distributed, with only a few specimens suffering 'poor' handling.

A strong relationship was found between extent of canopy pruning and outcome for *Pongamia pinnata*, where specimens that underwent less canopy pruning had a significantly greater chance of success.

Influence of Transplant Factors on Transplant Success or Failure

The results of the statistical analysis indicate distinct differences between species as to which transplant factors were influential in determining the outcome (success or failure) of the transplanting operation.

Failure rates were notably high, especially given that the specimens had been selected on the basis of having a high chance of survival. This reflects the complexity and site-specific nature of the transplanting process. Transplant shock was short lived, with trees either fully recovered or dead within 36 months. On average, recovery rates across the range of tree sizes were broadly in line with the 3-month recovery period measured on 0.25-m DBH field grown transplants in a subtropical climate in Florida (Beeson and Gilman, 1992; Gilman and Beeson, 1996a). However, with larger trunk diameter specimens (0.45-0.67 m) this figure would predict recovery times of 54 to 80 months, suggesting for the larger street trees used in this study that tolerance of growing conditions within a street was aligned with tolerance of being transplanted.

The finding that specimens of *Ficus microcarpa* and *Melaleuca quinquenervia* that had been growing in pavement tree pits were more successful than those that had been growing in open ground suggests that adaption to a poor quality soil environment of a pavement pit induced tolerance to transplanting. In open ground and raised planters in Hong Kong, soil is more exposed to the atmosphere, and so has higher water infiltration rates, improved rates of drainage, less compaction, greater soil oxygen, and higher organic matter and nutrient levels (Jim, 1998) than pavement pits, which are effectively surface sealed. Both of these species appeared to be able to take advantage of the improved soil conditions after relocation and re-establish their root system and water balance (Gilbertson and Bradshaw, 1990).

This finding is supported by data for *Bombax ceiba,* the fastest growing of the nine species, which had the highest transplant success rate. The majority of these specimens were originally growing in pavement pits with the poorest soil quality, suggesting that the ability to survive these conditions and to root rapidly when more favourable conditions occur are significant advantages in surviving transplanting.

Taller trees are likely to require a proportionately greater reduction in their canopy and root systems to facilitate transplanting. The finding that the success rate decreased as height increased for *Ficus benjamina*, *Melaleuca quinquenervia* and *Syzygium cumini* supports this concept, and aligns with the findings of previous studies that indicated that taller trees had lower survival rates (Zheng *et al*., 2007), and that older trees were less able to respond to transplanting impacts and re-establish than younger trees (Harris *et al*., 2004).

The lack of correlation with trunk diameter (a proxy for tree age), however, indicates that the age of the tree was not as important as its size in determining transplant outcome within this study. It was known that the trees in the study were mainly between 25 and 50 years old. A relationship between trunk diameter and transplant outcome might be more apparent with a wider spread of ages within the population.

The distinct relationship recorded between root pruning at particular times of the year and transplant outcome supports the view that for successful transplanting, pruning needs to be undertaken within periods of active root elongation (Richardson-Calfee and Harris, 2005) and outside periods of active shoot growth (Watson and Himelick, 1982). Indeed, *Ficus microcarpa* and *Melaleuca quinquenervia* were more successfully transplanted if root pruned in the autumn, within their active root period but outside of the period of active shoot growth in early spring. Likewise, a more favourable root pruning time for *Bombax ceiba*, *Ficus benjamina* and *Peltophorum pterocarpum* was in early spring, before periods of active shoot growth commence in late spring.

Although a standard root ball ratio (8:1) had been specified for all of the trees, practical difficulties in forming the root balls during the works resulted in a wide range of root ball ratios achieved, with smaller root balls, such as 3:1 for pavement pits due to surrounding structures, and larger root balls up to 13:1 for trees in open ground. The lack of a strong relationship between root ball ratio and outcome indicates that although the root ball is smaller for a pavement pit tree than an open ground tree, a similar or sufficient proportion of the root system may be captured within the root ball due to the higher density of root biomass close to the trunk (Sherman, 2012).

Roots encountered outside the tree pits tended to be small (<25 mm diameter) suggesting that for large trunk diameter trees the zone of rapid root taper was very close to the trunk and could be captured in relatively small root balls. It is also likely that root pruning operations during transplanting generated a sufficient mass of new fine water-absorbing roots to support the rapid re-establishment of these street trees.

Very shallow rooting patterns were observed on many of the trees in the study, in line with the findings of other studies (Crow, 2005; Wang *et al*., 2006). In general, increasing the depth of the root ball on street tree transplants would not significantly increase the amount of roots captured within it, and might be counterproductive by increasing operational difficulties and the potential for root ball collapse. The interrelationship between root ball depth and other transplant factors such as location and soil type is likely to have influenced the results. This supposition is emphasised by the variance recorded between the high transplant success rate with shallower root balls (*Ficus benjamina*) and the higher transplant success rate with deeper root balls (*Peltophorum pterocarpum, Ficus microcarpa*).

