Efficacy and Effect of Tree Stabilization Systems On Landscape Tree Growth and Establishment

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ABSTRACT

Various forms of staking, guying, and root ball anchoring are used to prevent post-transplant tree destabilization in the landscape, but little scientific evidence exists to support this practice. This experiment tested the efficacy of three generic tree stabilization systems (TSS) and their effect on tree growth and establishment.

In spring 2006, 48 balled and burlapped, 6.4 cm (2.5 inch) diameter, white ash (*Fraxinus americana* L. 'Autumn Purple') were transplanted to a field site in Blacksburg, VA. At planting, one of four TSS treatments (staking, guying, root ball anchoring, or non-stabilized) was installed on each tree. After five weeks, tree pulling tests were conducted on 24 trees to simulate a strong wind load using a cable winch mounted to a skid-steer loader. After one growing season, change in tree height, trunk diameter, and trunk taper were compared among the 24 remaining trees. Soil cores were taken and the length, diameter, and dry weight of roots within the cores were analyzed. TSS were then removed and tree pulling tests were conducted using the same method.

The five week tests showed that destabilization was significantly greater for non-stabilized trees (mean of 16^{o} from vertical) than for trees with TSS (all means less than 3^{o} from vertical). Yet after one growing season, there were no significant differences among any treatments in tree stability. We conclude that in locations with high wind speeds, TSS may be necessary for trees similar to those in our study, but only for a very short period of time.

Results also indicated that staking, guying, and root ball anchoring were equally effective, very robust, very durable, caused no tree injuries, and did not impact tree growth or establishment after one growing season. Practical considerations may therefore play a more important role when choosing which TSS to use. Although the time required for TSS installation was similar for each system, staking was more than twice as expensive as guying or root ball anchoring.

To all those who were taken from us
while pursuing their academic dreams.

April 16, 2007

May we never forget.

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Chapter 1 – INTRODUCTION

Various configurations of staking, guying, and anchoring materials are routinely installed on landscape trees at the time of transplanting. These materials are collectively referred to as tree stabilization systems (TSS). The predominant application of TSS is to stabilize a newly-transplanted tree until root development adequately anchors it in the soil. Excessive tree movement or repeated wind throw after transplanting are believed to interfere with proper root development (Appleton et al. 2007). According to Gilman (1997), slight movements of the root ball may potentially break new roots that have extended into the backfill soil and dramatically slow establishment. Both field- and container-grown trees are susceptible to destabilization by strong winds or similar mechanical disturbance during the period immediately following transplant because they lack a spreading or extensive root system. TSS are also installed to support trees with weak trunks or to protect trees from physical injury caused by machinery, animals, or people.

Tree stabilization is a common requirement of landscape tree planting specifications (Appleton et al. 2007). However, few specific recommendations exist for TSS use. Unlike for other tree care operations in the United States, standardized practices for the installation, maintenance, and removal of TSS have not been codified by the American National Standards Institute. It is unclear why TSS standards have not been developed. Their absence may be attributable to the lack of scientific studies on TSS or to the inherent difficulty of writing a standard that adequately addresses the numerous factors that impact TSS use.

The current lack of standards for TSS may be contributing to their overuse and unsuccessful use in the landscape. In a street tree inventory of three city sections in Boston, Massachusetts, Foster and Blaine (1978) found that staking caused more damage to trees than automobiles or vandalism. In a survey of over three hundred practitioners who use TSS, such as landscape contractors and arborists, Appleton et al. (2007) found that over 70% had observed tree damage as a result of TSS being installed for too long.

Compared to an unstabilized tree, a staked or guyed tree is more prone to trunk girdling and abrasion and trunk breakage (Leiser and Kemper 1968; Harris and Hamilton 1969; Leiser and Kemper 1973; Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004a; Appleton 2004b; Harris et al. 2004; Whitcomb 2006). Even when TSS are used properly, tree development can be negatively impacted. By reducing a tree's ability to sway in the wind, TSS can inhibit the necessary morphological changes that enable a tree to withstand high winds and support its own weight. A stabilized tree will be more likely to develop poor taper, a larger height to diameter ratio, a less structurally sound root system, and less reaction wood (Jacobs 1954; Larson 1965; Neel 1967; Harris and Hamilton 1969; Leiser et al. 1971; Neel and Harris 1971; Burton and Smith 1972; Fayle 1976; Wrigley and Smith 1978; Holbrook and Putz 1989; Mayhead and Jenkins 1992; Nicoll and Ray 1996; Mickovski and Ennos 2003; Mitchell 2003; Tamasi et al. 2005). These effects make a tree less able to stand without support and if supported, more subject to injury (Harris et al. 2004).

There are also practical limitations to the use of TSS in the field. Cost of materials at transplant, time required for transplant, and follow-up maintenance costs all increase when TSS are utilized. Above-ground systems can present a tripping hazard and can detract from the visual appeal of a tree. Root ball anchoring systems cannot be used with bare-root trees, those with broken or poor quality root balls, or those grown in soil-less container substrates (Appleton 2004b). Metal components of root ball anchoring systems left buried in the ground can be a safety risk to stump grinder operators.

A number of empirical studies have attempted to determine which staking or guying systems have the least impact on tree health and development. Studies have shown that systems that allow for the greatest trunk movement have the least detrimental effect on tree development (Neel 1967; Whalley 1982; Svihra et al. 1999; Schuch and Kelly 2004). Limited research has been conducted on root ball anchoring systems or on the mechanical strength of TSS components. Few studies have specifically focused on how stabilization affects the development of small, absorbing roots. Since one of the primary objectives of

TSS is to improve the growth of fine, absorbing roots and promote tree establishment, this is an important topic of research.

In this study, we examined the efficacy of three generic staking, guying, and root ball anchoring stabilization systems. Our first objective was to determine the effect of TSS on tree stability shortly after planting. This was accomplished by conducting tree pulling tests on staked, guyed, root ball anchored, and non-stabilized trees five weeks after installation. Change in trunk orientation was compared among treatments after a strong, wind-simulating force was applied to each tree using a cable winch mounted to a skid-steer loader. Our hypothesis was that change in trunk orientation would be greater for non-stabilized trees than for stabilized trees. To determine the mechanical strength of each system, the trees were pulled a second time and the peak force required to induce TSS breakage was compared among stabilized trees.

Our second objective was to determine if and how TSS affect tree stability and above- and below-ground growth and establishment after one growing season. Our hypothesis was that non-stabilized trees would have shorter shoot elongations, smaller height change, and greater diameter change, with greater trunk taper than stabilized trees. We also hypothesized that non-stabilized trees would have shorter and thinner roots with a smaller dry weight than stabilized trees. After removing TSS, the remaining trees were pulled in the same manner to determine the effect of TSS on tree stability after one growing season. Our hypothesis was that change in trunk orientation would be greater for non-stabilized trees than for trees that had been stabilized.

Lastly, our third objective was to evaluate the practical limitations of each system. The costs of TSS in terms of time and materials were calculated. Any visible signs of tree injury or system breakage were recorded. Our hypothesis was that after one growing season, all systems would remain intact and stabilized trees would remain free of injury.

Chapter 2 – LITERATURE REVIEW

Purpose of Tree Stabilization Systems

Various configurations of staking, guying, and anchoring materials are routinely installed on landscape trees at the time of transplanting. These materials are collectively referred to as tree stabilization systems (TSS), but their functional purpose can extend beyond tree stability. TSS are installed at transplanting to (1) stabilize trees with inadequate root anchorage, (2) support trees with weak trunks, or (3) protect trees from physical injury caused by machinery, animals, or people. These applications are not mutually exclusive. In some instances, a TSS is installed to fulfill all of these needs. However, the predominant application of TSS is to stabilize a newly-transplanted tree until root development adequately anchors it in the soil.

