A Comparison of Sinker Root Development in Urban and Forest Trees

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Studies of urban tree root systems often reveal a complete lack of vertical sinker and tap roots in the central structural root system. However, forest trees do have such sinker roots. This paper discusses possible reasons for the "disappearance" of central sinker roots in urban trees. First, tap and sinker root ontogenesis is discussed. Second, the functions of sinker roots with respect to anchorage, stem shape, hydrology, tree longevity and soil improvement are presented. Sinker root ontogenesis is then discussed in the framework of forest and urban tree life cycles. Finally, a number of hypotheses are formulated with regard to why urban trees are commonly lacking sinker roots.

Rationale

The difference between arborists and foresters in acknowledgment of deep structural tree roots is striking. Whereas forestry literature is filled with documentation, photos, and drawings showing rich development of tap and sinker roots (Figure 1), European arborists generally agree that urban trees do not have strong central vertical roots (Figure 2a). A study of root system drawings in U.S. literature indicates a similar understanding (Neely and Watson 1998;

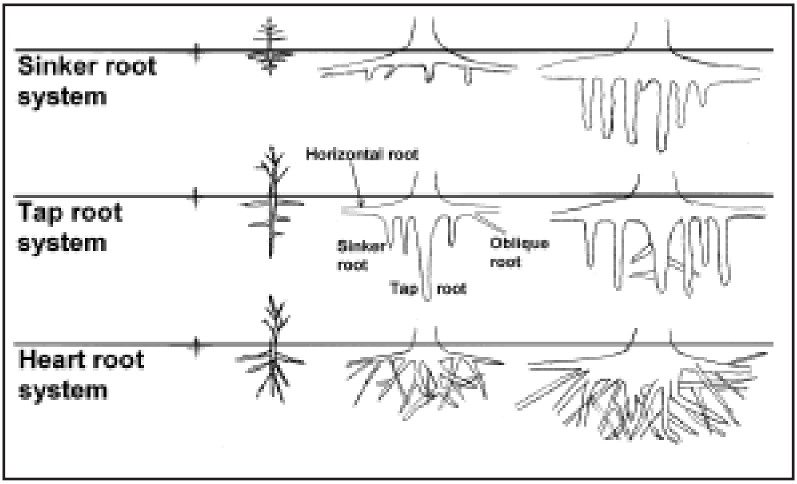

Figure 1. Typology of single roots according to position (see the root system in the center) and of root systems. *Picea abies* has a classical sinker root system. *Pinus sylvestris* and *Quercus robur* have typical tap root systems, but with varying dominance of tap roots. *Fagus sylvatica* has a classical heart root system, but soil conditions strongly modify the architecture of oblique and vertical roots (see site differences in Figure 4). Many other species have characters from more than one of the classes. [Drawing from Nielsen (2005). Further information to the classification by Köstler et al. 1968.]

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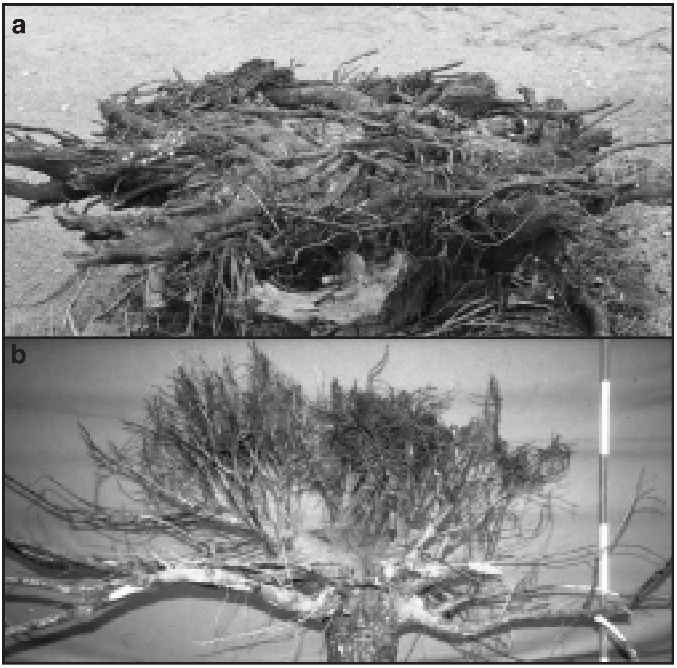

