Fundamentals of tree establishment: a review

'The best time to plant a tree was twenty years ago.
The second best time is now.'
Anonymous

Abstract

Mortality of landscape trees regularly reaches 30% in the first year after planting. This review aims to highlight the fundamental factors and procedures critical to tree establishment. If these are fully considered and acted upon, significant reductions in transplant losses can be expected. The principal elements essential for successful tree establishment have been identified as tree ecophysiology; rooting environment; plant quality and planting and post-planting. These are presented in a model which helps describes the multiplicity of factors involved in successful establishment and, importantly, their interrelated nature. An understanding of how transplant survival can be markedly influenced by these factors is paramount and failure to consider any one element may lead to tree mortality. Attention is also given to practices which have been demonstrated to greatly enhance tree vitality during the establishment phase.

The challenge of tree establishment

Keywords:

tree establishment, tree planting

Trees planted into urban landscapes such as streets, recreational areas and car parks provide important benefits to urban populations. These include absorption of pollutants, reduction of traffic noise, windbreaks and shelter, as well as reduction of radiation and solar heat gain through shading and evapotranspiration (NUFU, 2005; Hiemstra *et al.*, 2008; Forest Research, 2010). Trees also provide shape, scale, form and seasonal changes to the landscape. However, as early as the 1980s failure rates for amenity tree planting were commonly recorded as 30%, but failure rates of 70% were reached with disturbing regularity during the first growing season (Gilbertson and Bradshaw, 1985, 1990). Further research in the late 1990s and 2008 highlighted similar failure rates (Johnston and Rushton, 1999; Britt and Johnston, 2008). In view of the resource life-history an amenity tree has in terms of irrigation, fertilisers (if applied), transport costs, planting materials, labour, etc., in addition to the actual loss of the tree, the persistence of these failure rates can no longer be accepted. Such significant losses also challenge us to consider why, over a 30 year period, mortality rates of 30–50% are still commonplace during the first year after planting.

A number of reasons exist. While it is appreciated by professionals involved in urban tree management that trees are planted into suboptimal conditions for growth, the extent and diversity of stresses urban environments impose is frequently under-estimated. Table 1 identifies abiotic stresses which may affect urban trees.

Transplant survival is influenced by the range of factors outlined in Figure 1. *Tree ecophysiology* considers the genetic potential of trees to establish in a given environment and species characteristics which may reduce the impact of a particular stress. High *plant quality* is an essential foundation for any planting project. *Planting and post-planting* practices are fundamental to establishment success. The *rooting environment* is critical in ensuring future resource availability and anchorage. Failure to give full consideration to any one of these factors increases the likelihood of a high mortality rate in a tree planting scheme.

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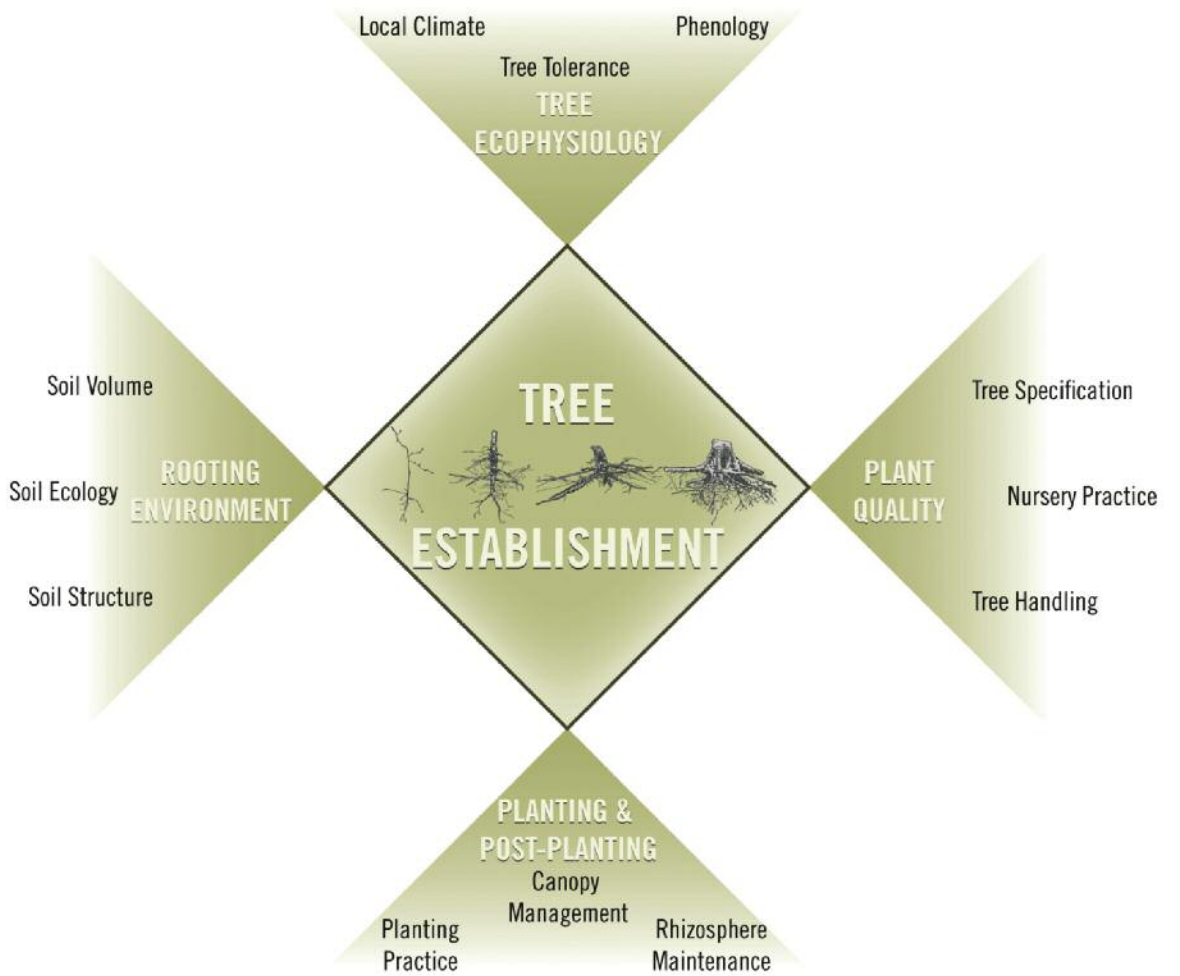
Table 1 Potential abiotic or non-living stresses affecting urban trees.