Root Development Following Transplanting

Field-grown trees lose a very large percentage of their root system when transplanted from the nursery to the landscape. One study found that between only 5 and 9% of the total length of roots ≥2 mm in diameter was retained in the harvested root ball of field-grown trees (Gilman 1988). Another study found that less than 15% of the total fine root mass (<2 mm diameter) was retained in the root ball of field-grown trees (Gilman and Beeson 1996). Due to the substantial loss of roots, field-grown trees typically experience a period of impaired physiological function following transplant. This response has been termed transplant shock and is primarily the result of reduced water uptake. The disruption of hormone synthesis by the root system may also play a role (Harris and Bassuk 1993). As a result, first-season shoot growth after transplanting may be only a few centimeters and leaf surface area may be significantly reduced (Struve and Joly 1992).

Another consequence of the transplanting process is physical instability of the tree. A newly-transplanted, field-grown tree does not possess the extensive root system that firmly anchored it in the soil at the nursery. Container-grown trees are similarly unstable when transplanted to the landscape because the root system has been confined to the relatively small dimensions of the container. As a result, both field- and container-grown trees are susceptible to destabilization by strong winds or similar mechanical disturbance during the period immediately following transplant.

Recovery of physiological function and physical stability of a newly-transplanted tree is dependent on new root growth into the backfill and bulk soil. This recovery period, typically referred to as the establishment period, lasts until the root system has regained a spread that is proportional to the tree's size, and normal tree growth rates for a given site have resumed. Numerous factors influence the duration of the establishment period, including species, tree size, environmental conditions, and management practices.

Species' genetic differences in root regeneration will affect rate of establishment. Struve and Rhodus (1988) report that initial root regeneration began twenty-four days after budbreak from the pruned lateral roots of red oak seedlings (*Quercus rubra* L.). Arnold and Struve (1989) found that budbreak of green ash seedlings (*Fraxinus pennsylvanica* Marsh.) began six to fifteen days after transplanting in one experiment and within seven days of transplanting in another experiment. In both experiments, long root regeneration from pruned root surfaces began seventeen to twenty-nine days after transplanting. Red oak is considered difficult to transplant, while green ash is considered an easy to transplant species.

It is generally accepted that large trees have a longer establishment period than small trees because the root system of a large tree must extend a proportionately greater distance to regain its normal dimensions (Watson and Himelick 1997). However, some evidence exists that large trees actually establish quicker but have a much higher mortality rate following transplant than small trees (Struve et al. 2000).

Environmental conditions such as soil temperature, moisture, aeration, density, and fertility influence root elongation rates and thus the duration of the establishment period. The optimum temperature range for root growth of temperate tree species is generally regarded as 10°C – 25°C, (50°F – 77°F) although root growth may continue as low as

1.7°C (35°F) and as high as 36°C (97°F) in some species (Lyr and Hoffman 1967). Within this range, root growth shows a positive response to increasing temperature. Below 6°C (43°F), root growth was negligible for six deciduous and evergreen tree species (Alvarez-Uria and Körner 2007).

Most root growth occurs at soil water potentials between the permanent wilting point (about -1.5 MPa) and field capacity (about -0.03 MPa). This range corresponds to volumetric water content between 10% – 20% in sandy loam soil and 25% – 40% in clay soil (Kramer and Boyer 1995). Within this range, root growth shows a positive response to increasing soil moisture. Empirical evidence suggests that tree root growth is negligible when soil water potential drops below about -0.7 MPa (Waring and Schlesinger 1985). In contrast, excessive soil moisture displaces air from the noncapillary pore space, resulting in oxygen deficiency that reduces root growth (Kramer and Boyer 1995). In most soils, a moisture content above 40% will impair root growth (Watson and Himelick 1997).

In temperate climates, maximum root growth typically occurs in spring and fall when soil temperature and moisture conditions are near optimum (Richardson-Calfee and Harris 2005). While soil temperature may reach its optimum during the summer, soil moisture conditions are often less favorable and thus root growth typically slows during the summer months. In irrigated landscapes, high rates of root production may persist throughout the summer. Although it is not uncommon to observe root growth during the dormant season, root production usually reaches its annual low during the winter months. Due to the seasonality of soil temperature and moisture, the timing of tree transplanting and irrigation practices can have a considerable impact on short-term root growth and the length of the establishment period.

Soil compaction negatively impacts root development of landscape trees. Urban soils are often compacted due to disturbance and traffic. For example, a California residential development was examined following landscape installation and bulk density of the silty clay loam soil ranged from 1.67 – 1.77 g/cm^3 (Lichter and Lindsey 1994). Depending on tree species and soil texture, bulk densities of 1.25 – 1.60 g/ cm^3 can inhibit root growth (Watson and Himelick 1997). High soil density negatively impacts root growth in two ways. First, excessive density diminishes soil porosity, which affects the rate of oxygen delivery to the roots. Without adequate oxygen, roots cannot respire and growth is inhibited. Second, excessive density increases soil strength, which is a measure of soil resistance to external force. Excessive soil strength inhibits root growth due to resistance of the soil particles to displacement by the elongating root tip. It has been observed that root growth is severely diminished when soil strength (as measured with a cone penetrometer) exceeds 3 MPa (Greacen et al. 1969). Landscape trees planted in compacted soil may experience impaired root development, which can threaten their stability and establishment.

Recently transplanted trees are sometimes fertilized with nitrogen and/or phosphorus to promote tree and root growth. However, a number of studies indicate that tree response to fertilization shortly after transplanting is minimal. In a recent study, Day and Harris (2007) found that fertilization of landscape-sized, field-grown, red maple (*Acer rubrum* L.) and littleleaf linden (*Tilia cordata* P. Mill.) did not aid tree establishment. Trees had been fertilized with 1.5 kg N/100 m^2 (3 lb. N/1000 $ft.^2$) each spring, each fall, or not fertilized for three years following transplanting. Because absorption of water is often the limiting growth factor of recently transplanted trees, addition of nutrients to the soil is likely to be ineffective until a plant has re-established its root system (Watson and Himelick 1997). Ferrini and Baietto (2006) note that a wide range of tree responses to fertilization is expected in the urban landscape due to the variety of soil properties, climates, plant materials, types of fertilizer, and fertilizer application methods.

Root development is also influenced by the tree’s stability following transplant. Excessive tree movement or repeated windthrow after transplanting are believed to interfere with proper root development (Appleton et al. 2007). According to Gilman (1997), slight movements of the root ball may potentially break new roots that have extended into the backfill soil and dramatically slow establishment. TSS are commonly used to reduce root ball movement and prevent damage to developing roots during the establishment period.

Depending on climate, tree establishment may take three to twelve months per 2.5 cm (1 in.) of trunk diameter, with trees generally establishing more quickly in warmer climates (Gilman 1994; 1997). However, management practices, especially irrigation, can greatly modify the length of the establishment period. A very rough estimate of the length of the establishment period in temperate climates was proposed by Watson (1985) to be about one year for every 2.5 cm of trunk diameter. A common method for evaluating establishment is to compare shoot growth rates before and after transplanting. When growth rate has recovered and annual shoot elongation becomes consistent, the tree is considered established (Gilman 1997). Upon establishment, the root system has adequately expanded to meet water and nutrient demands and firmly anchor the tree in the soil.

Supportive Tree Stabilization Systems

In addition to stabilizing trees with inadequate root anchorage, TSS are also used to support young trees with weak trunks. Such trees are usually the result of poor nursery production practices including excessive removal of lower lateral branches, excessive nitrogen fertilization, and inadequate spacing between trees (Whitcomb 2006). Although lower lateral branches may not be part of the mature tree's crown, they provide the important function of shading the trunk and providing photosynthate to the lower portion of the trunk, thereby developing proper taper. Lower laterals should be temporarily left on new transplants. Excessive fertilization with limiting nutrients may stimulate more height growth than diameter growth. Closely spaced, containerized plants in the nursery are shaded by one another, and more photosynthate must therefore be allocated to height growth rather than to diameter growth to obtain limiting light resources. These conditions may produce tall, spindly, weak-trunked trees in need of supportive TSS.

Other circumstances may also necessitate a supportive TSS. For example, a young tree may sustain a trunk injury from machinery, vandalism, or extreme weather (e.g., wind or ice) that requires support while it recovers.

