Urban Tree Establishment

The Impact of Nursery Production Systems and Assessment Methods

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Abstract

The aim of this PhD project was to study tree establishment, both how it may be improved in urban areas and how it is measured and defined. The establishment phase of trees is a period of reduced tree vitality, and a successful establishment is crucial for long-term survival and prosperity of newly planted trees. However, failed plantings and poor establishment is a common problem in the often harsh growing conditions present in urban areas. Improving tree establishment is thus important for securing the presence of trees in urban environments. Another important part is to understand how the process of establishment is expressed in trees, so that the needs of the trees can be met.

Tree nursery industry has recently developed production systems that aim to produce trees that are better prepared for transplanting. This study set out to investigate the effect nursery production systems might have on tree establishment success, and to examine different ways of assessing establishment, since the term is not consistently defined. Sweet cheery and red oak trees, cultivated as either bare-rooted (BR), balled & burlapped (B&B), root-pruned (RP), air-potted (AP) or fabric container (FC) grown were planted at one urban and one rural site in Southern Sweden. The trees were studied during the final nursery year and the four first post-transplant years. The production systems influenced total root length for both species, providing root systems with large differences in appearance. Shoot growth was restored to pre-transplant values for RP, FC and B&B sweet cherry trees at the rural site, three years after transplanting. Water status was significantly higher for AP trees than BR trees of both species, but only during the first year after transplanting, at the rural site. In general, effects of production system were more pronounced at the rural site with the higher water availability, indicating that none of the studied production systems was superior to use in urban plantings. Visual assessments of the establishment success of the trees were affected by leaf size, colour and shape. Leaf size was related to water status. Water status and shoot growth measurements were not correlated during the first years after transplanting. The term establishment can be used in different ways, and the differences might affect the outcome of an establishment assessment.

Keywords: Prunus avium, Quercus rubra, red oak, sweet cherry, transplant stress, tree cultivation, tree vitality, establishment evaluations

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Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Levinsson, A. (2013). Post-transplant shoot growth of trees from five different production methods is affected by site and species. *Arboriculture & Urban Forestry* 39(5), 201-210.

II Levinsson, A., Sæbø, A., and Fransson, AM. (2014). Influence of nursery production system on water status in transplanted trees. *Scientia Horticulturae* 178, 124-131.

III Levinsson, A., van den Bosch, C., Öxell, C., and Fransson, AM. (2015). Visual assessment of establishment success in urban *Prunus avium* (L) and *Quercus rubra* (L) in relation to water status and crown morphological characteristics. *Urban Forestry & Urban Greening*, *in press*.

IV Levinsson, A., Fransson, AM., and Emilsson, T. Measuring establishment and post-transplant performance of urban trees (manuscript).

Papers I-III are reproduced with the permission of the publishers.

The contribution of Anna Levinsson to the papers included in this thesis was as follows:

I Planned the study and collected the data. Did parts of the analyses and wrote the paper.

II Planned the study and collected the data. Analysed the data and wrote the paper, with feedback from the co-authors.

III Planned the study, collected and analysed the data together with the co-authors. Wrote the paper, with feedback from the co-authors.

IV Planned the study and collected the data. Did parts of the data analyses and wrote the paper, with feedback from the co-authors.

1 Introduction

Failed establishment and high young tree mortality is often reported in urban areas (Roman *et al*., 2014a; Roman *et al*., 2014b; Gilbertson & Bradshaw, 1990; Nowak *et al*., 1990). It is therefore essential to improve establishment success and provide a strong foundation for long-term survival and vitality, in order to increase the chances of trees reaching maturity and attaining a size at which they are most beneficial for the urban community. This is also important in justifying the financial investment in tree planting. Finding appropriate planting material is one component of improving establishment results, while another is to monitor the trees by assessing the duration of the establishment phase so that tree requirements can be met.

1.1 Urban forestry

1.1.1 Research context

This thesis has its academic roots within the multidisciplinary field of urban forestry. In the 1960s, the specific challenges of urban tree planting and management began to be recognised, and the concept of urban forestry started to spread, from Canada and the United States to the rest of the world (Konijnendijk *et al*., 2006). Today, urban forestry encompasses research concerning solitary street trees as well as tree communities in urban parks and peri-urban recreational areas. Urban forestry has been defined as:

> "The art, science, and technology of managing trees and forest resources in and around urban community ecosystems..." (Helms, 1998, p. 193).

A fundamental premise of urban forestry is that trees provide society with a range of aesthetic, physiological, environmental and economic benefits. Interconnected by these theories of benefits, researchers from various disciplines, working within the field of urban forestry are seeking to increase knowledge about the importance of trees for human and environmental well-being and about how to improve tree health so that the presence of trees in urban areas is secured. The present study focuses on the latter aspect. Furthermore, although urban forestry covers a broad spectrum and includes many types of trees and complex vegetation systems, the establishment of sparsely planted landscape-sized trees, with no vegetation or only grass as field layer has been the study's focus.

1.1.2 Current situation for newly planted urban trees

Urban areas are generally considered to be a harsh growing environment for trees, with a complex set of abiotic aboveground and belowground factors influencing tree vitality and growth. High surrounding buildings can prevent solar radiation from reaching the canopy, thereby reducing photosynthetic output. Moreover, heat and light reflected from surrounding hard surfaces in urban areas can be detrimental for trees by creating high temperatures at which the trees are no longer capable of keeping stomata open, even if water is available for the roots. Elevated night-time temperatures have been shown to increase night-time respiration, leading to decreased carbohydrate levels in the leaves, which might stimulate photosynthesis on the following day (Searle *et al*., 2012; Turnbull *et al*., 2002). However, for increased growth to occur, soil water contents has to be at sufficient levels to meet the demands of increased transpiration and photosynthesis.

The effect of a negative aboveground abiotic environment is exacerbated by suboptimal belowground conditions. In particular, plants in urban areas often have strictly limited or irregular soil water supply due to either improper growth substrates and/or insufficient available soil volumes (Grabosky & Bassuk, 1995). Belowground urban infrastructure leaves little space for tree roots and growth medium, and influences the water movements in the soil, preventing water flows or draining the soils. Soil compaction also limits root space and water flows, which may result in very dry or occasionally very wet anaerobic planting sites. Urban soils have higher amounts of heavy metals and have been shown to be more hydrophobic than surrounding rural soils, conditions that are negative for tree growth and vitality (Gregg *et al*., 2003; Pouyat *et al*., 1995). Although studies have shown that urban soils can have higher organic matter content than surrounding soils (Pouyat *et al*., 1995), at many sites the organic content may be restricted as fallen leaves are removed from the surface.

Planting of trees is associated with a subsequent period of reduced tree vitality. During this period, trees are typically less resistant to pathogens and temperatures outside the normal range, may experience reduced capacity for winter hardening and are sensitive to drought (Kozlowski & Pallardy, 2002; Rietveld, 1989). The phenomenon is often referred to as transplanting stress, transplant shock/check, or planting stress. Known origins of transplanting stress are the impaired function of the root system resulting from harvesting at the nursery and the transport to a new site, with different growing conditions (Koeser *et al*., 2009; Grossnickle, 2005; Buckstrup & Bassuk, 2000). Trees often experience transplanting stress as a consequence of reduced water uptake capacity. Reduced shoot growth, smaller leaves, reduced transpiration and a drought-stress appearance are often described symptoms of transplanting stress (e.g. Beeson & Gilman, 1992; Struve & Joly, 1992). If the transplanting stress is severe, the consequences can be desiccation or crown die-back, or even tree death. Restoring the water uptake capacity of the tree is thus crucial for a successful tree planting. Transplanting stress may be severe in the urban environment, due to low water availability, improper management after transplanting or insufficient plant quality.