Figure 2. (a) Root flare of a healthy *Tilia platiphyllos* tree (upside down). Notice the lack of vertical sinker roots. (b) Forest-grown Sitka spruce root system (upside down) showing the common spatial arrangement of sinker roots and horizontal roots in forest trees.

Harris et al. 2004; Trowbridge and Bassuk 2004; Urban 2008). This paper reviews and discusses the development and function of sinker roots based on literature reviews, and a few novel targeted analyses based on data from a large tree architectural database developed and coordinated by Nielsen and Hansen (2000). Instead of clear conclusions, the paper sets up a number of hypotheses, which hopefully put increased focus on tree functionality in future nursery and arboricultural practice.

Terminology, Ontogenesis, and Function of Vertical Roots

The following description is based on long-lived, woody roots of forest-grown trees without root deformations. The *horizontal roots* in an undisturbed root system spread radially out from the stump like the spokes of a wheel. They usually grow in the upper 20 to 30 cm (8 to 12 in) of the soil, with a growth angle to horizontal between 0 and 30 degrees. The first horizontal roots are lateral branches on the primary tap root, but later horizontal roots are either adventitious or second- or higher-order branches. In older forest trees, the horizontal roots commonly make up 80% to 98% of the root biomass (Nielsen and Hansen 2000). Modern urban tree nursery practice has focused on pruning horizontal roots for high regeneration capacity.

A *tap root* is a dominating, usually straight, root with very strong positive geotropism. Basically, it develops from the primary root after germination, but in practice the tap root is often reiterated after death of the apical root tip (Coutts 1989). Nevertheless, elder tap roots often appear very straight, are "carrot-like," and are located directly below the center of the stem. Although all tree species germinate with a primary vertical radicle, the long-term dominance of tap roots varies among genera. Oak (*Quercus*), pine (*Pinus*), and larch (*Larix*) have strong tap roots, whereas other root types quickly take over dominance in beech (*Fagus*) and spruce (*Picea*) (Köstler et al. 1968). Furthermore, the tap root(s) sometimes lose dominance, and sinker roots take over when trees grow older. In harsh soil conditions. the tap root often divides into several tap roots, which decreases the penetrative capacity of the tap root (Colin and Collet 2000; Collet et al. 2006).

The tap root is commonly undercut during nursery production. As a result, the tap root often ceases to exist. However, tree species with strong tap roots tend to regenerate the tap root after transplanting to the field. In four younger pedunculate oak stands, all planted with 2- to 3-year-old bare-rooted stock, tap root regeneration varied from almost nothing up to a dominance comparable to those of seeded stands (Nielsen and Hansen 2000). Stock quality, planting methods, and many other factors influence tap root regeneration. Regeneration of tap roots after field planting of small, bare-rooted trees is common (Köstler et al. 1968; Nielsen and Hansen 2000), but tap root regeneration in larger landscape trees after a number of nursery transplantations is less likely.

Sinker roots originate from structural horizontal roots, and grow more or less vertically into the soil, as they develop various degrees of positive geotropism (Figures 1; Figure 2b). The strength of geotropism is often lower with sinker roots than with tap roots. Coutts (1989) is the only author who seriously discusses ontogeny of sinker roots. He finds that new, nonadventitious roots emerge adjacent to vascular strands in the mother root (Figure 3). Because horizontal laterals—at least in conifers—generally are diarch (having two xylem strands), new second-order roots can develop only in the xylem line direction (Figure 3).