Protective Tree Stabilization Systems

Above-ground TSS, such as staking and guying, also protect young trees from physical injury caused by machinery, animals, or people (Watson and Himelick 1997; Lilly 2001; Harris et al. 2004). The bark of young trees is thin and provides limited protection against physical injury. Basal trunk injury from lawn mowers and string trimmers is a common and serious problem for young landscape trees (Watson and Himelick 1997). In many areas, deer antler rubbing is also a common cause of trunk injury. Other causes of injury include car bumpers, bicycle locking, and sign posting. Trunk injuries can provide entry points for insect pests and disease pathogens. The components of a TSS keep machinery and animals away from the trunk, thereby reducing the likelihood of injury. Whitcomb (2006) suggests that physical protection may be the most important function of an above-ground TSS.

In the urban environment, tree vandalism can be a serious problem. Numerous studies have shown that vandalism is among the most common causes of young tree mortality (Nowak et al. 1990). An above-ground TSS fortifies the young tree, making it more difficult to uproot or break. Additionally, the TSS provides a visual cue that the tree is new and may encourage the public to care for the tree by mulching or watering (D. Henry personal communication, April 12, 2006).

Tree Stabilization System Recommendations

Several authoritative references have provided general recommendations about the selection, installation, and maintenance of TSS (see Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004; Trowbridge and Bassuk 2004; Whitcomb 2006). There is consensus that TSS should be used only when there is a clear need, flexible staking is favored over rigid staking, tie materials should be nonabrasive, attachment points for stakes and guys should be kept low to permit trunk movement, and systems should be removed within one year in most situations. Few specific recommendations exist for TSS use and there is a lack of scientific research on the subject. Information on root ball anchoring is especially limited.

Conditions for use of TSS

Experts agree that TSS should be used only when there is a clear need for tree stabilization, support, or protection because TSS can negatively impact tree health and development, while increasing installation and maintenance costs (Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004; Trowbridge and Bassuk 2004; Whitcomb 2006). It is also evident that TSS should not be used to compensate for poor-quality nursery stock or improper planting practices (Appleton 2004b). However, the conditions that necessitate the use of TSS are poorly understood and there is considerable disagreement about the relative importance of certain factors. TSS recommendations are based largely on anecdotal evidence and the conditions for their use are described mostly in qualitative terms. Among the factors that have been observed to impact newly-transplanted tree stability are (1) site conditions, (2) tree characteristics, and (3) planting and maintenance practices. The following is a summary of possible reasons to install TSS on newly-transplanted trees.

<u>Site Conditions</u>

- The site has strong winds (Gilman 1997; Appleton 2004a; Appleton 2004b; Harris et al. 2004; Trowbridge and Bassuk 2004; Whitcomb 2006)
- The site is on a steep slope (Appleton 2004a; Appleton 2004b)
- The site is used as a playground or recreational field (Appleton 2004a; Appleton 2004b)
- Vehicular or foot traffic is heavy on the site (Appleton 2004a; Appleton 2004b; Harris et al. 2004)
- The soil is shallow, compacted, wet, or sandy (Appleton 2004a; Appleton 2004b)
- The soil is dense (Whitcomb 2006)

Tree Characteristics

- The tree cannot stand upright on its own (Gilman 1997; Watson and Himelick 1997; Lilly 2001; Harris et al. 2004; Trowbridge and Bassuk 2004; Whitcomb 2006)
- The trunk is tall or poorly tapered (Appleton 2004a; Appleton 2004b)
- The canopy is unusually large or dense (Gilman 1997; Appleton 2004a; Appleton 2004b; Trowbridge and Bassuk 2004; Whitcomb 2006)
- Trees larger than several inches (~7.5 – 10 cm) in diameter are planted (Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004)
- The root ball is small or poor quality (Gilman 1997; Appleton 2004a; Appleton 2004b; Trowbridge and Bassuk 2004; Whitcomb 2006)
- Root depth is inadequate (Appleton 2004a; Appleton 2004b)
- The tree was grown in a soil-less substrate (Appleton 2004b)
- The tree was grown in a rigid container (Watson and Himelick 1997; Lilly 2001)
- The tree was grown in a fabric container (Gilman 1997)
- The tree is bare root (Watson and Himelick 1997; Lilly 2001; Appleton 2004a; Appleton 2004b)

Planting and Maintenance Practices

- The root ball has been improperly handled, creating a cracked, broken, or loose root ball (Appleton 2004a; Appleton 2004b)
- The wire basket holding the root ball has been manipulated or completely removed (Appleton 2004a; Appleton 2004b)
- Lawnmowers or string trimmers are used close to the tree trunk (Appleton 2004a; Appleton 2004b)
- Transplanting occurs in late spring after bud swell (Whitcomb 2006)

The need for TSS must be considered on a site-by-site, tree-by-tree basis (Appleton 2004b). Following an evaluation of the site conditions, tree characteristics, and maintenance practices, a TSS is selected and configured to fulfill its intended function.

No single stabilization product or method is ideal for every landscape circumstance (Appleton 2004b).

TSS Configuration and Construction

Staking Systems

Height of Stakes- Tree stakes generally vary in height from 0.9 – 1.8 m (3 – 6 ft.) depending on tree size and intended function. For anchorage or protective staking, Harris et al. (2004) recommend using 1.2 m (4 ft.) stakes driven 45.7 – 71 cm (18 – 28 in.) into the ground. For anchorage staking, Gilman (1997) recommends using 1.5 m (5 ft.) stakes driven 61 cm (24 in.) into the ground. Appleton (2004b) suggests that all tree stakes should be driven into the soil to a depth of at least 45.7 – 61 cm (18 – 24 in.).

Number of Stakes- For trees up to 5 cm (2 in.) in diameter, a single stake placed on the windward side of the tree may be adequate for anchorage or support needs (Watson and Himelick 1997; Lilly 2001; Appleton 2004b). Gilman (1997), on the other hand, recommends using two stakes for all trees up to 5 cm (2 in.) in diameter. For trees 5 – 10 cm (2 – 4 in.) in diameter, two to three stakes are usually required (Gilman 1997; Watson and Himelick 1997). Appleton (2004b) suggests using two to three stakes for trees over 1.8 m (6 ft.) tall. Lilly (2001) notes that three stakes provide greater protection against mechanical injury and vandalism. A staking system is usually inadequate for stabilizing trees greater than 7.6 – 10 cm (3 – 4 in.) in diameter; in such cases, a guying system is recommended (Gilman 1997; Watson and Himelick 1997; Lilly 2001).

Harris et al. (2004) suggest using two stakes for support staking and two or three for anchorage or protective staking. If the trunk is poorly tapered, an additional auxiliary stake can be used to supplement the support stakes (Harris et al. 2004). The auxiliary stake should be placed directly next to the trunk and attached with polyethylene tape every 25.4 – 30.5 cm (10 – 12 in.). Its diameter and height should permit the trunk to flex, and it should be slender enough to minimally shade the trunk. The auxiliary stake may be made out of a fiberglass rod, spring-steel rod, bamboo, or split wood, and should be needed only through the first growing season (Harris et al. 2004).

Placement of Stakes- Whitcomb (2006) suggests that stakes be placed beyond the disturbed soil of the planting hole in order to provide greater anchorage and to avoid root damage. Stakes are more stable if they are driven into undisturbed soil beneath or beyond the planting hole (Gilman 1997). To make installation easier, Watson and Himelick (1997) note that stakes may be placed within the planting hole and driven into undisturbed soil underneath. Stakes should not be driven through the root ball because root damage may occur (Lilly 2001; Appleton 2004b).

If wind is not a problem, stakes should be oriented around the tree such that they provide the greatest protection from traffic and equipment (Harris et al. 2004). When a two stake system is used in locations with moderate to strong winds, an imaginary line drawn between the stakes should be at a right angle to the prevailing wind (Harris et al. 2004).