Abiotic stresses	
High irradiance (photoinhibition, photooxidation)	Herbicides, pesticides, fungicides
Heat (increased temperature)	Air pollutants (SO_2, NO, NO_2, NO_x)
Low temperature (chilling, frost)	Ozone (O_3) and photochemical smog
Drought (desiccation problems)	Formation of highly reactive oxygen species ($^1O_2$, radicals, O_2^- and OH, H_2O_2)
Natural mineral deficiency	Photooxidants (peroxyacylnitrates)
Waterlogging (root deoxygenation)	Acid rain, acid fog and acid morning dew
Competition for light, water, nutrients	Acid pH of soil and water
Excess de-icing salts (Na, Cl)	Over supply of nitrogen (dry and wet NO^3 deposits)
Heavy metals	Increased UV-radiation
Increased CO_2 levels (global climate change)	

Figure 1 A model of the key factors involved in successful tree establishment



Transplant stress

The common observation of slow growth, tree decline and/or death following transplanting is characterised as transplant stress. The marked reduction in root:shoot ratio due to the lifting process in the nursery results in a severe limitation to resource capture. Newly transplanted trees are, therefore, incapable of meeting the water and nutrient demands of the canopy. Consequently, the efficient return to a pre-transplant root:shoot ratio is essential for survival and establishment of transplanted trees (Davies *et al*., 2002).

Tree ecophysiology

Each tree species has an inherent capacity for growth. This relates to a complex array of morphological, anatomical and physiological attributes. Most obviously, these influence tolerance to climate (and microclimate), but a number of characteristics have been observed to promote tolerance to transplanting.

Local climate

The significance of climatic factors on tree performance is broadly appreciated by those involved in tree management. When, however, it is necessary to make decisions on tree selection for a given site it is soon apparent that robust data on climatic suitability is poorly developed or non-existent. Inherently poor climatic fit in terms of growing season temperature and solar radiation can markedly influence the performance of many species that are of continental European-Asian or North American distribution, which perform satisfactorily in South East England but struggle within a UK northern climate (Percival and Hitchmough, 1995). Problems can be exacerbated within an urban landscape where several microclimates (a local atmospheric zone where the climate differs from the surrounding area) may exist within very short distances. Microclimates exist, for example, near bodies of water which may cool the local atmosphere, or in heavily urban areas where brick, concrete and asphalt absorb the sun's energy and radiate that heat to the ambient air, resulting in an urban heat island. South-facing slopes are exposed to more direct sunlight than opposite slopes and are, therefore, warmer for longer. Tall buildings create their own microclimate, both by overshadowing large areas and by channelling strong winds to ground level. Local climate knowledge is important as the biological events of trees (flowering, seed set, bud burst, etc) are controlled by environmental triggers. Disruption to these triggers can be manifest for example by cherries under artificial street lights flowering in winter due to a disrupted photoperiod (Harris *et al.*, 2004). Consideration of the precise environmental conditions in which the tree will be located is an essential criterion for tree selection.

Tree tolerance

Tolerance to transplanting has been shown to vary widely between different genera with *Populus*, *Salix* and *Alnus* widely regarded as transplant tolerant while *Fagus*, *Juglans* and *Aesculus* are transplant sensitive (Watson and Himelick, 1997). Reasons for these differences are complex and have never been fully elucidated, although some of the salient factors have been identified.