The high average figure (38.5%) for the extent of canopy pruned to facilitate transplanting suggests that growing in a roadside location did not result in substantially less pruning being required. However, the lack of correlation with transplant success or failure for eight of the tree species suggests that a balance had been achieved between the amount of roots retained and the smaller amount of canopy retained, and thus the shoot-root ratios had not been so adversely affected.

Conclusions

This study highlights the variability in the transplanting process, and shows that the factors that influence the outcome of transplanting operations are both species and site specific.

Trees that were successfully transplanted returned to normal growth patterns within similar or shorter periods than previous studies had indicated for similar sized trees in a similar climate. Indeed, the nine street tree species covered in this study appear to be able to respond well to transplanting in Hong Kong.

The findings relating the quality of the original soil environment (location) to transplant outcome (success or failure) also support the contention that the characteristics that induce survival in streetscapes – adaptable, fast-growing rooting systems – also confer tolerance to transplantation.

The specific findings relating to root ball ratio and root ball depth suggest that the general presumption that larger root balls improve the chances of success in transplanting could be challenged, and that forming root balls in response to observed root patterns for street trees would make the transplanting process simpler without reducing the success rate.

The results show that the time of year of root pruning influences the outcome of the transplant operation, but that the most favourable time for these operations varies between species. The relationship between the timing of the root and canopy pruning operations and periods of active shoot growth in each of the species was identified as important.

The high overall failure rate amongst these common street tree species and of tree specimens originally thought suitable for transplanting raises questions about the efficacy of transplanting as an environmental remediation measure.

References

American Nursery and Landscape Association (2004) American Standard for Nursery Stock ANSI Z60.1 American Association of Nurserymen. Washington DC. Available at http://www.anla.org/docs/About%20ANLA/Industry%20Resources/ANLAStandard.pdf (accessed 28 February 2014).

Beeson, R.C., and E.F. Gilman. (1992) Diurnal water stress during landscape establishment of slash pine differs among three production methods. *Journal of Arboriculture* 18, 281–287.

Coder, K.D. (1998) Soil constraints on root growth. In: Tree Root Growth Control Series. Athens University of Georgia Cooperative Extension Service Publication FOR98-10.

Crow, P. (2005). *The Influence of Soils and Species on Tree Root Depth. Information Note FCIN078*. Forestry Commission, Edinburgh.

Day, S.D., Seiler, J.R. and Persaud, N. (2000) A comparison of root growth dynamics of silver maple and flowering dogwood in compacted soil at different soil water contents. *Tree Physiology* 20(4), 257-263.

Day, S.D., Wiseman, P.E., Dickinson, S.B. and Harris, J.R. (2010) Contemporary concepts of root system architecture of urban trees. *Arboriculture and Urban Forestry* 36(4), 149-159.

European Nurserystock Association (2010) European Technical and Quality Standards for Hardy Nursery Stock. Available at www.enaplants.eu/EXEN/site/quality.aspx (accessed 28 February 2014).

Gerhold, H.D., and A.D. Johnson. (2003) Root dimensions of landscape tree cultivars. *Journal of Arboriculture* 29, 322–325.

Gilbertson, P. and Bradshaw, A. (1990) Root growth and the problem of trees in urban and industrial areas. In Patch, D. (Ed.), Advances in Practical Arboriculture. *Forestry Commission Bulletin 65*. HMSO, London, pp. 59–66.

Gilbertson, P., Kendle, A.D. and Bradshaw, A. (1985) The survival of newly planted trees in inner cities. *Arboricultural Journal* 14, 287–309.

Gilman, E.F. (1988) Predicting root spread from trunk diameter and branch spread. *Journal of Arboriculture* 14, 85–89.

Gilman, E.F. (1990) Tree root growth and development: a response to culture, management and planting. *Journal of Environmental Horticulture* 8, 220–227.

Gilman, E.F., and Beeson, R.C. Jr. (1996a) Production method affects tree establishment in the landscape. *Journal of Environmental Horticulture* 14, 81–87.

Gilman, E.F., and Beeson, R.C. Jr. (1996b) Nursery production method affects root growth. *Journal of Environmental Horticulture* 14, 88–91.

Gilman, E.F., and Anderson, P. (2006) Root pruning and transplant success for Cathedral Oak® live oaks. *Journal of Environmental Horticulture* 24, 13–17.

Gilman, E.F., Beeson, R.C. Jr., and Black, R.J. (1992) Comparing root balls on laurel oak transplanted from the wild with those of nursery and container grown trees. *Journal of Arboriculture* 18, 124–129.

Gilman, E.F., Stodola, A. and Marshall, M.D. (2002) Root pruning but not irrigation in the nursery affects live oak root balls and digging survival. *Journal of Environmental Horticulture* 20, 122–126.

Hagen, B. 2001 The ecology of urban trees: Part II. *Western Arborist* 27(1), 40-43.

Hamilton, W.D. (1988) Significance of root severance on the performance of established trees. *Journal of Arboriculture* 14(12), 288–292.

Harris, J.R. and Gilman, E.F. (1991) Production method affects growth and root regeneration of Leyland cypress, Laurel oak and Slash pine. *Journal of Arboriculture* 17(3), 64–69.