Stake Materials- Tree stakes are constructed of various materials, including wood, metal, and synthetics. Gilman (1997) notes that these materials perform equally well, although some are more likely to cause trunk injury than others. Harris et al. (2004) describe the features, benefits, and faults of commonly used staking materials:

- Wooden stakes are often preservative-treated, which can contaminate the soil.
- Small-diameter wooden poles may split less easily than sawn wooden stakes while in use or being driven, but are difficult to remove without breaking.
- Metal stakes with a flange situated just below the soil surface are more robust than most wooden stakes; however, the flange can become entangled by roots, making the stake difficult to remove.
- Metal grillwork (a series of interconnected metal stakes arranged around the tree) is often used for protective staking around trees in high-use areas.
- Some commercial metal stakes, such as the Reddy Stake™ (Decorations for Generations, Inc., Turlock, CA), are designed to be screwed into the soil, which permits easy removal and re-use.

Attachment Materials- The material used to attach stakes to the trunk should be broad, smooth, and somewhat flexible (Gilman 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004) and be able to resist breakage and unfastening (Watson and Himelick 1997). If possible, the attachment material should also be photodegradable (Appleton 2004b). Gilman (1997) recommends using rubber or rubber-like products designed specifically for the purpose of tree attachments, or using elastic webbing, belting, or polyethylene tape. Polyethylene or fabric ties will minimize trunk girdling (Harris et al. 2004). ArborTie® (Deep Root Partners, LP., San Francisco, CA) is a flat, woven, polypropylene material that is commonly used as attachment material. Bio-Tie™ (Vitech Technologies, Inc., Berkeley, CA) is another commercial attachment that is plastic, has an adjustable tree collar, and is used with a single wooden stake (Harris et al. 2004).

Hose-covered wire as a stake attachment often causes trunk injury and should be used with caution (Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004; Whitcomb 2006). Any non-degradable, small diameter material with limited elasticity (rope, tire cording with wire ties, hose-covered wire, baling wire, covered electrical wire, string, and fishing line) is inappropriate for stake attachment (Appleton 2004b; Harris et al. 2004). Others consider hose-covered wire an appropriate attachment if it is not attached too snugly and is removed within a few months (Whitcomb 2006).

Anchorage and support stakes should be attached low on the trunk to minimize the potential for trunk breakage at the attachment point (Leiser and Kemper 1968; Watson and Himelick 1997; Lilly 2001; Harris et al. 2004; Whitcomb 2006). Recommendations on exact attachment height vary. Whitcomb (2006) recommends using two stakes attached as low as practical, given the size of the tree and site conditions. This will generally be 30.5 – 45.7 cm (12 – 18 in.) above the soil (Whitcomb 2006). For support staking, the stake should be attached 15.2 cm (6 in.) above the lowest level at which the trunk can be held upright (Gilman 1997; Watson and Himelick 1997; Harris et al. 2004). Stakes should be just high enough to keep the tree upright without the top bending over (Lilly 2001; Harris et al. 2004). This attachment point should be at least 0.9 m (3 ft.)

below the leader terminal (Harris et al. 2004). The support stakes should be attached so that the top of the tree is upright even if the trunk is not vertical (Harris et al. 2004).

To avoid trunk injury and detrimental effects on tree development, a staking system should be flexible and allow for some trunk movement (Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004b; Harris et al. 2004; Trowbridge and Bassuk 2004; Whitcomb 2006). However, the stakes should not be attached so loosely that the trunk or branches can rub against the stakes (Harris et al. 2004). When using a single stake, a figure-eight loop or proprietary tie can be used (Watson and Himelick 1997; Lilly 2001). Most attachments employ a figure-eight loop, although a plain loop is sometimes used for two or more stakes (Harris et al. 2004). The attachment should be taut to eliminate slack in the material while assuring flexibility (Gilman 1997).

On especially windy sites or when anchorage stakes will remain installed for more than a year, Whitcomb (2006) recommends attaching the stakes to lag screws or eyebolts inserted into the trunk. This will avoid girdling injury from attachment materials wrapped around the trunk. If callus tissue has begun to grow around the lag screws or eyebolts when stakes are ready to be removed, hardware should be left in place so that callus formation is not disturbed (Whitcomb 2006).

<u>Guying Systems</u>

Applications- Guying systems can be used as an alternative to staking systems on small trees (Gilman 1997). In such instances, ground anchors are substituted for stakes and an appropriate attachment material is installed from the anchors to the tree. Guying systems are recommended instead of staking systems for trees larger than 7.6 – 10.2 cm (3 – 4 in.) in diameter (Watson and Himelick 1997; Lilly 2001; Harris et al. 2004). Large transplanted trees typically have a wide, flat root ball that cannot be adequately stabilized with a staking system (Harris et al. 2004).

Components-

Ground Anchors- An assortment of devices are used as ground anchors for guying systems, including arrowhead-shaped soil anchors, wooden or metal stakes, and deadmen buried in the soil (Watson and Himelick 1997; Lilly 2001). Harris et al. (2004) recommend using steel or wooden stakes as anchors for trees up to 20.3 cm (8 in.) in diameter and deadmen for larger trees (2004). Good anchorage can be obtained with metal stakes that are 1.2 – 1.5 m (4 – 5 ft.) long (Harris et al. 2004). If wooden stakes are used as anchors, Gilman (1997) recommends that they be 76.2 cm (30 in.) long and driven flush with the soil surface to avoid a tripping hazard. Ideally, ground anchors should be placed away from the tree at a distance equal to the height of guy attachment on the trunk (Harris et al. 2004). At a minimum, ground anchors should be no less than two-thirds this distance (Harris et al. 2004). Each anchor should be driven into the soil in line with its guy (Lilly 2001).

Guy Materials- Guys can be constructed from the same attachment materials used in staking systems. Galvanized steel cable is the best guy material for heavy-duty applications (Watson and Himelick 1997; Lilly 2001). As with staking attachments, guys should be tightened only enough to eliminate slack (Gilman 1997), although there seems to be little agreement on the appropriate tension level. Some slack will likely develop in the weeks following planting, potentially causing trunk abrasion or tree destabilization. Turnbuckles can be installed on guys to allow for tension adjustment (Gilman 1997; Watson and Himelick 1997; Harris et al. 2004). Compression springs can also be installed to provide additional flexibility (Watson and Himelick 1997; Harris et al. 2004). For trees greater than 10.2 cm (4 in.) in diameter, three or more guys should be used per tree (Watson and Himelick 1997), although most guying systems employ the use of three guys per tree regardless of tree size.

Guy Attachment- Typically, guying systems are attached to the tree by looping the guy around the trunk above a branch of suitable size and height. If the system will remain installed for more than a few years, Harris et al. (2004) recommend using lag hooks or eye bolts to attach guys to the tree instead of wrapping the guys around the trunk. Guys should be attached with hardware of a size appropriate for the tree (Lilly 2001). When the system is removed, attachment hardware may be left in place if its removal will cause tree injury (Lilly 2001). Citing ANSI A300 Standards for Tree Support Systems, Harris et al. (2004) recommend that the guy attachment be located in the upper half of the crown. However, Appleton (2004b) notes that research indicates that the guy attachment should be as low on the trunk as possible, at a point no more than one-third the length of the trunk.

Root Ball Anchoring

Below-ground stabilization systems may need to be utilized in high traffic areas where above-ground systems present a tripping hazard (Gilman 1997; Watson and Himelick 1997; Trowbridge and Bassuk 2004). Root ball anchoring may also be used when aesthetics are a concern (Watson and Himelick 1997). Various root ball anchoring systems exist including the generic forms described below:

- One to three 1.3 – 1.9 cm (0.5 – 0.75 in.) diameter wooden dowels are driven through the root ball into soil beneath so that the top of the dowel is flush with the top of the root ball. This technique is appropriate for container-grown trees (Gilman 1997).
- Two sharpened 5 by 5 cm (2 by 2 in.) stakes are driven vertically into the soil against opposite sides of the root ball. A third 5 by 5 cm (2 by 2 in.) stake is laid horizontally and bolted or nailed over the root ball into the vertical stakes. The vertical stakes should be driven 61 cm (2 ft.) into undisturbed soil beneath the root ball (Gilman 1997) (Figure 2.1).
- A wooden frame is placed on top of the root ball and a wooden frame is placed at the bottom of the planting hole. Guy wires are used to secure the frames to one another (Watson and Himelick 1997).
- Three or four metal screw or wooden stakes are driven vertically against the root ball at least 30.5 cm (12 in.) into undisturbed soil. The stakes protrude 2.5 cm (1 in.) above the root ball surface and are tied snugly together with one loop of twelve-gauge galvanized wire. Within one year, the wire and the metal screw

stakes should be removed or the wooden stakes should be driven flush with the root ball surface (Harris et al. 2004).