1.1.3 The benefits of urban trees

Despite many examples of poor tree establishment in urban areas, new trees are continually being planted, not least because of the recognition that vegetation and green spaces are important for human health (Jackson *et al*., 2013; Rook, 2013; Ulrich, 1984). In dense urban areas, trees may be the dominant vegetation (Davies *et al*., 2011), and have been shown to improve the health of city dwellers by their presence (Donovan *et al*., 2011; Tyrväinen *et al*., 2007). Trees also provide aesthetic values in the urban landscape, as large canopies greatly influence the visual appearance of a site while providing shade at the same site (Summit & Sommer, 1999; Schroeder & Cannon, 1983).

Trees can also reduce the urban heat island effect, a mainly nocturnal phenomenon, in which the normal cooling at sunset is reduced due to heat-holding surfaces in buildings and ground materials (Oke, 1982). Negative effects of urban heat islands include increased energy consumption for cooling and compromised human health and comfort due to the high temperatures (Akbari, 2005). Transpiration from vegetation, together with shade from the tree canopies to cover heat energy-absorbing materials, may reduce night temperatures and thereby increase the health status of the urban inhabitants and reduce electricity costs.

Another environmental benefit attributed to urban trees is filtration of air pollutants such as particulate matter (PM) and ozone (Sæbø *et al*., 2012; Escobedo & Nowak, 2009; Beckett *et al*., 2000). It has been suggested that the ability of urban vegetation to remove air pollutants is insignificant in northern countries (Setala *et al*., 2013), a result that contradicts findings of other studies, which have demonstrated the positive impacts of urban trees on pollutant concentrations (Brack, 2002). Furthermore, trees sequester anthropogenic carbon dioxide potentially reducing the carbon footprint of the city (Searle *et al*., 2012; Davies *et al*., 2011; Nowak & Crane, 2002). Trees in urban areas may also improve biodiversity and provide habitats for many other organisms.

1.2 Background of this study

A continuous planting regime is essential in order to maintain the benefits provided by urban trees. Such planting is necessary because old urban trees decrease in vitality and are removed, new geographical areas are developed, or old urban areas redeveloped. Thus, we need to gain better knowledge of how to improve establishment success in different cities and under different conditions, in order to reduce the costs of failed plantings. As one response to failed plantings, the tree nursery industry has created different techniques and new systems designed to improve establishment results by stimulating fine-root growth and by ensuring that a greater proportion of the total root system is included during transplanting (Appleton, 1995). In Sweden, such systems for cultivating trees have been used in nursery production since 1992 (Johansson, personal communication, 2015 [1]), and are referred to as 'pre-establishing systems' by the tree nursery industry (LRF, 2012). However, the advantages of these systems have not been scientifically tested in comparative studies before in Sweden. Another aspect that might benefit establishment of trees is to gain a greater understanding of how transplanting stress is visually expressed in trees and thereby deduce how to assess their potential for long-term survival and vitality. Such knowledge could help secure a proper management regime for the trees during the establishment phase. Yet another aspect might be to discuss what we include in the term establishment, making contractors, assignors and researchers define the term as they use it.

1. Daniel Johansson, Tönnersjö Plantskola, e-mail 26/1 2015

2 Aims and research questions

The overall aim of this work was to explore the concept of tree establishment in urban areas, both as a biological process and as a practical term. There were two main sets of objectives. The first of these was to evaluate whether tree nursery production can influence post-transplant growth and vitality and whether some production systems are more suited than others to urban growing conditions (Papers I-II); to study the effect of production system on shoot growth after transplanting (Paper I); and on water status and stress symptoms (Paper II). I was also interested in studying the influence of root structure on nursery root growth and post-transplant shoot growth and water status and whether trees with different types of root systems benefit from different production systems and have a higher chance of a successful establishment (Paper I-II). Secondly, I wanted to evaluate and compare methods commonly used for measuring establishment (Papers III and IV) and to study what morphological and physiological features in the tree crown that have impact on visual evaluations of establishment success and which of these that are related to water status (Paper III). I also wanted to study the possibility of predicting post-transplant performance in the nursery (Paper IV). Establishment, vitality and responses to transplanting stress in plants are topics of particular interest to me, and the possibility to study and discuss them has been the focus throughout the work.

Based on these objectives, the following research questions were formulated:

i. How are nursery root growth and the following post-transplant shoot growth in trees with different root structures affected by different nursery production systems?
ii. Can nursery systems that stimulate fine-root development affect post-transplant water status, resulting in better water uptake

capacity, and what effect does site have on water status in red oak and sweet cherry trees produced in different nursery systems?

iii. Which morphological characteristics have the greatest influence on establishment assessments, and is it possible to determine tree water status visually during the establishment phase?

iv. Does the method used for determining establishment affect the results of an establishment study, and is it possible to predict post-transplant performance already in the nursery?

3 Research design & materials

This work is based on a designed field experiment. The main part of the work includes gathering and analysing quantitative data. However, Paper III also included a component of qualitative data collection and analysis.

3.1 Materials

3.1.1 Selection of trees

Throughout the study, the same trees were used to address the research questions. Red oak (*Quercus rubra* L.) and sweet cherry (*Prunus avium* L.) trees were selected at two Swedish nurseries in early spring 2007. The choice of species was based on a number of factors: 1) the two species had to be commonly used in urban plantings and well studied scientifically; 2) the two species had to be considered different in terms of transplantability and thus have different types of root structure; 3) since the aim was to investigate potential differences between species with different root structures, it was important to have planting material that was not propagated by inoculation. The trees of both species selected for this study were seed propagated, and the trees within each species were half-siblings. This meant that the risk of the results being affected by genetic variation could not be completely excluded, but the benefits of having trees on their own roots were considered more important. Partial control of genetic background for red oak by using half-siblings has been described by Struve *et al* (2000). With these preconditions, the selection of species was carried out in dialogue with City authorities of Malmö, who financed, planted and managed the trees in the city, and GRO (Swedish nursery association), to ensure that trees of appropriate size and quality were available, in suitable quantities.

The trees used in the study had a stem circumference of 14-17 cm at one meter above the root collar when the study started in spring 2007, and the trees were selected in the nurseries. In addition to stem size, tree selection was based on visual appearance of canopy, with the intention of selecting a group of trees that were as uniform as possible in terms of size and leaf density.

The trees were delivered for transplanting during 2008, when they were of the quality class 16-18, according to the Swedish system for quantifying size on delivery. They were studied at their growing site over the next four growing seasons (2008-2011).

3.1.2 Red oak

The genus *Quercus* belongs to the Fagus family. Oak trees are ring-porous, with a semi-determinate growth pattern, and may have several growth flushes during a growing season, if the conditions are favourable (Abrams, 1990; Hanson *et al*., 1986). Red oak has its natural habitat in North America, where the distribution extends from Nova Scotia to Georgia (Krüssmann, 1986). Most *Quercus* species are considered well adapted to dry growing conditions although red oak has been described as a species that is restricted to mesic sites in its natural environment (Abrams, 1990).

Red oak leaves are described as having a dark green surface and a pale underneath surface, are placed alternate, lobed with an oblong shape and have red to russet-red autumn colours (Dirr, 1983). Red oak has a wide-spreading crown and grows to around 20 meters in height.