Close to the tap root, the xylem line tends to be vertical, which predisposes the development of sinker roots. With increasing distance from the stem axis, the xylem line is reported to twist around the root axis, enabling root branches in other directions (also horizontal root branches—see Figure 3, second-order horizontal root). Coutts (1989) believes that second-order roots with a vertical direction develop a positive geotropism gradually by habituation. Later in the developmental stage, roots are also created as adventitious roots, which emerge from wound callus, cambial tissue, or phloem–parenchymateous tissue, out of the normal order, and often due to stress events (Puhe 2003).

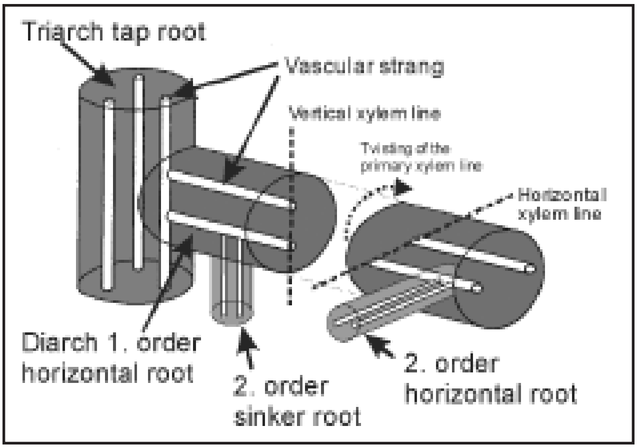

Figure 3. Direction of ordinary root branches is controlled by the internal order of vascular strands. Thus, sinker roots develop when the primary xylem line is more or less vertical, and sinker roots develop geotropism in the course of their function. [Modified from Coutts (1989).]

Sinker roots are adaptive to environmental influences and may later develop in directions other than straight vertical. A generally oblique direction away from the stem center is often found (Figure 2b) and is considered by the author to be caused by wind-induced, vertical movement of the horizontal mother roots. In forest terminology, sinker roots are restricted to a 2 to 4 m (7 to 12 ft) radius around the central root system (Figure 2b), and new forest data show a strong decline of sinker root intensity along a 2 m (7 ft) radius around the tree in six tree species (Figure 4). However, vertical root branches from long, superficial horizontal roots may also be designated as sinker roots because they penetrate the soil deeper than horizontal root branches—but not as deeply as sinker roots below the central root system (Figure 5). The literature is not conclusive as to *when* sinker roots are initiated. Excavations of young trees often reveal only horizontal roots or a dimorphic system with horizontal roots and a tap root. Thus, Melzer (1962) and Schmidt-Vogt (1977) believe sinker roots develop several years after establishment in the field.

At a first glance, this assumption is confirmed by the late development of vertical root mass (Nielsen and Hansen 2000). But this conclusion is rejected by Puhe (2003) and does not comply with the theory of Coutts (1989) about the way sinker roots emerge (Figure 3). It seems likely that thin vertical roots develop early during the genesis of the root system, but that these vertical roots remain thin [<2 mm (0.08 in) diameter] and with low physiological activity. A stronger longitudinal expansion and secondary thickening does not set in until the tree develops a "need" for deep roots (i.e., when "sinker" root meristems experience a competitive advantage compared to horizontal root tips). Such a change in growth allocation might set in when horizontal roots experience increasing competition with grass or other trees or experience problems with drought, for example. This complies with Coutts's (1989) understanding of sinker roots developing by "habituation" (i.e., a development driven by acquisition of water in deeper soil layers). Nevertheless, the timing of sinker root initiation remains an issue not well understood, which alone impedes any firm conclusions being made in this paper.