- Two 5 cm by 10.2 cm (2 by 4 in.) pieces of lumber are placed over the root ball. Two dead men are anchored deep in the adjacent soil. Two guy wires are attached to the dead men over the two pieces of lumber (Trowbridge and Bassuk 2004).

A number of commercial varieties of root ball anchoring systems exist including Tomahawk™ Tree Stabilizers (Border Concepts, Inc., Charlotte, NC), Terra Toggle™ (Accuplastics, Inc., Brooksville, FL), Tree Staple™ (Tree Staple, Inc., New Providence, NJ), and Upright Systems™ (Upright Systems, Inc., Kenmore, NY), When using wooden components for root ball anchoring, untreated wood is recommended (Gilman 1997; Appleton 2004b).

Figure 2.1 – Generic root ball anchoring system consisting of four vertical anchors and two horizontal crosspieces.

TSS Inspection and Maintenance

TSS require routine inspection and maintenance to ensure that they function properly and do not cause tree injury. Staking and guying attachments often lose tension in the first few weeks after transplanting due to soil and root ball settling. Extreme weather, machinery, and vandalism can also damage system components. TSS should be examined at least once during the growing season and adjusted or repaired accordingly

(Watson and Himelick 1997). Supportive systems should be checked every two months to see if the tree has developed the trunk strength to stand upright on its own (Gilman 1997). If support stakes are needed for more than a year, the attachment point should be lowered and the stakes shortened at the beginning of the second growing season (Harris et al. 2004).

TSS Service Life

In general, above-ground TSS should remain installed for one year or less (Gilman 1997; Watson and Himelick 1997). More recent sources recommend stakes should be left installed for only a few months and removed after one growing season (Lilly 2001; Harris et al. 2004; Whitcomb 2006). The stakes themselves (without the attachment ties) may be left in place longer to continue protecting from mechanical injury and vandalism (Harris et al. 2004).

Some circumstances call for periods of stabilization longer than one growing season. Field-grown trees transplanted in late spring may need to be staked for a full year if they were excavated from the field following budbreak (Whitcomb 2006). This is because the chemical signals associated with bud swell initiating rapid spring root growth have already passed (Whitcomb 2006). Large evergreens may need to be stabilized for up to two years due to the higher wind resistance of their canopies and the extra weight of snow and ice (Watson and Himelick 1997).

Supportive systems may be required for a few or several years (Harris et al. 2004; Whitcomb 2006). However, Watson and Himelick (1997) warn that if the tree cannot stand upright on its own after one year of staking, roots are not growing properly and site restrictions and maintenance practices should be reevaluated. If the tree requires support staking for more than a year, the tree may never develop the trunk strength to support itself (Gilman 1997). Lilly (2001) notes that stakes or guys left intact for more than two years increase the probability of girdling and potentially reduce the tree's long-term ability to stand alone.

To determine if an above-ground TSS can be removed, Watson and Himelick (1997) suggest grasping the trunk and moving the tree back and forth. If the root ball soil does not move, the stakes can be removed. A tree does not need support staking if it can stand erect after stakes are removed (Gilman 1997).

Tree Stabilization System Constraints

A number of constraints limit the prescription and use of TSS on landscape trees. These include: lack of standardization, practical limitations in the field, and negative effects on tree health and development.

Lack of Standardization

The American National Standard for Tree Care Operations

The previous discussion illustrates that recommendations for TSS prescription and use are quite variable. Authoritative references may provide the same, similar, or different recommendations depending on the specific topic. Such discrepancies may exist because standards have not been established for TSS by the tree care industry. Other tree care practices (pruning, tree fertilization, support systems, tree lightning protection systems, construction management, transplanting, and integrated vegetation management) have been standardized in the United States by the American National Standards Institute. These standards are codified in *ANSI A300, American National Standard for Tree Care Operations – Tree, Shrub, and Other Woody Plant Maintenance – Standard Practices*. The A300 standards were written by leading professionals in the tree care industry and represent the industry consensus on performing tree care operations.

Unlike many other tree care activities, the A300 standards do not provide recommendations for TSS installation and maintenance on recently-transplanted trees. *ANSI A300 (Part 6)-2005 Transplanting* only briefly mentions TSS. Under 63.5.6 (f) it is stated that stabilization systems "shall be considered prior to digging" (ANSI 2005). Under 63.7 it is stated that "[stabilization] systems shall not be specified or installed except when needed. [Stabilization] systems shall be installed according to ANSI A300

Part 3 Support Systems" (ANSI 2005). Although *ANSI A300 (Part 3)-2000 Support Systems* is referenced, it describes standards for the cabling, bracing, and guying of established landscape trees, and there is no mention of stabilizing recently-transplanted trees (ANSI 2000).

ANSI A300 Part 3 defines guying under 33.17 as "the installation of a steel cable or synthetic-fiber cable system between a tree and an external anchor to provide supplemental support" (ANSI 2000). Although this definition could include the use of guys to stabilize recently-transplanted trees, the standards are specifically written for established trees as stated under 41 (ANSI 2000). The practice of guying established trees is rare, but may be necessary for historical or memorial trees that cannot be removed and have serious root defects (Smiley and Lilly 2001). An established tree that has uprooted in a storm may also need to be guyed (Smiley and Lilly 2001). Experts such as Harris et al. (2004) have broadly interpreted the ANSI A300 Part 3 guying standards to include new transplants. However, caution should be taken when considering this practice because of the difference in objectives – to essentially immobilize a mature tree at the end of its life versus stabilizing a recently-transplanted tree to aid root establishment while promoting trunk development.

The International Society of Arboriculture's Best Management Practices

The International Society of Arboriculture (ISA) developed its *Best Management Practices* series to aid in the interpretation and implementation of the ANSI A300 standards. *Best Management Practices: Tree Planting* (Watson and Himelick 2005) is the companion publication to *ANSI A300 (Part 6)-2005 Transplanting*. The following recommendations on TSS applications have been summarized from the tree planting BMP. While these are not official standards, the recommendations represent the current state of practical knowledge on TSS.

Conditions for Use of TSS – Do not install TSS unless there is a clear need. TSS may be installed on bare-root trees as well as fabric-bag or container-grown trees with small, light-weight root balls. Large evergreens may need to be guyed. Trees that are planted at sites with persistent or strong winds may need to be stabilized.

TSS Configuration and Construction –

Staking –

- Height of Stakes – no recommendation is provided.
- Number of Stakes – two stakes are usually adequate.
- Placement of Stakes – stakes may be installed through the planting hole as long as they extend into undisturbed soil beneath.
- Stake Attachment and Materials – trees should not be staked rigidly, especially small trees. Attachment material should be wide, smooth, nonabrasive, flexible, and, if possible, photodegradable. Hose-covered wire can damage the trunk and is not recommended.

Guying – Guys and ground anchors are used on larger trees. Guys should be attached below two-thirds the height of the tree in order to avoid trunk breakage at the attachment point. Turnbuckles and compression springs may be installed to allow for adjustment and flexibility of the system. The BMP provides a table of minimum material requirements for tree guys.

Root Ball Anchoring – Root ball anchoring may be necessary for aesthetic or safety reasons. An untreated wooden frame held in place with underground guys may be used. Additional soil should never be placed over the root ball to cover the system. Steel ground anchors or cables installed underground may present future problems for stump grinding machines and their operators.

TSS Inspection and Maintenance – Guying should be examined at least once during the growing season.

TSS Service Life – In most cases, systems should be removed after one year.

While the BMP provides practical suggestions on the general use of TSS, specific recommendations are clearly lacking. It is unclear why TSS standards have not been developed for the tree care industry. Their absence may be attributable to the lack of scientific studies on TSS or to the inherent difficulty of writing a standard that adequately addresses the numerous factors that impact TSS use.