Soil moisture and temperature are most influential in determining the periodicity of root growth but in reality multiple factors are involved (Eissenstat and Yanai, 2002). Ease of transplanting has been linked with root morphology and the rate of root regeneration. For example, root regeneration rates of green ash began at 9 (root tip elongation) and 17 (formation of adventitious roots) days after planting, while in red oak such responses were not recorded until days 24 and 49 (Arnold, 1987). Species with fibrous root systems that have significantly more profusely branched root systems are suggested to be easier to transplant than species with coarse root systems (Struve, 1990). Although variation between species will exist, at least six or more lateral roots should be present when planting as lower numbers of lateral roots are associated with a decrease in survival rates (Struve, 1990). Likewise, trees that possess physiological adaptations to waterlogging such as the formation of aerenchyma (intercellular gas-filled spaces) in the root cortex, the development of adventitious roots and enlarged lenticels, anaerobic carbohydrate catabolism and oxidisation of the rhizosphere tend to have higher survival and establishment rates than species which do not possess these characteristics. Trees with specific anatomical features associated with drought (thicker waxy cuticle, presence of hairs on the leaf surface, sunken stomata located on the underside of the leaves) also tend to be associated with higher transplant success, as drought-induced water deficits are regarded as one of the major causes of failure of newly planted trees (Watson and Himelick, 1997; Pallardy, 2008).

Phenology

Phenology relates to the recurring patterns of plant development which occur in response to climate and environment (Larcher, 2003). Consideration of the tree development stage is important for successful tree establishment. Trees planted early in the dormant season (November-December) tend to survive and have higher survival rates than trees planted later in the growing season. However, there may be some advantage to spring planting in some species (Richardson-Calfee *et al.*, 2004). The importance of high concentrations of carbohydrate reserves within root tissue for survival and growth following transplanting are well recognised. Root growth is an energy-consuming process occurring at the expense of available carbohydrate reserves (Martinez-Trinidad *et al.*, 2009c). During cold storage carbohydrate reserves accumulated during the previous growing season are depleted due to respiration. Consequently, longer storage periods equate to less accumulated carbohydrate reserves. This may impact on canopy expansion in spring and a concomitant increase in transplant mortality (Lindqvist and Asp, 2002). Total tree energy levels can decrease by 40 to 70% between bud-break and total canopy development depending on species (Struve, 1990). Storage compounds become more important to establishment success as planting conditions worsen. Reduced photosynthetic leaf tissue during bud-burst and initial leaf expansion in deciduous trees means energy for these processes comes mainly at the expense of reserve carbohydrates (Martinez-Trinidad *et al.*, 2009a, 2009b).

Plant quality

Without exception, healthy landscape trees are derived from high quality nursery stock. Ensuring high quality trees are available for planting is essential if successful establishment is to take place. While mechanisms such as tree specification can play important roles in securing good quality stock, it is vital that tree handling procedures during transport and on-site adequately protect plant material from damage.

Tree specification

Considerable variation exists across tree nurseries so purchasers of trees should learn to evaluate nurseries and if necessary discriminate against those which fail to consistently deliver high quality stock. Some authors (Clark, 2003; Sellmer and Kuhns, 2007) advocate the use of tree specifications which provide robust and precise guidelines detailing tree characteristics required at the time of purchase (Table 2).

Nursery practice

A number of nursery production practices can influence the establishment of trees. Perhaps of greatest significance is the extent to which the root system can be diminished during transplanting; Watson and Himelick (1982) estimated that up to 98% of the roots may be left at the nursery. This leaves an inadequate root area for resource acquisition and is the determining factor in many transplant failures. Maximising the volume of roots taken with the tree at time of transplanting is critical to successful establishment. Practices and methods which seek to achieve this are essential in producing high quality amenity trees.

Root pruning can, if done routinely, promote and maintain a compact fibrous root system (Watson and Sydnor, 1987). This is generally observed to improve transplant survival (Gilman *et al.*, 2002) but others have observed little effect on growth as a result of root pruning (Harris and Fanelli, 1998).

Seedlings grown in containers for too long can develop circling root defects which will persist in form to such an extent that they can girdle the tree causing instability and restriction in the translocation of materials (Watson and Himelick, 1997). Formation of girdling roots is also associated with stimulation of lateral roots in response to a main root severance (Watson *et al.*, 1990). Pot design which facilitates the air pruning of lateral roots (e.g. Air-Pots™) can significantly reduce root defects and subsequent problems of root circling (Single and Single, 2010). White fabric containers (e.g. Barcham Light Pots™) which allow the transmission of some light through have also been shown to reduce root circling (Grimshaw and Bayton, 2010). Where trees are grown in containers, it is good practice to identify a

Table 2 Important tree specification criteria.

Tree specification criteria	
Above ground	**Below ground**
Specimen true to species or variety type	High root ball occupancy
Graft compatibility (if appropriate)	Diversity in rooting direction
Healthy with good vitality[1]	Good root division
Free from pests, disease or abiotic stress	Extensive fibrous root system
Free from injury	Free from root defects (e.g. circling roots)
Self-supporting with good stem taper	Free from pests, disease or abiotic stress
Stem-branch transition height	
Sound branch attachment and structure	
Good pruning wound occlusion	
Canopy symmetry	

[1] *Visual assessment could be supported with chlorophyll fluorescence data*

'shelf-life' to prevent landscape trees from inheriting root defects from tree nurseries.

High density spacing between plants in the nursery can have two potential impacts on tree establishment. First, stem taper is diminished when trees are grown in very close stands; this impacts the future ability of the tree to be self-supporting. Secondly, shading becomes more significant, which reduces the level of photosynthesis and its products. Losses in carbon available for growth and storage as a result of this may have an impact on transplant success (Sellmer and Kuhns, 2007).