Similarly to other oak species, red oak has deep penetrating roots with a clear tap root (Abrams, 1990). According to Struve (2009), red oak is a coarse-rooted species and relatively difficult to transplant, although it has been described as one of the more easily transplanted of the oak species (Dirr, 2004). According to Watson & Himelick (1997), *Quercus* species are best suited for spring transplanting.

3.1.3 Sweet cherry

Prunus is a genus within the Rosaceae family, consisting of about 430 species, and sweet cherry belongs to the subgenus *Cerasus* (Krüssmann, 1986). Sweet cherry is semi-ring-porous and can have a semi-determinate growth pattern, with more than one growth flush per season. However, under normal Swedish conditions it is determinate, with one flush per season. The root system is fibrous. Sweet cherry grows across Europe to Asia Minor, the Caucasus and western Siberia (Krüssmann, 1986).

Sweet cherry has a reddish brown bark. Its leaves are ovate-oblong shaped, bronze coloured in spring and turn dark green during the growing season. The autumn colours are yellow to red and bronzed (Dirr, 2004). The crown is wide-spreading and the trees can grow to approximately 15-20 meters in height.

Prunus has been described as best suited for spring planting (Watson & Himelick, 1997).

3.1.4 Nurseries and production systems

In Sweden, most trees are traditionally field grown. However, there are some more modern production systems that are defined as 'pre-establishing' by the nursery industry (GRO). The theory is that these systems produce a tree with a high amount of fine-roots and that this in turn is beneficial during transplanting and should facilitate establishment. Another theory is that transplanting stress could be partly handled in the nursery, under a more controlled environment, leaving the trees better prepared once they arrive at their final destination. Commonly, field-grown trees are installed in a pre-establishing system for one or two years prior to transplanting.

In this project, trees from five different production systems were included. The intention was to choose both traditional and more recently developed production systems, all of which are commonly used in current Swedish plantings. The trees' production systems were: bare-rooted (BR), balled & burlapped (B&B), root-pruned (RP), air-potted (AP), and fabric-container (FC) grown. Up to the start of the study in spring 2007, all trees had been treated similarly. They were field-grown, nine years old and had been replanted three times. The red oak trees were cultivated in a moderately organic loam and the sweet cherry trees in a moderately organic sandy loam. The trees were randomly divided into five different groups and treated according to standard practice for the selected production system during the final nursery growing season. The treatments were:

- BR and B&B trees were kept undisturbed in the field. At the final harvesting in spring 2008, both groups were excavated, and all the soil was shaken off from the root systems of the BR trees. The root balls (roots and soil) of the B&B trees were wrapped in degradable burlap with a surrounding wire.
- RP trees were subjected to root pruning in spring 2007 without being lifted from their growing location and were kept mixed with the BR and B&B trees throughout the season. At the final harvesting in 2008, they were treated as B&B trees.
- The AP trees were harvested in spring 2007, treated according to the B&B treatment and moved to an experienced air-potting nursery. The trees were placed above-ground on a polypropylene ground-cloth and the root ball of each was wrapped with perforated plastic, making a container (Fig. 1). A sand-peat mixture was used to fill the space between the root ball and the plastic. At the final harvesting, the plastic was removed and the trees were burlapped before transportation.

• The FC trees were also harvested in 2007 and delivered as BR trees to the nursery. The roots were pruned and the trees were planted in a sand-peat mixture in a fabric container. The fabric containers were then installed in-ground in the field (Fig. 2). At the final harvesting in spring 2008, the trees were lifted from the field and delivered with the fabric container around the root ball. The container was removed at transplanting.


Figure 1 and 2. Trees placed in air-pots, with the perforation of the plastic visible in the upper part of the pots and field-grown trees in the background (left), and a red oak tree placed in an in-ground fabric container (right).

3.1.5 Planting sites

After the final harvesting in the nurseries, the trees were delivered to the planting sites before bud burst in spring 2008. To study whether the post-transplant reactions to the production systems were site-specific, the trees were planted at two different sites, within the City of Malmö and in the experimental fields at the University of Agricultural Sciences in Alnarp.

In Malmö, the trees were planted along two streets in a high-rise residential area, with one street for each species. The trees were placed in blocks, with one tree from each production system in each block. The trees were planted in a three meter wide grass-strip alongside the street (Fig 3). There was some variation in the immediate surroundings of the grass-strip, which comprised houses, parking spaces or playgrounds. The soil had a silty loam texture and the experimental trees replaced old *Ulmus* trees, using the same planting positions. A circle one meter in diameter around the trees was kept grass-free by a layer of gravel. The trees were irrigated by the City of Malmö according to their tree establishment programme, resulting in the trees being irrigated approximately every two weeks during the growing seasons for two years. No irrigation was supplied during the following years.

Figure 3. The newly planted red oak trees in Malmö.

In the experimental fields in Alnarp, which lie on a sandy loam soil, the trees were planted 4.5 meters apart (Fig. 4). The trees were placed in rows consisting of five trees (one from each production system), in a randomised complete block design. A drip-irrigation system was installed and the trees were irrigated at night-time during the two first post-transplant years. The water flow was modified to meet the seasonal variation in order to ensure adequate water availability. The soil was covered by a single-layered polypropylene ground-cloth to prevent competition from weeds.

No formative pruning or fertilization was performed on any of the trees during the study period. One sweet cherry FC tree died in the nursery and was not replaced, and one BR red oak tree died in Malmö during the first winter after transplanting and was replaced by the city. The new tree was not included in the experiment.

Figure 4. The trees planted in the experimental fields at Alnarp, with sweet cherry in the upper part of the field, and red oak in the lower.

4 Measurements and results

4.1 Impact of nursery production system on root and shoot growth of trees with different root structure (Paper I)

Determinations of total fine-root length of the trees from the different production systems showed that the two species seemed to react to the fine-root-stimulating measures in the nursery, except for root pruning of red oak. Air-potting stimulated fine-root growth for both species, resulting in root systems showing several-fold greater total length of small-diameter roots than the undisturbed field-grown trees. Fabric container cultivation also had a positive impact on fine-root length for both species. However, root pruning appeared to have no positive effect on new root formation in red oak, and fine-root length in RP red oak trees did not differ from that in B&B trees. The RP sweet cherry trees had the highest fine-root length of the five production systems studied.

Shoot growth was determined during the last nursery year and in the four first years after transplanting. All trees of both species exhibited significantly reduced shoot growth during the two first years after transplanting at both planting sites, compared with the shoot growth in the nursery ($p<0.001$, both sites and species). This reduction persisted throughout the study for the red oak trees, which still had very limited shoot growth four years after transplanting at both sites. However, all sweet cherry trees showed a significant increase in shoot growth during the third growing season at Alnarp and B&B, FC and RP trees regained their pre-transplant shoot growth values during that season. The shoot growth was less than the growth in the nursery year for all production systems again in the following year (2011), but still clearly higher than in the two first post-transplant years. During this year, there were no differences between the production systems. There was an increase in shoot growth for sweet cherry during the two last years of the study in Malmö, but shoot growth was still significantly lower than the pre-transplant values.

4.2 Impact of production system and site on post-transplant water status (Paper II)

Shoot water potential (Ψ) was measured midday (Ψ_M) and the following pre-dawn (Ψ_{PD}) during the three first years after transplanting, in order to study tree water status. Leaf stomatal conductance and soil moisture content were determined at the time of the midday water potential measurements. Leaf surface area was also determined, since water stress reduces leaf area, and transplanting stress has been shown to affect leaf size, but not number of leaves (Struve & Joly, 1992).