The current lack of standards for TSS may be contributing to their overuse and unsuccessful use in the landscape. TSS are a common requirement of most landscape tree planting specifications (Appleton et al. 2007). Unfortunately, specifications that do not consider unique tree or site conditions lead to trees being needlessly staked (Appleton and Beatty 2004). Other times, landscape plans do not contain any instructions for staking, and contractors are left to "improvise" in the field (Knoche 1995). Furthermore, landscape plans often fail to consider what type of follow-up maintenance will occur on the site (Appleton 2004b). The establishment of standard practices for the installation, maintenance, and removal of TSS could help ameliorate this problem.

Practical Limitations in the Field

There are practical limitations to the use of TSS in the field. TSS installation is expensive and time-consuming (Gilman 1997; Watson and Himelick 1997; Appleton 2004b; Harris et al. 2004; Watson and Himelick 2005). Cost of materials at transplant, time required for transplant, and follow-up maintenance costs all increase when TSS are utilized. In a survey of TSS manufacturers, Appleton et al. (2007) found that manufacturers considered rapid and easy installation and ease of product removal to be the most important criteria when developing or selecting TSS.

Staking and guying attachments need to be regularly inspected and adjusted to prevent excessive trunk movement or girdling (Watson and Himelick 1997). Although TSS inspection should be part of a regular maintenance routine for newly-transplanted trees, it is seldom performed (Harris et al. 2004). Bark may be constricted in just one year, especially if the tree has grown rapidly. Keeping track of a tree's growth is essential for knowing when to remove guying and staking attachments (Knoche 1995). Ron Morrow, urban forestry manager for the City of Anaheim, California, states that this is the most difficult problem he has encountered with staking (Knoche 1995).

Above-ground systems can also present a tripping hazard (Gilman 1997; Watson and Himelick 1997; Appleton and Beatty 2004; Appleton 2004b; Appleton et al. 2004; Trowbridge and Bassuk 2004; Watson and Himelick 2005). Flagging on guy wires, signs, and mulching beneath the tree may reduce the safety risk (Harris et al. 2004). Above-ground systems can also detract from the visual appeal of a tree (Watson and Himelick 1997; Appleton 2004a; Appleton 2004b; Harris et al. 2004).

As for root ball anchoring, this system cannot be used with bare-root trees, those with broken or poor quality root balls, or those grown in soil-less container substrates (Appleton 2004b). Root ball anchoring and short staking are inappropriate for supporting trees that lack the trunk strength to stand upright on their own (Schuch and Kelly 2004). Furthermore, if metal components of the root ball anchoring system are left buried in the ground, injury to stump grinders and their operators can result.

Effect of Tree Stabilization Systems on Tree Health and Development

Another concern with the use of TSS is the potential negative effects on tree health and development. In a street tree inventory of three city sections in Boston, Massachusetts, Foster and Blaine (1978) found that staking caused more damage to trees than automobiles or vandalism. In a survey of over three hundred practitioners who use TSS, such as landscape contractors and arborists, Appleton et al. (2007) found that over 70% had observed tree damage as a result of TSS being installed for too long. It was also found that the two most important criteria for practitioners selecting a TSS, was whether it allowed for taper development and provided immediate stabilization for root growth.

Compared to a non-stabilized tree, a staked or guyed tree will be more prone to trunk girdling and abrasion and trunk breakage (Leiser and Kemper 1968; Harris and Hamilton 1969; Leiser and Kemper 1973; Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004a; Appleton 2004b; Harris et al. 2004; Whitcomb 2006). The tree will also be more likely to develop poor taper, a larger height to diameter ratio, a less structurally sound root system, and less reaction wood (Jacobs 1954; Larson 1965; Neel 1967; Harris and Hamilton 1969; Leiser et al. 1971; Neel and Harris 1971; Burton and Smith 1972; Fayle 1976; Wrigley and Smith 1978; Holbrook and Putz 1989; Mayhead and Jenkins 1992; Nicoll and Ray 1996; Mickovski and Ennos 2003; Mitchell 2003; Tamasi et al. 2005). These effects make a tree less able to stand without support and if supported, more subject to injury (Harris et al. 2004).

Tree Health Impacts

Staked or guyed trees are susceptible to girdling and abrasion from attachment ties (Leiser and Kemper 1968; Harris and Hamilton 1969; Gilman 1997; Watson and Himelick 1997; Lilly 2001; Appleton 2004a; Appleton 2004b; Harris et al. 2004; Whitcomb 2006). Attachment ties can loosen, causing the tie to rub against and directly injure the trunk. Loosened attachment ties may also enable the tree to rub against the stakes, causing abrasion and injury. Alternatively, ties may become too tight and girdle the trunk. This occurs when ties are left on for too long and/or when the tree grows in diameter rapidly. Girdling ties can physically impede translocation in tree vascular systems.

Brown (1987) attempted to simulate the pressure of attachment ties exerted on a tree trunk. Using a hard, rubber pad with weights attached to it, he exerted pressures from 0.2 to 25.3 g/mm^2 on the trunks of one-year-old, greenhouse-grown birch (*Betula* spp.) seedlings. No consistent differences in change of trunk diameter increment were found over the course of seventeen weeks. However, under a microscope, abnormal cells resembling callus were observed in sections of the trunk where diameter measurements had repeatedly been taken. Brown noted that similar abnormal cells were observed in the wood of an elm branch that had been girdled by a rope. Vessel elements, tracheids, and fibers were reduced, and disorganized parenchyma tissue increased. Practices as seemingly benign as taking repeated diameter measurements may elicit a tree response.

In addition to trunk abrasion and girdling, TSS can predispose a tree to trunk breakage (Leiser and Kemper 1968; Harris and Hamilton 1969; Leiser and Kemper 1973; Harris et al. 2004). Staked trees have been observed with their stems broken at the point of attachment (Patch 1987). Staking attachments have been shown to create critically high areas of stress on the tree trunk. Leiser and Kemper (1968) developed models estimating that high, rigid staking can create stress on the trunk that is three to five times higher per unit area than on non-staked trees. The stress was critically high when stakes were attached above two-thirds the total tree height. To avoid critical stress, stakes should be attached as low on the trunk as possible (Leiser and Kemper 1968; Watson and Himelick 1997; Lilly 2001; Harris et al. 2004; Whitcomb 2006).

Staking not only directly increases the likelihood of trunk breakage, but also indirectly by inhibiting trunk taper development (Leiser and Kemper 1968; 1973). Using mathematical models, Leiser and Kemper (1973) found that saplings grown without staking or pruning developed an optimal trunk taper that uniformly distributed stress on the lower two-thirds of the trunk and were therefore less subject to breakage in the landscape. They found that sapling trunks of greatly different species – ginkgo (*Ginkgo biloba* L.), sweetgum (*Liquidambar styraciflua* L.), carob or St. John's bread (*Ceratonia siliqua* L.), and European white birch (*Betula pendula* Roth.) – all developed the optimal taper parameter of -0.6 when not staked (Leiser and Kemper 1973).

Tree Development Impacts

In the past, it was assumed that staking was essential for support of new transplants and had no detrimental impact on tree development (Wrigley and Smith 1978). However, the structure and architecture of a tree is directly influenced by abiotic stresses, including wind (Read and Stokes 2006). To acclimate to a particular environment, trees need to perceive and respond to wind-induced movement (Telewski 2006). Research has shown that trees alter their morphology in response to changes in wind exposure (Nicoll and Ray

1996; Telewski 2006). All plants respond to mechanical stimulation (Cannell and Coutts 1988). Plant growth responses to wind and other types of mechanical stimulation, known as thigmomorphogenesis, include changes in branch and foliar development, trunk shape and mass, buttressing, and adaptive root growth and shape alteration (Nicoll and Ray 1996). The formation of reaction wood has also been observed to be a response to wind and other forces (Larson 1965; Telewski 2006).

By being morphologically plastic, trees are able to acclimate to local wind regimes and adjust to changes in mechanical loading as they increase in size (Mitchell 2003). However, TSS can interfere with this process. By reducing a tree's ability to sway in the wind, TSS can inhibit the necessary morphological changes that enable a tree to withstand high winds and support its own weight. Both trunk and root morphology can be negatively affected by TSS.