Shoot or canopy pruning can, if done appropriately, enhance the future structure of the tree by reducing conflicts between branches, removing branches with poor attachments and encouraging crown symmetry. However, poor practice may destroy natural form, excessively reduce leaf area and extensively wound stems. Working with growers to develop best practice is of strategic importance in enhancing tree establishment. The collaboration and cooperation across sectors involved in the specification, production and planting of trees should be encouraged by all stakeholders.

Tree handling

Care should be taken when trees are transported from the nursery to the planting site. Use a covered vehicle that protects the roots from wind and temperature extremes. Trees should be watered prior to shipping and ideally the root ball checked for moisture at arrival using a soil moisture probe. On site material should be maintained under shade and irrigated at least twice daily if temperatures are ≥24°C. Plants should be healed-in if required and protected from extremes in temperature (frost, etc.). Ideally, handle trees by the root ball using straps or powered equipment rather than lifting using branches or the trunk. The trunk should also be wrapped during shipping and the planting process for protection. Exposed roots desiccate very rapidly in air and it is imperative that this is not allowed to happen at any stage of handling. Failure to do so often results in tree mortality.

Rooting environment

In one of the earliest arboricultural texts, Solotaroff (1911) states 'a great deal, if not all of the success in tree growing, depends upon the nature and the preparation of the soil'. This observation has, over time, been proven to be true.

Soil provides a vital medium for tree growth and development through the provision of water and mineral nutrients and by acting as a substrate for plant anchorage (Kozlowski *et al*., 1991). While soil is extremely heterogeneous, healthy natural soils are associated with a balance of solid material, air and water in a typical volumetric composition. Rock particles (mineral matter) make up 45%, organic matter 5%, while air and water each occupy 20–30% of the soil volume (Brady and Weil, 2008). The solid materials host a labyrinth of pore spaces which in turn provide aeration and hold water within the soil profile. Soil texture, soil structure and soil biota are further characteristics which control soil functions vital for tree growth.

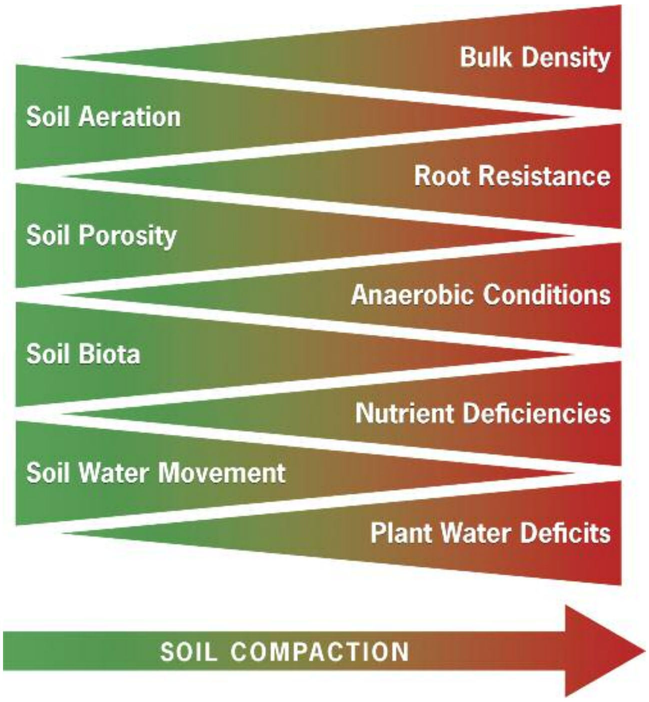
Soils in urban landscapes are generally thought of as highly disturbed, highly variable and of low fertility (Craul, 1999). However, Pouyat *et al*. (2010) provide evidence that observations of entire landscapes have shown that soils which are largely undisturbed or of high fertility may also be found in urban areas. High variability in nitrogen availability in urban soils was also found by Scharenbroch and Lloyd (2006). Such diversity, therefore, requires professionals and practitioners involved with tree establishment to have a high level of knowledge relating to tree development under different prevailing soil conditions.

The extent of soil compaction has particular significance for the process of tree establishment because it acts on a range of criteria which may limit tree vitality (Figure 2). As soil is compacted, physical resistance to roots is increased; soil aggregates break down and pore space is diminished. This reduces soil aeration, detrimentally affecting biological respiration of roots and soil biota, which in turn impacts nutrient cycling and availability. Modification of soil structure also changes hydraulic properties and significantly slows water movement through the soil presenting both water deficits and waterlogging as potential problems (Kozlowski, 1999).

It is generally accepted that most roots are unable to penetrate moist soils of a bulk density greater than 1.4–1.6 $g\,cm^{-3}$ in fine textured soils and 1.75 $g\,cm^{-3}$ in more coarsely textured soils although this will be reduced in drier soils and variation does exist across species (Kozlowski, 1999; Brady and Weil, 2008).