Oblique roots have horizontal angles at between 30 and 60 degrees and are very

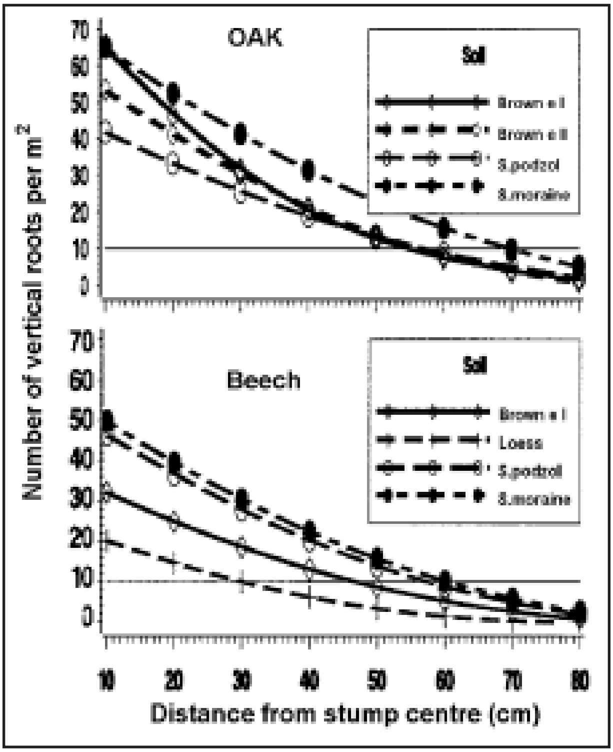

Figure 4. The gradient of sinker root intensity with increasing distance from stump center. The figure is based on number of roots per m^2 (per 10.8 ft^2) soil surface. [From Nielsen and Hansen (2000).]

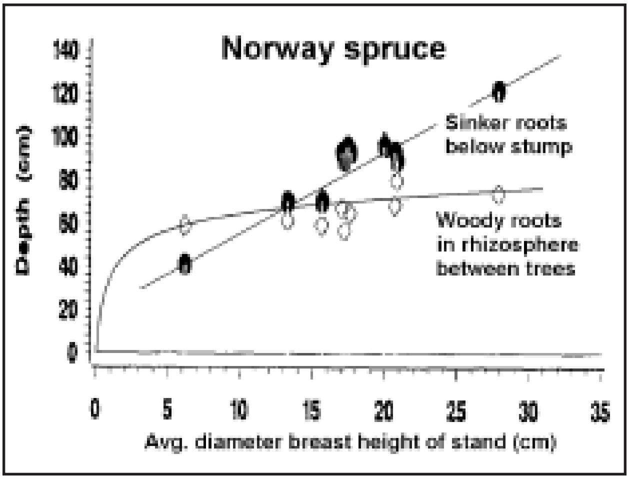

Figure 5. Chronosequence of maximum rooting depth (y axis) in roots between trees and below trees. Each point represents a Norway spruce (*Picea abies*) forest stand (Nielsen and Hansen 2000), showing the average of either 10 to 15 tree root systems or 10 to 12 between-tree soil cores [each 0.16 m^2 (1.2 ft^2)]. The stand average values are based on the deepest woody sinker root within each root system or on the deepest root occurrence detectable in each soil core. Maximum depth within soil cores was often caused by one single root with sinker tendency. [From Nielsen and Hansen (2000).]

common in some species [e.g., *Fagus sylvatica* (European beech)]. Basically, oblique roots originate in the same way as sinker roots, but lack of positive geotropism lets them take a varied growth direction. The differentiation between sinker and oblique roots can be questioned (see next section regarding function).

Functions of Sinker Roots in Mature Trees

Vertical roots contribute to various functions:

Anchorage of trees. Four components of anchorage should be considered: (1) root ball (or root plate = root + soil), (2) supporting or bending function of roots, (3) tension function of roots, and (4) homogeneity of stress distribution within the root system (Nielsen 2005). Experimental tree-pulling investigations with various root manipulations in forest trees have shown that the root ball component constitutes 60% to 70% of total moment of anchorage (Coutts 1986; Nielsen 1990; Nielsen 1995; Crook and Ennos 1996; Nielsen 2005). Because the intensity and depth of sinker roots determine the amount of soil attached to the root system, anchorage of forest trees strongly depends on sinker root development. Similar experiments were conducted more recently on solitary trees, but without root manipulations. But we know that the biomechanical adaptation of roots is much stronger in solitary compared to forest trees. Thus, root plate size should not be attributed the same importance in urban trees. Nevertheless, lack of a deep root plate should not be ignored and is probably commonly co-responsible for tilting of trees in tree lines, etc.