There were significant differences in Ψ_M for both species between the production systems on the midday measuring occasions in Alnarp during the first year after transplanting. AP trees had significantly higher Ψ_M values than BR trees. For red oak, FC and RP trees were also statistically separated from BR trees. These differences persisted at the pre-dawn measurements for red oak. However, for sweet cherry there were no differences in Ψ_{PD} between the production systems. There were no differences between the production systems at Alnarp for either of the species during the following years.

Occasional differences between the production systems were identified for red oak in Malmö during the years of the study. AP and RP trees had higher Ψ_M than BR and B&B trees ($p=0.001$) at the first measurement occasion during the first year. FC red oak trees had higher values than RP trees on a minority of measuring occasions during the second year. No differences were found during the third season for red oak. For sweet cherry, no differences were found in Malmö on any measuring occasion over the years.

During the first year after transplanting, leaf surface area was strongly reduced compared with that of the trees in the nursery year at both sites for both species, except for AP red oak at Alnarp, which had a leaf area comparable to the nursery values. Also in Malmö, AP red oak had significantly larger leaves than the other trees, although not comparable to leaf surface area in the nursery year. This difference did not persist during the second year, when trees in all the other production systems exhibited a small increase in leaf surface area, while AP red oak had a decreased leaf surface area compared with the previous year. In general, the trees had the smallest leaf surface area during the first post-transplant year, and the leaf surface area increased in every year throughout the study. For the trees at Alnarp, this increase led to regained pre-transplant leaf surface area three years after planting. There were no differences between production systems after the first post-transplant year.

4.3 Impact of morphological characteristics on establishment assessments and their relationship to water status (Paper III)

Establishment success was assessed on all trees by seven professional establishment evaluators during the third season after transplanting. The visual assessments were comparable to the commonly performed establishment evaluations that are carried out on street trees as common practice after transplanting. The objective of the study was to compare the assessments with morphological characteristics of the leaves and crown, and with water status, with the aim to find leaf morphological links between water status and visual establishment assessments. The evaluators performed their assessments on two partly cloudy days, followed their own protocols for evaluations and had no time limitations for the assessment. The assessments were accompanied by a short survey with both closed and open-ended questions, in which the evaluators graded the importance of different characteristics in their assessments and described how secure they felt in their assessments.

A number of leaf morphological characteristics were determined on the trees, including: leaf colour, leaf area and leaf length and, for red oak, leaf shape and number of lobes. Moreover, crown density, crown shape and die-back were estimated and shoot growth was measured.

The relationships between the visual establishment assessments and the results from determination of morphological characteristics were studied, as were the relationships between seasonal mean pre-dawn shoot water potential (Ψ_{PD}) and visual establishment assessment and crown characteristics.

Multiple regressions showed that the visual establishment assessments were strongly related to leaf shape and leaf colour for red oak and to leaf area for sweet cherry. Leaf area was the parameter most strongly related to water status for both species. However, we found no obvious relationship between the water status and visual establishment assessments for either of the species.

4.4 Impact of measuring method in determining tree establishment, and the possibility to predict field performance (Paper IV)

Midday and pre-dawn shoot water potential (Ψ_M and Ψ_{PD}), leaf stomatal conductance (g_s), terminal and lateral shoot elongation and leaf area measurements were included in species-specific principal component analysis (PCA), including both the urban and the field sites. The objective of the analyses was to study whether and how the different techniques for determining establishment were related to each other. Linear regression analyses were performed to study the relationship between Ψ_M and Ψ_{PD}, and a nightly recovery index (NR) was developed as an indicator of the capability of the individual tree to nightly recovery from midday water status. The index also permitted inclusion of both midday and pre-dawn measurements in the same value.

Photosynthetic capacity was monitored by determination of chlorophyll fluorescence measured as Fv/Fm, during the nursery year. The Fv/Fm measurements, as well as shoot growth measurements and determinations of stem circumference in the nursery, were used in linear regression analyses and tested against post-transplant shoot growth (both terminal and lateral), stem circumference increment during the first post-transplant year, annual mean NR, and crown die-back, to test if post-transplant performance could be predicted in the nursery. Crown die-back values were determined as the weight of all dead parts in the canopy after the first post-transplant winter. The objective of this part of the study was to study whether post-transplant performance could be predicted on an individual level in the nursery.

The PCA showed that Ψ_M and Ψ_{PD} values were strongly correlated, and both were also correlated to conductance. The R^2 values of the linear regressions showed that Ψ_M could be explained better by Ψ_{PD} values in each year. This tendency was clear for both species, potentially indicating that the relationship between the two measurements strengthens with establishment. The R^2 values were 0.93 and 0.83 for red oak and sweet cherry, respectively, during the third year after transplanting.

The PCA also showed that terminal and lateral shoot growth were strongly correlated but not connected to the water-related measurements, during all years. However, the annual multiple regressions with NR as response showed that there was a relationship between NR and shoot growth during the third year of the study.

Post-transplant performance could not be predicted by either nursery chlorophyll fluorescence values or nursery shoot growth measurements in this study. Separating the trees into production system-specific groups did not change these results.

5 Discussion

There are many factors influencing the outcome of tree transplanting. Selection of species, tree size, time of year, nursery production system, site conditions and post-transplant management are all examples of factors often discussed as having great impact on tree establishment success. Hirons and Percival (2012) listed four groups of key factors involved in successful tree establishment: plant quality, planting and post-planting, rooting environment, and tree ecophysiology. Skill in combining all relevant factors determines the outcome of the planting. Nonetheless, transplanting causes symptoms of stress. Transplanting stress is inevitable and some degree of stress is to be expected even under very good conditions (Rietveld, 1989). However, if the stress becomes too severe the trees may not survive the transplanting. The development of new nursery production systems aims at improving plant quality in order to increase survival and post-transplant vitality for landscape-sized trees. Another aim is to grow trees that are suitable for urban conditions, and that have an extended planting period (Ferrini & Nicese, 2006; Ferrini *et al*., 2000).

5.1 Production of trees for urban landscapes

Post-transplant behaviour, with typically reduced growth rates, reduced crown density and low vitality, is a well-known phenomenon that has been attributed to reduced water uptake capacity. The loss of roots at harvesting and/or the loss of contact between roots and soil have significant impact on post-transplant water uptake (Burdett, 1990). In traditional field-growing production systems, trees inevitably lose a great proportion of their root system at harvesting. Field-grown trees have been shown to lose 32% of their dry root weight at harvest or 88% of their fine-root system measured as total fine-root length (Gilman & Beeson, 1996a). In attempts to improve post-transplant growth and vitality, various modifications of nursery treatments have been conducted (Aghai *et al.*, 2014; Harris *et al.*, 1998; Struve *et al.*, 1989). Widening the root-balls had a positive effect on leaf size and shoot elongation, compared with trees produced with industry standard root balls (Struve *et al.*, 1989). Solfjeld and Hansen (2004) concluded that a large root ball is more beneficial than a small root ball but Harris *et al.* (1998) found that differences in root ball size did not affect post-transplant trunk and height growth.