Soil compaction beyond these thresholds frequently exists in urban situations as a result of vehicular and pedestrian traffic but may also be necessary for engineering purposes. Where such densities exist, the soil volume available for tree root growth is significantly reduced. This has led a number of authors to suggest that available soil volume is the most limiting factor in the growth of urban trees (Kopinga, 1991; Craul, 1992; Lindsey and Bassuk, 1992; Grabosky and

Figure 2 Soil characteristics modified by soil compaction.



Bassuk, 1995). A number of approaches have been explored to calculate the soil volume a tree requires; these are generally based on either nutritional or water requirements. Lindsey and Bassuk (1991) developed a calculation based on potential crown projection, where this was equivalent to the area under the tree's drip line; leaf area index (LAI) and local meteorological conditions to determine daily whole tree water use. This is then integrated to the known water holding capacity of the soil in order to determine the volume of soil required to meet the water needs of a tree. As a general estimate 0.06 m^3 of soil is recommended for every 0.09 m^2 of crown projection. While this approach is helpful, functional diversity across tree water use strategies, heterogeneity in soil moisture release characteristics and peculiarities of local microclimate dictate that an assessment of genuine tree soil volume requirements are highly complex. Despite the potential uncertainty surrounding absolute soil requirements, a resounding message from various soil volume calculations is that soil volumes frequently found in urban environments are inadequate.

In recognition of the need to enhance soil volumes artificial substrates known as 'structural soils' (e.g. Amsterdam tree soil; Cornell University structural soil; Stalite) have been designed to take limited engineering loads while maintaining a structure which still facilitates root development (Couenberg, 1994; Grabosky and Bassuk, 1995; Kristoffersen, 1998). This approach undoubtedly enhances available rooting volumes but, as a result of the high sand and stone fraction in these soils, persistent retention of water and nutrients has been cited as a potential problem (Trowbridge and Bassuk, 2004). Smiley *et al*. (2006) compared growth parameters on trees established in structural and non-compacted soil and surrounded by pavement. Trees in the non-compacted soil treatment out-performed structural and compacted soils in almost every parameter measured. This underscores the importance of compaction in urban soils and highlights the limitations of some structural soils in providing a suitable substrate for tree establishment.

Recently, structural cells (e.g. SilvaCell® and StrataCell™) have been developed to help enhance the soil volumes available to tree roots. These cells have a rigid framework capable of bearing loads encountered in urban environments and voids designed to contain high quality soil. As a result, compaction within the rooting environment is prevented and soil conditions which promote tree vitality can be maintained (Urban, 2008). However, long-term studies which assess the value of these systems are needed to provide robust evidence of their value: none currently exist.

Planting and post-planting

Frequently, the right tree has been selected for the right place, a high quality plant has been secure from the nursery and the root environment is capable of providing resources for tree development, but deficient planting practices and inadequate post-planting aftercare cause tree failure. Education clearly has a role, but good practice should be enforced through robust management and the extensive use of planting specifications which give precise expectations of all planting and post-planting operations. Practitioners can then be accountable to this specification and audits may be carried out to monitor work standards.

Planting practice

Several best management practices regarding tree planting can be found in the established arboricultural literature (e.g. Watson and Himelick 1997; Harris *et al*., 2004). While some challenges in tree planting are yet to be fully resolved, the fundamental practices are apparent.

i. *Assess the roots or root ball for potential defects*; the upper roots must not be more than a few centimetres below the soil surface; the stem flare must be visible; and roots which circle over one third of the root ball should be removed.
ii. *Prepare the planting site*; an area two to three times the diameter of the root ball should be decompacted; and the planting hole itself should be no deeper than the existing

root ball or the root-stem transition. In urban sites the preparation of the planting site may include additional infrastructure such as structural cells, irrigation and aeration systems and root management systems.