Water balance. Investigations of root distribution are commonly carried out between trees or radially around trees, and rarely in the rhizosphere just below the central root system. Thus, our understanding of the rhizosphere and the active root space is often biased. In park environments with unlimited horizontal root spread, the vertical gradient of fine and thin woody roots [0 to 2 mm (0 to 0.08 in) diameter] in the space between generally reflects an exponentially decreasing root intensity with increasing depth (Nielsen and Hansen 2000; Göransson et al. 2006). Thus, when the plant-available water in the upper 50 cm (20 in) of the soil is depleted, older trees without deep sinker roots often become seriously water stressed (Nielsen and Hansen 2000; Nielsen and Knudsen 2004). In dry situations like that, deep woody sinker roots collect water from deeper soil layers (Dawson and Pate 1996; Moreira et al. 2003; Nielsen and Knudsen 2004). Nielsen and Hansen (2000) show how the woody sinker roots of mature, forest-grown spruce (*Picea*), oak (*Quercus*), beech (*Fagus*), and pine (*Pinus*) trees in Denmark generally develop to a soil depth twice that of roots in the "between-tree domain"—even across different soil types (Figure 5). This differentiation between horizontal and vertical roots in occupation of the soil may, however, have minor relevance for urban trees planted in small-volume planting pits.

Tree health. Root breakage due to poor anchorage and harmful droughts are among the most important degeneration mechanisms in trees in Europe. These two mechanisms even interact and reinforce each other. Thus, droughts occurring shortly after a severe storm have excessive negative impact (Nielsen and Knudsen 2004). Sufficient and deep vertical rooting reduces both stress factors.

Stem shape. Except in windy climates, poor stem form is often connected to insufficient anchorage. Instability may be due to poor radial symmetry of horizontal roots, as is often found with root deformations, or due to disturbances of vertical roots. The stem form was found to be determined by tap root development in Scots pine (*Pinus sylvestris*) by Bibelriether (1964), and the frequent basal sweep in the stems of pine (*Pinus*), larch (*Larix*), and Douglas-fir (*Pseudotsuga menziesii*) was attributed to poor root development after transplanting and to fast height growth. Lack of deep sinker roots reduces the depth and weight of the root ball, which predisposes older trees to tilting (often seen in *Pinus*). Sometimes the upper part of the tree adapts with negative geotrophic growth to grow vertically again (often seen in *Picea* and *Fagus*).

Soil improvement. The vertical penetration of central sinker roots often reaches a maximum in late youth (age 30 to 60 years)—in the phase of high vigor. Dieback of vertical roots is frequently observed in older trees (Köstler et al. 1968; Nielsen and Knudsen 2004). Decayed roots form "root channels" in deep soil layers, which improve aeration and drainage, and form pathways for new roots to penetrate deep layers (Köstler et al. 1968; Schmidt-Vogt 1977). This benefit from the tree's biological activity is lost, of course, if soil engineering takes place.

The relevance of these functions varies with site, tree species, and tree age. Nevertheless, vertical roots are important for tree functionality in many situations and seem to be an issue worth considering.

Life Cycle Analysis of Vertical Roots in Forest and Urban Trees

In forestry, root systems of 1- to 4-year-old seedlings often become deformed during production or planting, but the majority of trees tend to outgrow these deformations after 5 to 25 years. Root deformations are commonly related to either container types (Nielsen 1998; Rune 2003) or to the planting process (Nielsen 2005) (Figure 6). However, due to the small plant size, relative increment is high (often above 100%), and regenerative capacity is considerable. Many new adventitious roots are formed after planting, which provides a more "undisturbed" and well-adapted root system. Species with poor development of stemborne adventitious roots have slower and poorer regenerative capacity (e.g., *Pinus* and *Abies*). Asymmetric distribution of roots is compensated through biomechanically adaptive growth in supporting roots having some distance from neighboring roots (Nielsen 1990; Coutts et al. 1999). Data from more than 700 trees in 60 stands (Nielsen and Hansen 2000) show that only a minority of older forest trees continue to have deformations (Figure 7). We know that adaptive improvement of root system architecture takes place (Coutts et al. 1999), but it is not clear to what extent the apparent symmetry improvement shown in Figure 7 is due to adaptive development or to thinning selection in the stands. Nevertheless, Figure 7 shows that root-deformed trees remain common in many older, planted forest stands. Except from a strongly varying tap root performance (due to being undercut in the nursery), most forest trees arising from 1- to 4-year-old seedlings develop comparable natural horizontal roots from which sinker roots (or oblique roots) evolve.