Several studies have confirmed that nursery production systems, such as different container types, significantly alter the plant root systems (Paper I, Amoroso *et al.*, 2010; Gilman *et al.*, 2010a; Campbell *et al.*, 2006). However, there is little consistency among studies in how these differences affect post-transplant performance or whether they even have any effect on post-transplant performance (Gilman *et al.*, 2010b; Buckstrup & Bassuk, 2000; Ferrini *et al.*, 2000; Harris & Gilman, 1993). The reasons mentioned for the inconsistency between studies are differences in protocols, post-transplant management and site conditions (Ferrini *et al.*, 2000). One conclusion might be that production systems do not have a fundamental or superior effect on post-transplant performance, but that in order for a production system to be beneficial for trees, certain conditions are needed. The results in this project did not indicate that any of the five production systems studied was more beneficial for the dryer, urban growing site in Malmö. The results also indicated that post-transplant survival and vitality was possible for trees from all the studied production systems (Papers I and II).

The management of the trees in the nursery has also been discussed as a factor of importance for tree establishment. Burdett (1990) suggested that planting material can be prepared in the nursery for dry planting sites by acclimatising the plants to restricted water availability. In a study on deficit irrigation, drought-tolerant species were concluded to improve their post-transplant performance when irrigation was withheld in the nursery (Ferrini, personal communication[2]). However, such treatment was not recommended for drought-avoiding species. Lloyd *et al.* (2006) showed that nutrient loading in the nursery could have a positive effect on post-transplant growth, during the first year after transplanting. However, the trees with a higher post-transplant growth rate also experienced higher photosynthetic reduction during drought. Another study showed that fertilisation of red oak seedlings in the nursery had a negative impact on post-transplant survival and growth, an effect attributed to a high shoot:root ratio (Bumgarner *et al.*, 2008). It has also been argued that the large biological investment in creating a high number of fine-roots in the

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nursery might deplete the tree's carbohydrate reserves, forcing it to focus on assimilating carbon before it can grow new tissues (Campbell *et al*., 2006). Jones *et al*. (2002) argued that the response of seedlings to the production system used in the nursery does not predict post-transplant performance.

Comparing BR and B&B trees, Buckstrup and Bassuk (2000) found that there were differences in growth between trees from these two production systems during the first post-transplant year, and that the differences depended on both species and time of planting. The differences did not persist during the second year. However, in this project differences in shoot growth between the different production systems were detectable for both species during the three first post-transplant years, and also during the fourth post-transplant year for sweet cherry (Paper I). Gilman and co-workers found in several experiments comparing different production systems that there were no differences between the various production systems after one year when irrigation was sufficient (Gilman, 2001; Gilman & Beeson, 1996b). However, container-grown trees died faster and to a greater extent than field-grown, root-pruned, B&B trees under limited water supply (Gilman, 2001). In this project, the effects of the production systems increased when water availability was higher (Papers I and II). There is reported to be a risk of very dry soil in the rooting environment around container-grown trees because container substrates often have high air-filled porosity, which is favourable during production, but after transplanting, water can be pulled out from the container soil as this does not have an as good water holding capacity as the surrounding soil matrix (Harris, 2007). The trees from AP and FC in this project were cultivated in a peat-sand mixture, a very different texture from the soils at the transplanting sites. This could have influenced the outcome.

5.1.1 Species and tree size effects

The choice of species may have an effect on the response of tree or seedling to a certain nursery system (Anella *et al*., 2008; Ferrini & Nicese, 2006; Struve, 1993). It has been argued that species with fibrous root systems are more easily acclimatised to various container types than coarse-rooted species (Schuch *et al*., 2000). In the present study, the two species responded to the different fine-root stimulating nursery treatments, except for RP red oak, which did not react positively to the root treatment, whereas sweet cherry RP trees had a high fine-root amount (Paper I). The two species also showed similar post-transplant shoot water potential reactions to the production systems, but showed differences in shoot growth and leaf surface area (Papers I and II). Other factors that might influence a species response to nursery production systems might be whether the species is described as shallow-rooted, or whether it stores carbohydrates in the finer or in the coarser parts of the root system (Ferrini & Nicese, 2006; vanHees, 1997).

Moreover, species are often described in terms of how easily they are transplanted, and some species or genera are considered difficult to transplant. Struve (2009) argued that species with fibrous root systems are more easily transplanted because they have a higher root regeneration potential than coarse-rooted species. It is also argued that ring-porous species are more sensitive to “rough handling” than defuse-porous species, due to the risk of xylem dysfunction (Struve, 2009). Sweet cherry is generally considered to be easier to transplant than red oak. However, Suokup *et al*. (2004) pointed out that there is a clear difference in susceptibility to environmental differences between species, and that due to better formation of secondary protective tissue in roots of oak than of cherry, oak seedlings have higher endurance during acclimation. In this project, the fibrous-rooted sweet cherry had regained pre-transplant shoot growth three seasons after planting at Alnarp, whereas the coarse-rooted red oak trees still had significantly lower shoot growth even four years after transplanting (Paper I). There was also a smaller variation in visual appearance between the sweet cherry trees in the third season after transplanting than between the red oak trees (Paper III). These results are in line with the claims by Struve (2009) regarding root structure and transplantability. The results reported by Soukup *et al*. (2004) were not confirmed in this project, since the red oak trees at the dry site in Malmö did not show better results than the sweet cherry trees at the same site.

There have been discussions on whether a small or a large tree is more easily established. The size parameter was kept constant in this study. Still, Struve *et al*. (2000) mention that the common perception of better performance of smaller trees could be due to transplanted small trees being individuals that have grown faster than their surrounding trees in the nursery and are ready to be harvested sooner. Thus, good results are not because of the smaller size of the tree, but because of the tree’s high vitality and growth capacity (Struve *et al*., 2000). Those authors also note that the larger trees may have been exposed to potentially harmful treatments if kept in the nursery for a longer time, such as compaction of the soil when harvesting other trees, and refer to a study by Neal and Whitlow (1997) that found that growth rates had declined for large trees before transplanting. Based on trunk calliper and height growth, Struve *et al* (2000) concluded that smaller trees had a higher survival rate, but that larger trees instead had a faster establishment. These results contradict the model by Watson (1985), showing that the expected time for a large tree to regain roots lost at harvesting and start to put on growth is so long that a small tree will outgrow it in a few years after transplanting. In a study by Gilman *et al*.

(1998), small-sized trees increased their trunk diameter and tree height faster during the first 27 months after transplanting than the larger trees. Similar results have been reported in a size-comparison study by Lauderdale *et al*. (1995). It has also been argued that smaller trees have higher plasticity to acclimatise to the new growing site. On the other hand, larger trees have potentially stored reserves to a greater extent than smaller trees. Today, increasingly large trees are being planted in urban settings. The desire for fast aesthetic improvements and immediate effects of planting are likely to be the driving force behind the trend, but a reduced risk of vandalism might also contribute. This development trend places high demands on the nursery industry to produce trees that are possible to transplant in large sizes.

5.2 Urban tree planting and management

5.2.1 Site

The particular challenge of urban tree establishment is often connected with the harsh conditions at the growing site and great efforts have been made to find on-site technical solutions to improve establishment and vitality results. First introduced in 1995, load-bearing structural soils of various types have become often occurring elements when constructing new growing sites (Grabosky & Bassuk, 1995), permitting roots to explore spaces otherwise filled with compacted soil. In Copenhagen, so-called super-planting pits have been introduced in an attempt to increase the amount of root-available soil for street trees and thus increase urban tree vitality (Buhler *et al*., 2007). Attempts have also been made to construct root paths that permit roots to reach other root-friendly areas for example on the other side of a pavement, by providing root tunnels from the growing site. However, these root paths have not yet been evaluated in scientific studies (Watson & Himelick, 2013).