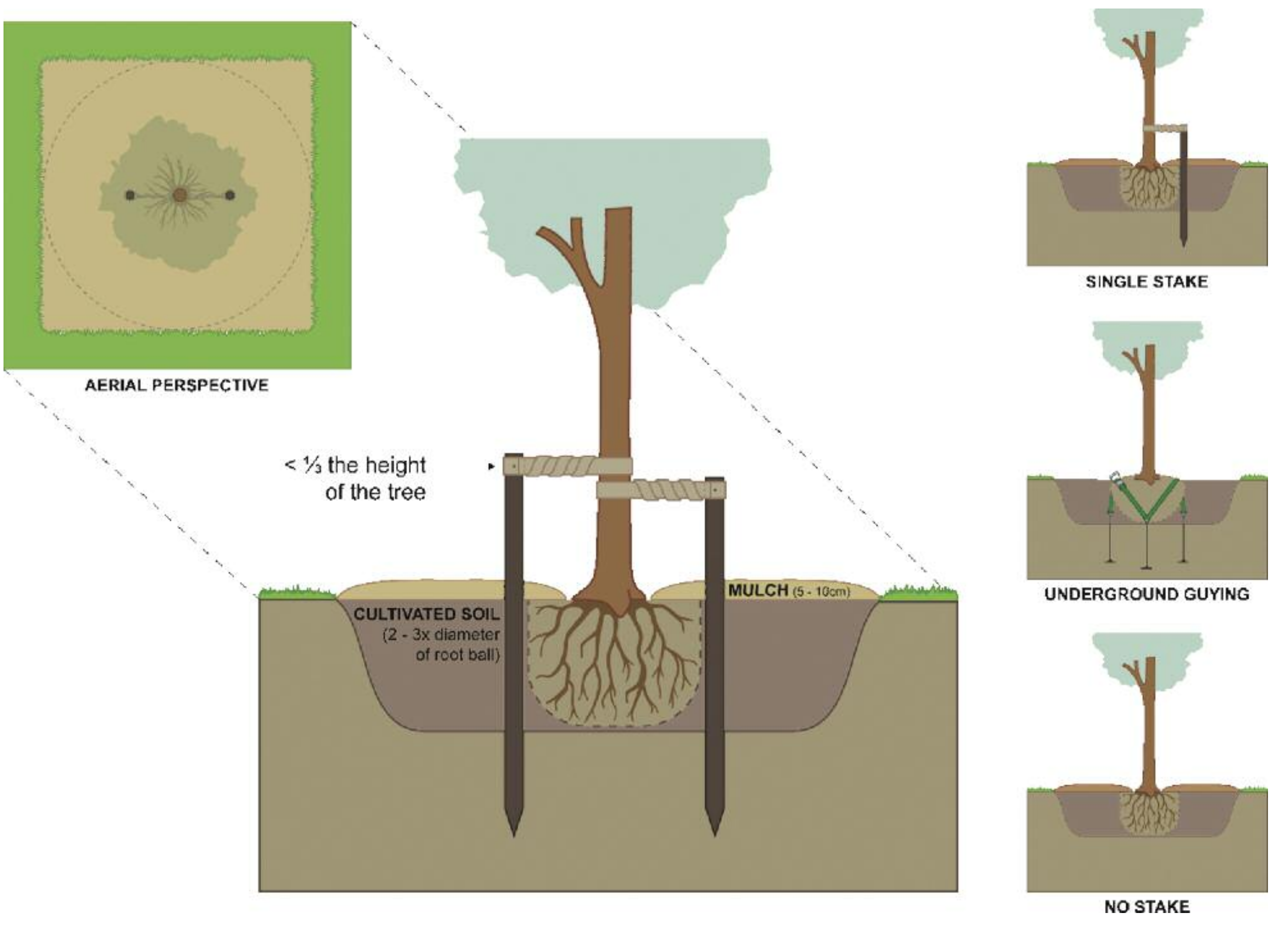
iii. *Plant the tree* so that the root ball or root-stem transition is level with the existing host soil. Add backfill gradually ensuring the tree is held upright and be careful not to cause excessive compaction when firming in. Soil removed from the hole makes the best backfill. Water the root ball and planting area immediately after planting. Support systems of trees are considered below (Figure 3).

One of the most common errors in tree planting is that the root ball is either planted too deep or too high, both of which can cause serious problems. Planting trees 7–8 cm below the root ball, for example, resulted in 30–50% death rates of several different species representing a wide range of different genera (Arnold *et al.*, 2007). In fact, Arnold *et al.* (2007) suggest that in some species planting 7–8 cm above grade may confer some advantage to establishment. It is also of critical importance to ensure that the roots are not allowed to desiccate at any stage during handling or planting. This causes irreversible damage to the root system and greatly increases the likelihood of transplant failure.

Tree maintenance

A number of approaches have been advocated to physically support trees. Regardless of technique, the support system should allow stem and canopy movement so that reaction wood develops the stem taper and root growth is stimulated. Support systems which restrict canopy and stem movement also restrict these processes from occurring. Best management practices, therefore, recommend the support as low as possible (Appleton *et al.*, 2008). Tree ties should seek to spread the load of support on the stem with a wide band (usually hessian or rubber); this must also facilitate radial expansion of the stem. Alternatively, below-ground root anchor systems may be used: these allow full above-ground movement and help give the impression of an established tree. Furthermore, in pedestrian areas trip hazards are avoided. Do not anchor trees too high on the trunk and avoid securing guides in narrow crotch angles of branches. Prevent bark abrasion by using rubber straps, pads, hessian ties or springs with supports or stakes. Remove all forms of support after new root growth adequately stabilises the tree. This can vary by tree species, size, soil type, etc. As a general guide it should be acceptable to remove all support within two years of planting.

Figure 3 Planting and staking techniques.



Formative pruning can help achieve good branch structure and reduce future hazards (Harris *et al*., 2004). It may be necessary to remove broken branches (from handling procedures) and occasional branches which show serious conflict with others. However, it is essential that as much of the canopy remain intact as possible as a reduction in leaf area directly impacts carbon gain and, therefore, the energy resources available for root development. Any pruning should follow the natural target pruning method outlined in standard arboricultural texts (Gilman, 2002; Brown and Kirkham, 2004; Harris *et al*., 2004).