Why do many urban landscape trees have no ordinary sinker roots in the central part of the root system? Or in light of the life cycle analysis, at which life stage do urban trees lose their dominant sinker roots?

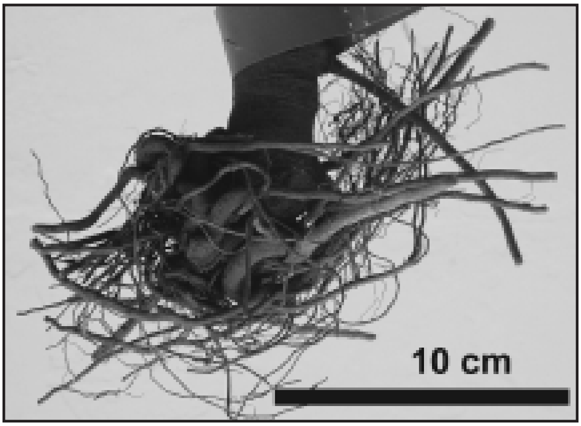

Figure 6. Root system of *Abies procera* spade-planted as 3-year-old bare-rooted plant and dug up after three growing seasons in the field. Adventitious roots develop very slowly in the *Abies* genus. Thus, the deformation of nursery roots during the planting process is still clearly visible.

Internal Competition for Carbohydrates Within the Root System

We know quite well how some roots become dominant and other cease growth (Coutts et al. 1999). There is strong competition for carbohydrates (sugar, starch, etc.) among meristematic cells (tips and cambiums of roots) within the tree. Water and nutrient uptake and biomechanical stress also play a role in determining which roots become dominant. Small, vertical roots gradually develop into sinker roots because the sink strength of horizontal roots declines in relation to more deeply developed roots. This is a useful explanation for forest trees. Could it be different for trees in the urban landscape?

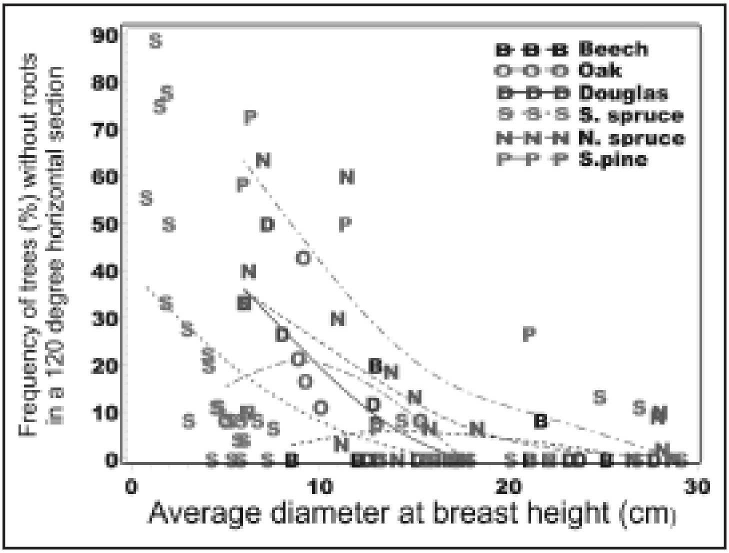

Figure 7. Frequency of trees within stands with no horizontal roots in a 120-degree radial section. Every point in the figure represents the average of a stand, each with 10 to 25 trees. Novel analysis based on data from Nielsen and Hansen (2000).