Tests have also been made on constructing sites where stormwater is lead to root available reservoirs, instead of straight to the storm water pipes (Bartens *et al*., 2009). Such systems could improve both urban tree water status and stormwater management.

5.2.2 Transplanting and management

Transplanting exposes trees to a great number of stress factors, starting with harvesting in the nursery and proceeding until full establishment has been reached at the new growing site (Koeser *et al*., 2009). Trees risk having their trunk or root systems clamped during transportation, and vibrations from vehicles may further disrupt the root systems and cause damage to crowns and trunks. Moreover, the risk of dehydration of the root systems is great during transport, particularly for bare-rooted trees. However, dehydration may also occur in trees that are delivered with their growth medium still surrounding the root ball, since harvesting and transportation may affect the contact between root and soil, and it is in this contact that most water uptake by the roots occur. Long transport distances or strong exposure to sun at the planting site before transplanting can also dry out the root ball.

Time of year may also affect the outcome of the planting. In a study of root and shoot periodicity in the Northern hemisphere, only planting in July seemed to negatively affect post-transplant growth of trees compared with planting in November, December, March and April (Richardson-Calfee *et al.*, 2007). Several studies have shown that the optimal planting time is species-dependent (Yin *et al.*, 2014; Solfjeld & Hansen, 2004), or that time of planting may have little effect on establishment for some species (Solfjeld & Pedersen, 2006).

In many cases, trees are planted at sites with sun exposure that differs from the exposure in the nursery, in different hardiness zones and/or at sites with different humidity levels (Watson & Himelick, 1997). In an acclimatisation study, trees that had been grown under partly shady conditions displayed a lower capacity to preserve water balance under drought stress than trees grown in full sunlight, indicating that the nursery conditions may influence acclimatisation after transplanting of leaved trees (Fini *et al.*, 2014).

Furthermore, poor establishment management affects post-transplant survival and vitality. Studies by Gilman and co-workers have shown that frequency of irrigation can have a greater influence on post-transplant performance than production system, and that regular irrigation gave better results than irregular (Gilman, 2001; Gilman *et al.*, 1998). In this project, adequate irrigation during the two first post-transplant years had a positive effect on post-transplant performance (Papers I and II).

5.2.3 What is more important: a vital tree or good planting and establishment management?

A reoccurring issue within studies of establishment is whether good plant material or good establishment management is more important for successful tree establishment. It has been stated several times by Gilman and co-workers that regular irrigation has the highest impact on post-transplant growth (Gilman, 2001; Gilman *et al.*, 1998). In a comparative study, Koeser *et al.* (2009) found that rough handling and transport of the trees had a greater impact on post-transplant growth and survival than the unavoidable root loss at harvesting. Struve (2009) suggest that handling during production, shipping and transplanting, together with poor site qualities, have greater effects on transplant shock than biological limitations of the trees. Lindqvist (2000) on the other hand, argues that bad plant quality cannot be compensated for by intensive establishment management, while Pinto *et al*. (2011) reason that the outcome of a silvicultural planting often relies on pre-planting decisions.

In this study, nursery measurements indicated that all trees had an acceptable vitality at transplanting (Paper IV). The Fv/Fm values ranged from 0.77 to 0.85 and shoot water measurements indicated that water availability and water uptake capacity were normal, and that the trees were no more than mildly stressed at any measuring occasion in the last nursery year (data not published). Site conditions seemed to have at least as great an influence on post-transplant results as production system (Papers I and II) indicating that a drier planting site could not be compensated for with pre-establishing measures in the nursery. Provided that all trees are of acceptable quality at harvesting, post-harvest measures might be more important for transplantability than the nursery production systems compared in this project.

5.3 Urban tree establishment

5.3.1 Establishment

Burdett (1990) distinguish the tree establishment phase as a period when tree performance is not only dependent on genetic factors, plant interactions and site, but also its environmental history, such as nursery management and conditions. Establishment, establishment success, early establishment, establishment phase, established and fully established are words often used in tree studies concerning the cultivation, transplanting and post-transplant behaviour of trees and seedlings (e.g. Aghai *et al*., 2014; Pinto *et al*., 2011b). Although frequently used, the term establishment lacks a workable definition (Struve, 1990). Establishment success is often used synonymously with survival (Pinto *et al*., 2011b; Löf *et al*., 2004) growth (Solfjeld & Hansen, 2004; Gilman *et al*., 1998) or water status (Scheiber *et al.,* 2007; Beeson, 1994). The term establishment can also be used technically, describing the planting occasion or installation of trees (Roman *et al*., 2014b; Buhler *et al*., 2007; Jacobs *et al*., 2005).

In this project, the morphological and physiological responses to transplanting were studied, as well as pre-transplant factors that could have an effect on these processes. The term establishment therefore included post-transplant processes beyond transplant survival, and the establishment phases and the meaning of full establishment in focus.

Balance of root and shoot

The assumption that a tree can be considered established once it has restored its root-shoot balance is generally used in establishment studies (e.g. Harris *et al*., 1998; Beeson & Gilman, 1992; Watson, 1985), although measured in several different ways. Rietveld (1989) argued that rapid growth signals establishment success, and Day and Harris (2007) mentioned that trees need to put on significant growth to be established and that when the establishment phase is over, the trees reach a more environmentally productive phase. They also suggested that an established tree may no longer need irrigation. Scheiber *et al.,* (2007) focused on water uptake during the establishment phase, hypothesizing that the establishment phase is over when water potential values are similar to values of surrounding trees that have not been transplanted. This implies that the root system is capable of meeting the water demand of the tree and that a balance is restored. Struve *et al*. (2000) considered trees to be established when they did not show signs of water stress after a period of mild drought.

There is still not a full understanding of how captured resources are distributed and of the mechanisms that govern partitioning (Marschner *et al*., 1996). Hypotheses describing the distribution of captured resources between roots and shoots have been formulated. The most common hypothesis assumes a balanced growth, meaning that the partitioning of resources is allocated so that the tissue providing the most limiting resource is favoured (Shipley & Meziane, 2002).

The functional equilibrium described by Brouwer (1983) explains the continuous modification of tree roots and shoots to obtain a ratio that is functional under the conditions present. It has been shown that as a response to changes in their environment, trees may modify their shoot:root ratio (Hermans *et al*., 2006; Mcartney & Ferree, 1999). It has also been shown that the responses to different types of environmental changes or stresses, vary with the type of stress imposed (Wang *et al*., 2012), time of the imposed stress (Mcmillin & Wagner, 1995) and species (vanHees, 1997), and that shoot:root ratio differs between species even in similar conditions (Gilman & Beeson, 1996a). In a study of responses in pedunculate oak (*Quercus robur*) and beech (*Fagus sylvatica*) to drought and shade, vanHees (1997) showed that both species responded to shade with reduced shoot growth, increased partitioning to stem and roots and increased leaf area, but that when drought stressed, beech increased the partitioning to fine roots and oak increased the partitioning to the coarse roots.

The hypothesis of functional equilibrium implies that trees produced in systems where they do not lose an extensive amount of roots before transplanting may still be affected by the transplanting since they need to modify their growth to meet the new growing conditions. For a landscape-sized tree, this restoration of balance might take several years (Watson, 1985).