Rhizosphere maintenance

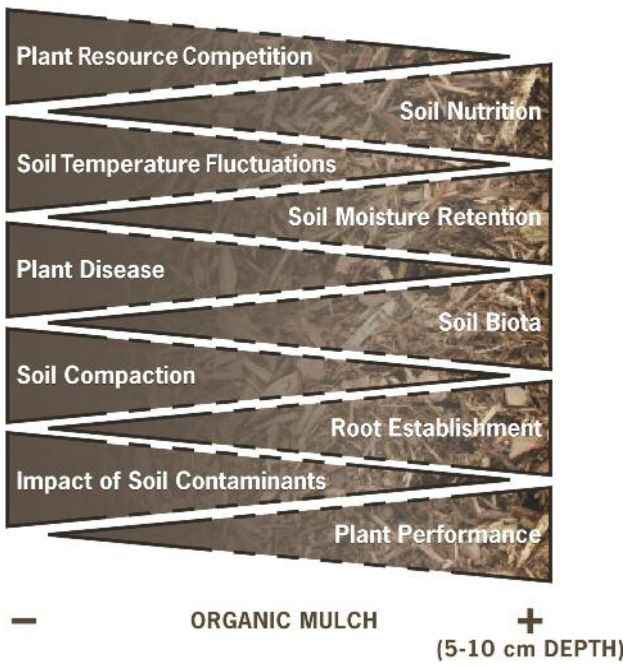
The rhizosphere is the region of soil in intimate contact with the roots of a plant and its health is critical to plant performance. It contains a complex array of plant-associated communities of organisms vital for soil health (Buée *et al*., 2009). While it is difficult to directly influence the actual rhizosphere, interventions to promote soil ecology and good soil structure will promote rhizosphere health and concomitantly improve tree performance. It is essential that soil health is on the agenda of those seeking to establish trees in the urban environment.

The use of various soil amendments to include auxins, mycorrhiza, biostimulants, sugars and hydrogels have been advocated as a means of reducing transplant losses. However, data from several independent research trials demonstrate widely conflicting opinions as to their usefulness. While the potential of these amendments is appreciated, further research is required before definitive conclusions can be reached regarding their use (Smiley *et al*., 1997; Percival and Fraser, 2005; Barnes and Percival, 2006).

Mulching is an essential component to reduce transplant losses and should always be undertaken. Benefits of mulches include minimising fluctuations of soil temperature and soil moisture; weed suppression; soil nutritional enrichment; the prevention of soil erosion from heavy rains; regulation of pH and cation exchange capacity (CEC); pathogen suppression; increasing soil microbial activity and improving aeration (Figure 4). In addition mulches can prevent mower and strimmer damage to the tree trunk and act as a buffer in preventing excess de-icing salts from percolating into the soil to around the root zone (Chalker-Scott, 2007). Landscape mulches include both inorganic (e.g. crushed stone, crushed brick, gravel, polyethylene films) and organic mulches (shredded branches and leaves, softwood and hardwood tree bark, wood chips, sawdust, pine straw, recycled pallets and mixes of the above). The use of organic rather than inorganic mulches in urban landscapes is suggested for improved root growth of establishing trees (Chalker-Scott, 2007). Recent studies have focused on the effectiveness of organic mulches derived solely from a single tree species (defined as a 'pure' mulch). Results demonstrated that pure mulches can have a substantial effect on tree survival rate and growth at the end of the growing season and are an area worthy of future research (Percival *et al*., 2009).

Mulch should be between 5 and 10 cm thick and applied from the drip line to the trunk. If this is not practical, minimum mulch circle radii should be 0.3 m for small trees, 1 m for medium trees and 3 m for large trees. Mulch should not be placed against the trunk as this will retain moisture against the trunk that may result in disease.

Figure 4 The multiple biological effects of organic mulching. Dashed lines indicate that it is unlikely to be a linear transition.



Water deficits affect almost every aspect of tree growth and development (Pallardy, 2008). Tree water deficits are nearly always associated with periodic drought but the significant damage to tree root systems and limited soil volumes, often observed on urban planting sites, frequently contribute to serious tree water deficits. Transpirational demands cannot be met as a result of root loss during transplanting or restricted access to soil water. Post-planting irrigation has been cited as the most important maintenance practice (Watson and Himelick, 1997) and critical to tree establishment. Water deficits are regarded as the major causes of failure of newly planted trees resulting in loss of leaf turgor, stomatal closure, decreased photosynthesis and reduced metabolic functions. In areas where newly planted trees are not irrigated initial establishment relies heavily on precipitation. If the transplant does not receive sufficient precipitation during the period of new root regeneration, its internal water deficits increase considerably due to excessive water transpiration and non-absorption of water from the soil. Determining when to irrigate, or scheduling, irrigation should integrate knowledge of meteorological data, soil moisture release characteristics and tree species response to water deficit.

If irrigation seeks to replace evapotranspiration then calculations based on standard formulas have been applied for a wide range of crops (Allen *et al.*, 1999); however, the diversity of species, planting densities and microclimate have led Costello *et al*. (2000) to develop a modified approach for landscape plantings. While this has significant merit at the landscape scale it cannot take account of the significant heterogeneity in urban soils and relies on the availability of meteorological data. Assessment of soil moisture has greater value on individual sites as it can relate to the specific conditions experienced by vegetation and takes account of local soil hydrology.