The intense pruning of horizontal roots in landscape tree stock may increase the number of vigorous horizontal root tips at the time when sinker roots are forming, and the tips of vertical roots may not be able to win the internal battle for carbohydrates. Root pruning may also remove the portion of the horizontal roots on which young and thin vertical roots develop. During transport between nursery and field site, sinker roots can be broken, bent, desiccated, or harmed by direct sunlight, and compacted subsoil may obstruct the development of vertical sinker roots.

Forest tree sinker roots may grow "dominant" due to increased horizontal root competition in forest stands. However, this hypothesis is given minor credibility with regard to urban trees in narrow planting pits, where vertical roots should constitute an environmental advantage.

Root movement during wind load may also cause root losses (Hintikka 1972). Newly planted trees are staked to prevent root movement and snapping the new fine roots. However, vertical movement of the root plate many years after establishment will cause eventual sinker roots to move up and down. This harms the fine roots on the woody vertical roots. Loss of absorbing roots will reduce the carbohydrate sink strength to almost zero, and the sinker roots will fade away. Such root plate movements were found to kill old sinker roots after sudden increase of wind exposure in released forest trees (Nielsen and Knudsen 2004). This mechanism may also harm street trees with spatially limited root plates.

Is the problem related to size of the planted tree? Figure 8 shows that a 2- to 4-year-old forest plant takes up much less "space" within the final older tree than does urban tree stock. Thus, a

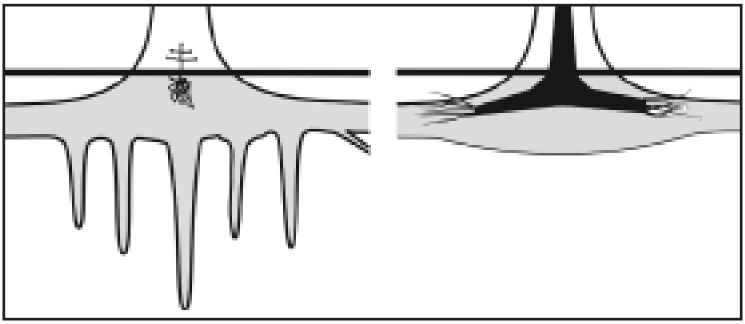

Figure 8. Is there more "space/time/juvenile tissue" for reiteration and architectural repair in a tree arising from a deformed forest plant compared with a tree arising from urban tree stock?

larger part of the central forest root system develops undisturbed, whereas large parts of the urban tree root system are repeatedly disturbed. Furthermore, because the capacity to adjust tree architecture to field environment depends on the relative growth rate, adaptability declines exponentially with planting stock size.

Discussion

The purpose of this paper was primarily to acknowledge the difference between forest and urban tree root architecture and to analyze why urban trees may become "crippled" and hindered from natural development in ways not well understood.

The introductory analysis of sinker root genesis reveals a lack of precise and operational knowledge. Literature indicates that vertical woody structures are initiated early but remain small and thin until given a competitive advantage over the superficial horizontal roots. Thus, in forest trees, sinker roots tend to expand during and after the thicket stage. In street planting pits, sinker roots most likely have accelerated growth when horizontal roots "exploit" the surface root space—if such space is available. Tap roots are generally removed by undercutting in bare-root nurseries, but species with strong tap root tendencies may regenerate tap roots after transplanting to the field.

Sinker roots tend to become increasingly important for tree function as trees become mature. Anchorage is reinforced as deep roots develop a heavy root plate. The improved anchorage prevents tilting and leaning stems, and the excessive rooting depth of sinker roots enhances water balance, wound encapsulation, resistance against pests, and tree longevity. Thus, whenever the soil environment allows deep roots to develop, focus on sinker and tap roots is promising.