Harris (2007) argues that the better results from B&B trees compared with container grown trees, reported in some studies might be due to the B&B trees root tips being disturbed, which could stimulate root growth, hastening the restoration of the shoot:root balance. However, disturbance of the root tips may also affect the production of hormones that are important for bud break and shoot elongation, which are often produced in roots and transported to the shoots via the vascular system (Gregory, 2006; Taiz & Zeiger, 1998; Lavender *et al*., 1973). The complex systems and interactions of hormones are not handled or discussed in this study.

Establishment process and phases

Described as a process by Rietveld (1989), the establishment can be separated into different phases. The first phase starts at transplanting, after which trees experience various degrees of stress. This occurs since trees need to rely on the existing roots and stored carbohydrates for water uptake and root regeneration (Grossnickle, 2005). If the tree survives the initial planting stress it enters the next phases, in which it restores the root-shoot balance by adjusting to the new growing environment (Grossnickle, 2005; Rietveld, 1989).

Although establishment is a commonly used term within studies of transplanting, it is not clear when a tree is fully established. Rapid growth is the signal that the seedling is established, according to Rietveld (1989). Grossnickle (2005) states that a seedling is established when it is coupled to the hydrological cycle of the site. This refers to water being absorbed by plant roots and transpired from stomata or being directly evaporated from the soil to the atmosphere from which it eventually falls as rain (Raven *et al*., 1999). Some of the sweet cherry trees in this project had regained pre-transplant shoot growth after three growing seasons at Alnarp (Paper I), and might be considered established at that point, using the suggestion by Day and Harris (2007) and Rietveld (1989). During that year, both species regained leaf surface area at Alnarp comparable to the pre-transplant values (Paper II). However, on visual examination, most trees of both species and from both sites were assessed as established (Paper III). There were no control trees included in this project, so the comparison suggested by Scheiber *et al*. (2007) could not be performed for the trees. It was found that during the third year there was a relationship between shoot growth and water status (Paper IV), whereas, during the preceding years, water status and shoot growth were not related. These results indicate that on a shorter time scale, the choice of measuring method affects the assessment whether trees can be considered established. The differences in the results between the production systems in Paper I and II also indicate this. If only growth measurements had been included in the project, the conclusion would have been that the differences between the production systems persisted throughout the study and that the effect of production systems was larger on RP, FC and B&B sweet cherry trees. However, had the project relied on measurements of Ψ, red oak would have been considered most affected by the various treatments in the nursery, and AP would have appeared preferable for good post-transplant performance. And the differences between production systems would only have lasted during the first year after transplant.

5.3.2 Tree vitality and establishment

Vitality is a theoretical concept (Dobbertin, 2005), described as a tree's capability to grow under the prevailing conditions, or ability to handle stress. Vitality and establishment are two closely related concepts, since success of establishment is dependent on the tree's vitality. However, there are differences between the concepts, since an established tree might experience reduced vitality. Vitality is often determined on a whole-plant level, regarding canopy shape and density, colour, growth and occurrence of pathogens (Johnstone *et al*., 2013). A study within this project indicated that leaf colour was important in visual determinations of establishment, but not strongly related to the water status of the trees (Paper III). Since it is connected to nutrient uptake and supply, the leaf colour could be an important factor in vitality assessment (Martinez-Trinidad *et al*., 2010), but it may say little of the tree's connection to the hydrological cycle at the new site, if that is used as definition of establishment success.

5.4 Reflections on experimental set-up, materials and methods

5.4.1 The trees and the nursery production systems

As part of this project, potential differences in post-transplant behaviour between trees produced in five existing nursery systems in Sweden were examined. The main aim of these production systems is to modify the root system so that the trees have a greater amount of roots at transplanting and thereby better resources for water uptake, since water has been stated to be the crucial factor for establishment success. This conclusion was not questioned, and its relevance was not tested. The trees were subjected to the treatments according to industry standards (LRF, 2012) and subjected to common practices in the existing nurseries. This involved moving some trees to new nurseries, where they were installed in new growth medium and given different amounts of fertilisers. As a consequence, the amounts of accessible nutrients for the trees during the first year of the study differed between the production systems. It has been shown that the nursery growth substrate can have a post-transplant effect on plant material (Pacifici *et al*., 2013), and the benefits and disadvantages of applying large amounts of fertiliser in the nursery before transplanting have been discussed (Bumgarner *et al*., 2008; Lloyd *et al*., 2006). Thus, there were potential differences in nutrient amounts within the trees at transplanting, which might have affected the outcomes. It is impossible to say whether the results obtained would have been the same had the fertilization regimes been different. However, since one essential part of the pre-establishing systems include installing the trees in containers with fine-root stimulating substrates of their own mixture, the inequality of nutrients could not have been avoided, and equality had also not been relevant, since that would have provided a non-existing nursery production system. It has been argued that providing different amounts of irrigation and fertilisation to different nursery regimes create confounding effects in trials and should be avoided (Pinto *et al*., 2011a). However, providing the same amounts in this project would have been confounding, since the prerequisites during the last nursery year differed between production systems, resulting in different demands depending on system. Standardised management would not have reflected existing nursery systems. However, including determinations of the nutrient status of the trees throughout the work would have provided a better understanding of the potential impact of these differences on post-transplant performance. It could also have potentially shed light on the differences in leaf colour, observed in Paper III. Leaf nutrient status was determined at the end of the growing season in 2009, two seasons after transplanting, for all trees. Although there were differences in nutrient status between the red oak trees, these differences were not related to any of the other measurements performed during that season. It was also inevitable that trees were delivered with root balls of different sizes. However, root ball size was not essential for total fine-root length (Paper I).

It has been suggested that different production systems provide trees of different root quality (Wilson *et al*., 2007). The quality of the root systems was not investigated in this study. In addition, it was not possible to study the effects on long-term vitality and survival during the limited amount of time available.

All the trees were planted in early spring. One argument for container growing of trees is that it provides trees that are transplantable at any time of year, including in the growing season, whereas it is normally considered only suitable to plant bare-rooted and balled & burlapped trees outside the growing season. Thus, this potential advantage of the pre-establishing systems was not exploited in this project. The aim with the experimental set-up was to avoid any time of year considered unfavourable for any of the production systems.

5.4.2 The measuring methods

Water status and chlorophyll fluorescence

For determinations of water status, shoot water potential was measured midday and pre-dawn, combined with determinations of leaf stomatal conductance. Water potential measurement is a well-known method, developed by Scholander and co-workers (Scholander *et al*., 1965) and is frequently used in determinations of water status in trees (Rahman *et al*., 2014; Resco *et al*., 2008). It is recognised for its ease of use, particularly in field (Turner, 1988). By installing a cut-off shoot tip in a pressure chamber and increasing the pressure within the chamber by letting in nitrogen, the water that was withdrawn from the cut surface when the water column was broken returns to the cut surface. The amount of pressure needed to regain that water to the surface is an estimate of the water potential in the shoot, and thus an indication of the amount of water in the shoot. Water potential measurements are recognised as a valid method in determinations of water status during establishment (Scheiber *et al*., 2007; Beeson, 1994). Williams and Arajou (2002) has shown in a study on grape vine a strong relationship between midday and pre-dawn water potential measurements and stem water potential. Similar results were found in the present project on comparing midday- and pre-dawn shoot water potential and stomatal conductance values (Paper IV). Measuring midday water potential in a pressure bomb has also been recognized as a tool for determining water status in *Prunus* (Abdelfatah *et al*., 2013). Although water potential measurements are common and often used, including other determinations of water status and physiological response to transplanting would have provided a fuller picture of the differences between measuring methods, described in Paper IV. Possible complementary methods could include determination of water use efficiency by determination of photosynthetic rate/transpiration (Pacifici *et al*., 2013) or determination of the concentration of the carbon-isotope 13C (δ 13C) in leaves. First shown by Farquhar and Richards (1984), δ 13C analyses can be used to determine water-use efficiency based on the principle that plants discriminate against 13C during CO2 assimilation and the relative amount is increased as stomatal closure is more frequent during periods of photosynthesis. Such determinations could have provided a seasonal value, instead of values from discrete events in time.