Harris, R., Clark, J. and Matheny, N. (2004) Integration of growth over time. In: *Arboriculture: Integrated Management of Landscape Trees, Shrubs, and Vines*, 4th edn. Prentice Hall, pp. 49–51.

Henwood, K. (1973) A structural model of forces in buttressed tropical rain forest trees. *Biotropica* 5(2), 83–93.

HKSAR Government. (2008) HQ/GN/13 Interim guidelines for tree transplanting works under Highways Department's vegetation maintenance ambit. Highways Department Task Force on Tree Transplanting. HKSAR Government.

Jim, C.Y. (1998) Urban soil characteristics and limitations for landscape planting in Hong Kong. *Landscape And Urban Planning* 40(4), 235–249.

Koeser, A., and J.R. Stewart. (2009) Effects of transplanting on the growth and survival of nursery stock. In: G. Watson *et al*. (eds.) The Landscape Below Ground III. International Society of Arboriculture, Savoy, IL. USA, pp. 222–229.

Nowak, D.J., Kuroda, M, and Crane, D.E. (2004) Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry and Urban Greening* 2, 139–147.

Peltier, P., and Watson G.W. (2000) Transplanting trees: Part II. *Arbor Age* February, 8–11.

Percival, G. and Gerritsen, J. (1998) The influence of plant growth regulators on root and shoot growth of containerised trees following root removal. *Journal Horticultural Science Biotechnology* 73, 353–359.

Percival, G.C. (2007) Transplanting shock: getting to the root of the problem. *Essential Arboriculture 23.*

Percival, G.C. and Fraser, G.A. (2005) Use of sugars to improve root growth and increase transplant success of Birch (*Betula pendula* Roth.). *Journal of Arboriculture* 31, 66–78.

Reichwein, S. (2002) Tree roots under sidewalks (in German). Doctoral dissertation, Fachbereich Landschaftsarchitektur und Umweltentwicklung, Universität Hanover. Hanover, Germany.

Richardson-Calfee, L.E. and Harris, J.R. (2005) A review of the effects of transplant timing on landscape establishment of field-grown deciduous trees in temperate climates. *Horticultural Technology* 15(1), 132–135.

Sands, R. (1984) Transplanting stress in Radiate pine. *Australian Forest Research* 14(1), 67–72.

Sherman, A. (2012) Growth and establishment of newly planted street trees. In: *Proceedings of the ISA Conference 2012*. International Society of Arboriculture, Portland, Oregon.

Sjöman, H. and Nielsen, A.B. (2010) Selecting trees for urban paved sites in Scandinavia – a review of information on stress tolerance and its relation to the requirements of tree planners. *Urban Forestry and Urban Greening* 9, 281–293.

South, D.B. and Zwolinski, J.B. (1997) Transplant stress index: a proposed method of quantifying planting checks. *New Forests* 13, 315–328.

Struve, D.K., L. Burchfield, and Maupin, C. (2000) Survival and growth of transplanted large- and small-caliper red oaks. *Journal of Arboriculture* 26, 162–169.

Toky O.P. and Bisht R.P. (1992) Observations on rooting patterns of some agroforestry trees in an arid region of north-western India. *Agroforestry Systems* 18, 245–263.

Transport Department. (1997) Road Traffic (Traffic Control) Regulation: 55 (Cap 374 sub. Leg. G) and Road Traffic (Registration and Licensing of Vehicles) Regulations (Cap 374 sub. Leg. E). HKSAR Government.

Urbis Limited. (2013) A comprehensive street tree management plan for Hong Kong. (Unpublished report). Development Bureau, Works Branch, HKSAR Government.

Wang, Z. Guo, D. Wang, J. and Mei, L. (2006) Fine root architecture, morphology and biomass of different branch orders of two Chinese temperate tree species. *Plant and Soil* 288(1), 155–171.

Watson G. W. (2010) Transplant shock: Severity dependent on tree size and restoration of root-shoot balance, Morton Arboretum. Available at: http://www.ag.purdue.edu/counties/vanderburgh/Documents/Horticulture/Transplant%20Shock-Morton%20Arb.pdf (accessed 28 February 2014).

Watson G.W. (1998) Tree growth after trenching and compensatory crown pruning. *Journal of Arboriculture* 24(1), 47–53.

Watson, G.W, and Himelick E.B. (1982) Seasonal variations in root regenerations of transplanted trees. *Journal of Arboriculture* 8, 305–310.

Watson, G.W. (1985) Tree size affects root regeneration and top growth after transplanting. *Journal of Arboriculture* 11, 37–40.

Watson, G.W. (1992) Root development after transplanting. In: Neely, D. and Watson, G.W. (eds.). *The Landscape below Ground I: Proceedings of an International Conference on Tree Root Development in Urban Soils*. International Society of Arboriculture. Champaign, Illinois, pp. 55–68.

Watson, G.W. and Himelick, E.B. (2013) *The Practical Science of Planting Trees*. International Society of Arboriculture.

Zheng Feng., 郑芳, 王春弘, 罗彩云, 刘喜平, 阎德祺. **(2007)** Discussion on transplanting techniques of big trees in landscape projects. *Journal of Anhui Agricultural Science* 35(11), 3229–3230, 3232.