Trunk Response to Wind

Numerous studies have compared the morphology of stabilized trees to that of non-stabilized trees. Other studies have compared mechanically stimulated trees to non-stabilized trees. Both types of studies have yielded similar results. Trunk responses to wind include:

- Reduced height growth (Jacobs 1954; Neel 1967; Harris and Hamilton 1969; Leiser et al. 1971; Neel and Harris 1971; Wrigley and Smith 1978; Holbrook and Putz 1989; Mitchell 2003)
- Increased diameter growth at the base of the tree, producing a more strongly tapered trunk and a smaller height to diameter ratio (Jacobs 1954; Larson 1965; Neel 1967; Harris and Hamilton 1969; Leiser et al. 1971; Neel and Harris 1971; Burton and Smith 1972; Wrigley and Smith 1978; Holbrook and Putz 1989; Mitchell 2003)
- Formation of reaction wood and flexure wood (Larson 1965; Neel 1967; Burton and Smith 1972)

Reaction wood is a special type of wood formed by a tree in response to mechanical stresses that helps to maintain the proper position of plant parts. Compression wood is the type of reaction wood formed in conifers, while tension wood is the type of reaction wood formed in hardwoods. The fibers in compression wood are thicker, denser, and contain higher amounts of lignin, which increase wood strength. Tension wood has fewer vessels which increases its tensile strength (Cannell and Coutts 1988). Flexure wood is similar to compression wood but has altered structure, mechanical properties, and density which provide greater flexibility to stems and branches when under stress (Telewski 1989).

Guying Studies

Jacobs (1954) was one of the first to pioneer the study of the effects of wind sway on tree form and development. In a series of experiments, Monterey pine (*Pinus radiata* D. Don) were guyed for six or more years. Compared to non-stabilized trees, guyed trees grew less in diameter over the lower portion of the trunk, were taller, and had reduced diameter growth of roots. Jacobs concludes that after only two years, guyed trees "were no longer stable in a normal environment."

Larson (1965) examined annual growth increments along the trunk of four-year-old tamarack (*Larix laricina* (Du Roi) K. Koch) and found that exposure to wind caused a pronounced downward shift of increment towards the trunk base, typically at the expense of the upper trunk. This phenomenon was largely eliminated when trees were prevented from swaying in the wind. It was also found that trees exposed to unilateral winds produced eccentric growth on the lower trunk consisting of a high proportion of reaction wood.

Burton and Smith (1972) found similar results for 19-year-old loblolly pine (*Pinus taeda* L.). Trees that were restrained with two sets of three guy wires anchored into the trunk had significantly decreased trunk taper and slightly altered wood properties compared to non-stabilized trees after three years. For non-stabilized trees, radial growth was at a maximum at the base of the trunk, while for guyed trees, radial growth was at a maximum just above the upper guys. Height growth was not significantly affected by guying. Guyed trees had reduced specific gravity, numbers of earlywood and latewood tracheids, latewood tracheid diameter, and amount of compression wood.

Similar results were found for hardwood saplings. Holbrook and Putz (1989) found that four-year-old sweetgum (*Liquidambar styraciflua* L.) saplings that had been guyed for two years were taller and had thinner, less-tapered stems than non-stabilized saplings. However, total above-ground biomass and total leaf area were not changed. Wood density and wood flexibility were also not significantly different among treatments. They concluded that non-stabilized trees were the most structurally stable and that trees that allocate proportionately more biomass to height growth than to diameter growth are at greater risk of structural failure due to their own weight, rain, or wind.

Staking Studies

Neel (1967) applied various staking treatments to one-year-old, containerized sweetgum, Japanese zelkova (*Zelkova serrata* (Thunb.) Makino), mountain birch (*Betula pubescens* Ehrh.), and Chinese pistache (*Pistacia chinensis* Bunge). Trees were staked with one 0.5 cm (0.2 in.) flexible steel rod, one 2.5 by 2.5 cm (1 by 1 in.) redwood stake, one 2.5 by 2.5 cm (1 by 1 in.) redwood stake with additional support for the lateral branches, or were not staked. Results indicated that staking decreased the rate of diameter growth, increased height growth, inhibited the formation of reaction wood, and decreased trunk taper progressively as degree of immobilization increased.

Harris and Hamilton (1969) tested the effect of staking on ngaio tree (*Myoporum laetum* G. Forst.) transplanted from containers to a windy hilltop where stabilization would presumably be necessary. The average height of the trees was 2.9 m (9.5 ft.). Afternoon wind speeds of 6.7 – 11.2 m/sec (15 – 25 mph) were common. The trees were rigidly secured to a 3 m (10 ft.), 2.5 by 2.5 cm (1 by 1 in.) stake for the first year, and a 3 m (10 ft.), 5 by 5 cm (2 by 2 in.) stake the second year. Several trees were injured due to rubbing against the stake. After two years, staked trees grew 50% more in height, 50% less in trunk area, and had significantly less trunk taper than trees that were guyed for only the first few months.

Leiser et al. (1971) evaluated nine species of containerized trees that were rigidly staked for five months. Staked trees had 25% more height growth, 15% less diameter growth, and were 24% less tapered than non-staked trees. A number of staked trees had inverted taper, with greater diameter near the top of the stake than at the base of the trunk.

Wrigley and Smith (1978) found similar results for rigidly staked seedlings growing in planter bags in a greenhouse. Staking consisted of tying each tree to a single pine wood stake. Staking in this manner for fifteen weeks caused a significant increase in height growth for coastal wattle (*Acacia longifolia* (Andr.) Willd. ssp. *sophorae* (Labill.) Court), willow-leaved gum (*Eucalyptus nicholi* Maid. & Blakely), river sheoak (*Casuarina cunninghamiana* Miq.) and a significant decrease in base diameter and taper for the above species as well as for New England peppermint (*Eucalyptus nova-anglica* L.) When untied, the staked trees could not stand upright and bent away from the stake.

Mechanical Stimulation Studies

Neel and Harris (1971) investigated the relationship between trunk movement and height growth of containerized sweetgum growing in a greenhouse. Moderate manual shaking of the seedlings resulted in height growth that was only 20-30% of the height growth of seedlings that had not been shaken. Taper in the portion of the trunk that was formed during the experiment was significantly greater for shaken trees. Vessel members were significantly smaller in length and diameter for shaken trees. When greenhouse-grown trees were placed outside, they found that rigidly staked trees set terminal buds three weeks after non-stabilized trees.

Mitchell (2003) found that three-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) seedlings that were bent side to side to a 45 degree angle from vertical thirty-five times, twice per week throughout the growing season, showed reduced height increment and greater diameter increment towards the base of the trunk. Correlations among the data led Mitchell to suggest that taper development is limited by photosynthate availability, and that taper development during acclimation to new environmental conditions is a priority for initially poorly-tapered trees. Mitchell also found that rigid staking with bamboo attached at two-thirds the seedling height did not affect diameter increment or tree morphology after one growing season.

Root Response to Wind

It is becoming clear that wind has just as important an influence on below-ground plant morphology as it does on above-ground morphology (Ennos 2000). The adaptive growth responses of roots to wind may be even more striking than responses of the shoot (Read and Stokes 2006) and consequently have been the main focus of more recent studies. Root responses to wind may include:

- Development of a larger root system (Leiser et al. 1971; Mayhead and Jenkins 1992)
- An increase in the root to shoot ratio (Nicoll and Ray 1996)
- More numerous, longer, and thicker roots, especially lateral roots in the plane of wind or stimulation (Jacobs 1954; Fayle 1976; Mickovski and Ennos 2003; Tamasi et al. 2005)
- 'I-beam' or 'T-beam' shape development of roots, especially in the plane of wind or stimulation, which is believed to use a minimum of materials while maximizing resistance to bending or flexing within the soil (Nicoll and Ray 1996).
- A shorter taproot, if one exists (Tamasi et al. 2005)

Tree anchorage considerations may play a more important role in root system morphological development than water absorption considerations (Ennos 2000). To prevent uprooting or trunk breakage, external forces such as wind must be transferred down the tree trunk into the soil via the roots (Stokes et al. 1998). The root system of a tree must therefore be strong and large enough to withstand and dissipate these forces. Similar to studies on trunk development, researchers have utilized guying or staking and mechanical stimulation studies to investigate root response to wind.