However, it seems that "ordinary" sinker roots are often missing in the central root system of urban trees. The analysis reveals many different mechanisms and reasons for absence of sinker roots. Some mechanisms are related to the nursery process, other mechanisms are related to the planting process, and others to the field environment. To grow urban trees with ordinary sinker roots, it is necessary to eliminate restrictions on sinker root development through all three phases in the process, which is a fairly ambitious project that requires new guidelines and coordination across business sectors. Nevertheless, the reader might want some operational messages. In the following suggestions, deductions from the theoretical analysis may provide some operational aid. However, these conclusions should not be considered absolute scientific guidance; rather, they should be seen as inspiration for further studies and development of new products.

Avoid transplantation in landscape nurseries. There are good reasons for transplantations in landscape tree nurseries: Root pruning, optimal utilization of space, rational crown pruning, rational irrigation, logistics, etc. However, roots are deformed with every transplanting process, and sinker root initials will almost certainly be bent into a horizontal position during the planting process. The increasing need for crown space with increasing tree size could be met by thinning. Thus, sell some and transplant some, but leave as many trees as possible undisturbed. Larger trees may develop thick sinker roots that are sustained after movement to the field site. If root pruning is eventually needed, it could be performed with a soil-going chain saw.

Use drought cycles or horizontal root disturbances in nurseries. Drought cycles are used in container plant production to enhance drought resistance. Frequent tilling and pruning of horizontal roots is used by Greek olive farmers to stimulate the development of deep roots. Similar treatments may stimulate sinker root development in landscape tree nurseries.

Perform less pruning of horizontal roots. The ability of a tree to re-establish after transplanting is improved by the pruning of horizontal roots. But do we also remove the sinker root initials? And do we reduce the sink strength (carbohydrate competition) of sinker root initials by increasing the number horizontal root tips?

Conserve sinker roots by balled-and-burlapped transplanting. If any of the previous techniques succeed in developing sinker roots in the nursery, those roots are most likely to be maintained through transplanting to the field as B&B trees.

Use air-pruning container systems. Forest plant container systems with air-pruning systems have been shown to preserve the tap root and enable normal tap root development after planting in the field (Nielsen 2005). Perhaps new container-production systems with air pruning could be developed for urban trees.

Prune loose and hanging vertical roots. Because replacing loose vertical roots in their correct vertical position in a new planting hole is normally impossible (see the next suggestion, however), such roots should be pruned. Tap or sinker roots might regenerate from the cut.

Remove spiraling roots. Beside the negative effects on architecture and establishment, spiraling roots also have a reduced ability to branch. Thus, at all phases of handling, spiraling roots must be removed by root pruning.

Use a new bare-root planting method to improve sinker roots. The planter may introduce existing or new sinker roots by placing them in a vertical position. Placing the root system on two wooden boards across an open planting hole enables the planter to let some roots hang down before filling in around these new "sinker root initials." Whether such roots develop into functional sinker roots will depend on how beneficial the subsoil is and how much the horizontal roots are supported by irrigation and other post-transplant care.

Provide adequate rooting depth in planting pits. The first prerequisite for development of sinker roots is root-friendly conditions in deep soil layers below the root flare. The risk of the root flare sinking into loose soil can be overcome by using structural soil, wooden boards below the planted root ball, or other support methods. Drainage and aeration of the deeper soil layers should also be enhanced.

Prevent root plate loosening and loss of deep roots. A stable and physiologically healthy tree is facilitated by symmetrical development of supporting roots in all directions (avoid using a narrow planting pit) and by a deep root ball.

Use small trees with high regenerative capacity whenever possible. The smaller the tree, the larger the relative growth rate and the regenerating capacity of root system architecture.

These suggestions should be tested. Tests should reveal where, why, and when sinker roots disappear. We need to improve our knowledge about sinker root ontogenesis. In forestry, we find significant site differences in sinker root intensity; the cause, however, is unknown (Nielsen and Hansen 2000).

We also lack literature on dieback of deep sinker roots as trees get older. Some research of the mechanisms is available (Köstler et al. 1968; Nielsen and Knudsen 2004). However, until we grow vertical roots in the first place, longevity of such roots may be a secondary question.

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