The most important soil characteristic to evaluate is the matric potential (soil water potential): usually this is assessed using a tensiometer. Each soil has an individual moisture release characteristic which is determined by factors such as texture, parent material and organic matter content. This results in significant differences in soil water availability even when soil volumetric content is consistent across different soil types. For example, a sandy soil with a volumetric water content of 5% will contain water which is readily available to the tree, whereas, a loam-based soil at the equivalent volumetric content will contain no available water. Assessing the volumetric water content is therefore of limited value unless the corresponding matric potential of the soil is known (Kramer and Boyer, 1995).

A further factor is the variation in the ability of a particular species to withstand periods of water shortage and flooding. Niinemets and Valladares (2006) provide a tolerance index which may be used to assist the assessment of relative species' drought and waterlogging tolerance. However, it should be noted that variation in drought tolerance is also observed in different cultivars of the same species (Fini *et al.*, 2009).

Post-planting irrigation can aid establishment but variation in irrigation frequency had a greater impact on the establishment of live oak (*Quercus virginiana*) and red maple (*Acer rubrum*) (Gilman *et al.*, 1998, 2003) than irrigation volume. However, caution is needed when applying findings of research from contrasting climates, species drought tolerance and soil types as irrigation requirements may differ greatly.

Prior to large-scale plantings soil analysis should always be undertaken to take into consideration pH, macro and micronutrient deficiencies, heavy metal content and salinity. Planting trees into soils with, for example, an inappropriate pH or elevated heavy metal content will only compound transplant losses (Percival, 2007). According to several researchers transplant growth can be regulated to a large extent by nutrient levels present in a fertiliser with nitrogen (N) identified as the macronutrient having the greatest influence (Zandstra and Liptay, 1999). However, the effects of N fertilisers upon survival of trees post-planting are conflicting (see Percival and Barnes, 2007, for a full review). Proliferation of tree root systems in a moist N-rich environment has been demonstrated and work elsewhere concluded that fine root turnover of trees increased exponentially with soil N availability (Gilbertson *et al.*, 1985). Researchers at the Morton Arboretum in the USA concluded that only application of granular N significantly increased root density of honeylocust (*Gleditsia triacanthos* var. inermis) and pin oak (*Quercus palustris*) compared to granular potassium and phosphorus fertilizers (Watson, 1994). Contrary to this, other researchers studying the influence of N fertilisers on alterations to root:shoot ratios demonstrated little or no impact on root stimulation (Day and Harris, 2007). These results are consistent with those obtained from other studies using *Hopea odorata* and *Mimusops elengi*, *Pseudoacacia menziesii*, *Liriodendron tulipifera*, *Acer rubrum*, *Tilia cordata* and *Azadirachta excelsa* as test species (Zainudin *et al.*, 2003; Day and Harris, 2007). Regarding use of fertilisers as a means of reducing transplant stress the conclusions reached by most researchers are:

i. Prior to large-scale plantings, cores of soil should be sent to a reputable laboratory for soil nutrient analysis and any nutrient deficiencies remediated with appropriate fertilisation.

ii. Trees planted in a well-drained, aerated soil which contains an adequate supply of nutrients do not need fertilising.

iii. In general, applications of fertilisers result in more balanced growth vital for plants growing in harsh urban environments where competition for water and nutrients is high and/or resource availability is low.

Where the bulk density of the soil is demonstrated to be limiting to tree development, decompaction of the rooting environment has considerable value regardless of tree age.

While a variety of approaches are available to 'decompact', the value of some equipment has been questioned (Smiley *et al*., 1990; Smiley, 1994; Hascher and Wells, 2007). It is now clear that only those approaches which result in a significant and widespread reduction in soil bulk density throughout the rooting volume have appreciable merit. High pressure pneumatic soil excavation tools (e.g. Air Spade®, Supersonic Air Knife, Soil Pick©) have been demonstrated to achieve this and are capable of cultivating the soil to a depth of 25–30 cm using compressed air to excavate soil with minimal disturbance or damage to tree roots (Felix, 2004). Fite *et al*. (2009) found this approach to be particularly valuable when combined with a nutritional amendment in a technique known as Root Invigoration™. Since there is so little damage, larger areas can be excavated, which greatly expand the available area for root growth and development (Smiley, 1999). However, concern has been raised regarding the potential damage of applying compressed air to the soil surface and root system (Kosola *et al*., 2007). Further research in this area is ongoing but, at present, it seems likely that the long-term benefits of soil decompaction outweigh the minor damage to the fine root system.

Conclusions

This paper identifies a framework which, if fully evaluated, will greatly enhance tree establishment rates. Landscape professionals should consider *tree ecophysiology*, the *rooting environment*, *plant quality* and *planting and post-planting practice* in every new tree planting scheme. Empirical evidence, in addition to academic literature, suggests that neglecting to consider any of these fundamental factors will result in the unacceptable failure rates observed in recent decades. The integration and application of current best practice in each of these areas will greatly improve the current situation. This presents an immediate opportunity to enhance tree establishment in our urban environment by simply integrating and applying existing knowledge more effectively.

Urban trees remain highly relevant to the built environment and society. However, their value can only be realised if trees are managed effectively from the inception of a planting scheme to full maturity in the landscape.

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