In this project, an index for calculation of nightly recovery (NR) was suggested. It allowed values from the two shoot water potential measuring occasions to be combined into one value. However, the full relevance of the NR index needs to be further investigated.

Soil water content was monitored with a HH2 moisture meter, which was used to determine volumetric soil moisture at four different depths: 10, 20, 30 and 40 cm below the soil surface. Tubes were installed at the planting sites to obtain a mean/representative value of water availability on the shoot water potential measurement occasions. At Alnarp, the tubes were also used to check water levels, so that irrigation was regularly modified to adequate levels. In Malmö the tubes were installed in different blocks, to check that water levels did not differ between the trees within the planting site. However, another way of monitoring soil water could have been to continuously log soil water content, for a fuller picture, particularly in Malmö, where the trees did not have as regular a water supply as at Alnarp. This would have made the differences between the sites more visible for the whole growing season.

The use of Fv/Fm as a method for determining tree vitality is wide spread (Rahman *et al*., 2014) and it has also been shown to be a predictor of field capacity for landscape nursery trees (Percival, 2004). However, it has been argued that its sensitivity to detect reduced vitality is restricted to plants that have experienced drought during an extensive period (Resco *et al*., 2008) which might explain the lack of relationship between Fv/Fm and post-transplant performance in paper IV.

All measuring techniques used in this study are relative and therefore useful in comparative studies where different treatments are being compared. However, since water status is dependent not only on water uptake capacity, but also on water supply and vapour pressure deficit, and since normal shoot growth and leaf area are related to several factors such as species, ontogeny and site, there is no absolute value for any of these determinations that can confirm successful establishment on an individual level. Pre-transplant shoot growth might never be expected on sites with significantly poorer conditions than those in the nursery, potentially making such determinations hard to interpret in an urban context. Having a reliable method for determining establishment success would increase the comprehensiveness both in studies of establishment and in practice, e.g. in contracts between contractors and assignors, specifying that trees will be established after a certain time, which are potential sources of conflicts. Using the suggested recovery index (Paper IV) might be one such method, but its relevance has to be further investigated.

6 Conclusions

This study aimed at improving our understanding of urban tree establishment by examining four research questions. The main findings of the work are summarised below, in relation to the respective research question.

i. How are nursery root growth and the following post-transplant shoot growth in trees with different root structures affected by different nursery production systems?

The pre-establishing nursery systems – air-potting and fabric container cultivation – had a positive effect on fine-root growth of both red oak and sweet cherry. The two species reacted differently to root pruning, which only had a positive effect on root-growth of the fibrous-rooted sweet cherry. Regardless of production system, shoot growth was strictly limited after transplanting in both species. Shoot growth values were regained in sweet cherry trees from the fabric container, root pruning and balled & burlapped systems three years after transplanting at the site with adequate water availability (Alnarp). There was no absolute similarity between root length at transplanting and post-transplant shoot growth, showing that fine-root stimulation in the nursery does not ensure vivid post-transplant growth. The coarse-rooted red oak trees took a longer time to regain pre-transplant shoot growth than the fibrous-rooted sweet cherry, regardless of the production system used. The results showed that even under good growing conditions, it can take several years for shoot growth to be regained, even for easily transplanted species with fibrous root systems.

ii. Can nursery systems that stimulate fine-root development affect post-transplant water status, resulting in better water uptake capacity, and what effect does site have on water status in red oak and sweet cherry trees produced in different nursery systems?

Air-potted trees of both species showed significantly higher midday shoot water potential values than bare-rooted trees on every measuring occasion during the first year after transplanting at the site with adequate water availability. The fabric-container grown and the root-pruned red oak trees also had significantly higher values than bare-rooted red oak trees. The differences persisted at the pre-dawn measurements during the first post-transplant season for red oak. There were few occasions with differences between production systems for red oak trees at the urban site (Malmö) during the years of the study and no consistency in the results. The results indicate that for the fine-root stimulating measures to be beneficial for water uptake, there has to be adequate water availability at the planting site, indicating that increased amounts of fine-roots cannot compensate for the conditions at dry, urban sites. The results also indicate that for initial acclimatisation to the site conditions, the air-potting system was advantageous, but that the advantages only persisted during the early post-transplant period.

iii. Which morphological characteristics have the greatest influence on establishment assessments, and is it possible to determine tree water status visually during the establishment phase?

The most influential morphological characteristics for visual establishment assessments were leaf colour and leaf shape for red oak and leaf size for sweet cherry. For both species, the characteristic most related to water status was leaf size. No relationship was noticed between visual assessments and water status for either species. Study results suggest that leaf area is a good indicator of progress for the establishment process, but that leaf colour was less important when establishment was defined as the tree’s water status, although considered important by tree establishment evaluators. The leaf shape of red oak trees seemed to influence the appearance of the trees to a larger extent than is recognized by evaluators.

iv. Does the method used for determining establishment affect the results of an establishment study, and is it possible to predict post-transplant performance already in the nursery?

Comparisons of some commonly used methods for determination of establishment showed that pre-dawn and midday shoot water potential and stomatal conductance were strongly correlated. Terminal and lateral shoot growths were correlated with each other, but the two groups were uncorrelated, when using measurements from the first three post-transplant years for red oak and sweet cherry. The study also indicated that the results from the different measuring methods converged over time. The results from the study indicate that the chosen measuring method influence how establishment is perceived, and that the time scale matters for the results. If establishment is assumed to be restoration of the water balance in the tree, measured as the capability for adequate water uptake, then measuring growth during the first post-transplant period might not reveal the tree's condition. However, if establishment success is assumed to be growth, initial shoot water potential measurements might not show the tree's future capacity for vivid growth. Thus defining what we want to capture when studying tree establishment is relevant for better understanding, within different research studies, and between practitioners. Currently, there is no absolute determination for establishment success, since every measure is dependent on the surrounding circumstances. Moreover, normality is relative, making determinations of e.g. growth difficult to interpret. A calculation of nightly recovery is suggested in this project as one way of including both midday- and pre-dawn shoot water potential measurements. The relevance of the NR index needs to be further investigated.

Post-transplant performance on individual tree level could not be predicted by determination of chlorophyll fluorescence, shoot growth or stem circumference in the nursery. Possible explanations for the lack of relation between pre- and post-transplant performance of the landscape-sized trees included in the study are that the complexity of the tree history increases with tree size and/or that other factors, such as transport from the nursery to the transplant site, have a larger influence over post-transplant vitality than nursery vitality.

7 Future studies

This project focused on the first part of the post-transplant life of trees in urban areas. The potential influence of different production systems on long-term survival and prosperity has been little investigated and should be of interest in future studies. Moreover, the long-term effects of production system on root systems would be interesting to follow. In studies of root-shoot balance there are discussions on the functionality of the root systems. Further studies are needed to determine whether the different nursery production systems included in the study provide roots of different quality or functionality. The way in which the term establishment is used and how that affects the assessment of trees after transplanting also needs clarification.

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