Guying Studies

An investigation of Monterey pine guyed for six or more years revealed that guyed trees had reduced diameter growth of roots (Jacobs 1954). Root measurements indicated that sway increased the diameter growth of roots as far away as two feet from the base of the trunk.

After guying young Scots pine (*Pinus sylvestris* L.) for two years, Fayle (1976) found that horizontal and vertical roots originating from the trunk-root junction of guyed trees had grown in width only about half that of non-stabilized trees. He also found that compression wood was more frequently present and in greater quantities on the exposed, horizontal roots of non-stabilized trees. Guyed trees also decreased in trunk taper.

Staking Studies

Leiser et al. (1971) found that after only five months of rigid staking, the fresh weight of the root systems of staked trees growing in containers tended to be less than that of non-staked trees, although there were no significant differences. The authors conclude that pruning of lateral branches had a greater influence on root weight than staking.

Significant differences in the root systems of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) were found when stakes were installed for a longer period of time on seedlings growing in a field plot (Mayhead and Jenkins 1992). After three years, trees stabilized with a single stake had significantly less dry root mass than non-stabilized trees. Also, the area, depth, and volume of soil occupied by excavated roots ≥0.2 cm (0.08 in.) in diameter were significantly less for staked trees. The actual volume of soil occupied by the roots of staked trees was about half that of non-stabilized trees. The root:shoot ratio of staked trees was smaller, although not significantly different than non-stabilized trees. Mayhead and Jenkins concluded that these differences, especially in area and volume of soil occupied by roots, present concerns for short-term tree stability.

Mechanical Stimulation Studies

The development of the lateral root system plays a key role in anchorage (Tamasi et al. 2005). Mickovski and Ennos (2003) examined the response of four-year-old Scots pine seedlings to unidirectional flexing. The seedlings were flexed in one particular direction for one minute every day, five days a week, for six months. Flexed seedlings significantly increased in total major lateral root cross-sectional area and average number of major lateral roots. The increase in cross-sectional area and number of lateral roots was most dramatic in the plane of flexing. Furthermore, flexed trees provided significantly more resistance to deflection when pulled 56 degrees from vertical in the windward direction. However, the root:shoot ratio, root dry mass, and the mechanical wood properties of flexed trees were not significantly different from that of non-flexed trees. The authors concluded that maximum strength and stability was optimized by the larger allocation of available assimilates to the roots parallel to the plane of flexing. Flexing may have increased the average growth ring density by increasing the mass and volume of xylem produced per square inch of cambial surface area.

The increased growth of lateral roots as a response to wind loading may be at the expense of the taproot. After subjecting English oak (*Quercus robur* L.) seedlings to artificial wind loading for 30 seconds every hour for seven months, it was found that wind loaded trees had a greater number of primary lateral roots, double the total lateral root length of non-stabilized trees, but significantly shorter tap roots (Tamasi et al. 2005). There were no differences in root or shoot biomass between wind loaded and non-stabilized trees. The authors felt that their results lent support to the theory that the lateral root system, rather than the taproot, is the main component of tree root anchorage.

It should be noted that different types and durations of mechanical stimulation may provoke somewhat different morphological changes (Mickovski and Ennos 2003). Genetics also play a key role in secondary root growth (Ennos 2000). The effect of soil properties such as soil type, water status, and density on root morphology and anchorage is largely unknown (Ennos 2000).

Underlying Physiological Processes

The above research has shown that trees preferentially lay down wood in areas where mechanical stresses are the highest – at the base of the trunk and along the top and bottom of lateral roots – to provide additional strength where it is most needed. The underlying process causing these morphological changes has been termed the thigmo-mechanoresponse cascade (Telewski 2006). The first perceptible physiological response of plant cells to a mechanical stimulus is an increase in action potential and electrical resistance, which occurs within seconds after a perturbation (Telewski 2006). A cascade of responses then occurs at the cellular level, including the blockage of phloem transport, an increase in intracellular Ca^{2+}, an increase in hydrogen peroxide and other reactive oxygen species, and ethylene biosynthesis. An increase in cell division by the vascular cambium is the end result. The synthesis of ethylene has been found to be a fairly common response to a number of environmental stresses including wind. In response to mechanical stimuli, ethylene appears to affect secondary growth and subsequent development of the vascular cambium and does not appear to impact primary growth of the apical meristem (Telewski 2006).

<u>Minimizing TSS Impacts on Tree Health and Development</u>

TSS must be properly constructed to avoid or minimize negative effects on tree health and development. Guys and stake ties should to be attached tightly enough to prevent loosening and subsequent abrasion, but not so tightly that they cause trunk girdling. Frequent inspection of guys and stake ties during the growing season and prompt removal when they are no longer needed minimizes injury to the tree. Supportive stakes should be attached at a height that allows a weak-trunked tree to stand upright, but not so high as to cause excessive stress on the trunk, which increases the risk of trunk breakage. TSS must be constructed with enough rigidity to prevent new roots from breaking, while providing enough flexibility to allow for proper development of the trunk and root system.

Empirical Research on TSS – Staking and Guying

A number of empirical studies have attempted to determine which staking or guying systems have the least impact on tree health and development. Harris and Hamilton

(1969) found that guying with hemp rope for three months caused no bark injury or girdling to 2.9 m (9.5 ft.) tall ngaio trees transplanted to a windy hilltop. The three guys for each tree were looped around the lowest permanent branch crotch about 1.2 m (4 ft.) above the ground. Afternoon wind speeds of 6.7 – 11.2 m/sec (15 – 25 mph) were common. Once the guys were removed, all trees remained straight and upright.

Whalley (1982) studied the stability of container-grown Leyland cypress (*x Cupressocyparis leylandii* Dallimore & Jackson) using three different staking materials. The trees were transplanted and then staked for three years. In the two years following stake removal, 92% of trees that had been staked with a heavy, metal pole blew over, 10% of trees staked with a medium-weight bamboo stake blew over, 2% of trees staked with a light-weight cane stake blew over, and none of the non-staked trees blew over.

More recently, Svihra et al. (1999) tested three above-ground systems on 2.74 m (9 ft.) tall Callery pear (*Pyrus calleryana* Dcne.) that had been transplanted from containers and were unable to stand upright on their own. Results showed that double-staked trees with 2 m (6.5 ft.) tall stakes grew significantly more in height one year after installation than trees that had been staked with Bio-Tie™ (a flexible single stake system) or with Tree Saver™ Tree Anchoring System (a guying system) (Lawson & Lawson, Inc., Indianapolis, IN). Two years after installation, flexible single-staked trees had significantly more taper than the other systems. Trunk girdling was observed beneath the rubber guy straps of guyed trees. One year after TSS had been removed, there were no significant differences in height, but the flexible single-staked trees were still more highly tapered.

Gilman (2006) tested three different staking systems on container-grown red maple and willow oak (*Quercus phellos* L.). After transplanting, all trees were support staked with a single 61 cm (24 in.) long steel rod for one year until they could stand upright. Afterwards, one third of the trees were staked with a 2.4 m (8 ft.) metal conduit, one third with a 2.4 m (8 ft.) steel rod, and one third were non-staked. TSS were removed after 30 months. No significant differences in diameter or tree height were found for the maples when measurements were taken 15 months after TSS installation or 37 months after installation. Willow oaks that had only had the short steel rod staking were significantly greater in diameter after 15 months, but after 37 months, there were no significant differences in diameter or tree height.

Empirical Research on TSS – Root Ball Anchoring

The effects of staking and guying on tree health and development have been well-documented, but the effects of root ball anchoring systems are essentially unknown. Below-ground systems are advantageous because they do not have components that can inflict injury to the tree trunk. Nevertheless, root ball anchoring is a relatively new and infrequently used alternative to staking and guying. In a recent survey of over three hundred practitioners, such as landscape contractors and arborists, Appleton et al. (2007) found that over 80% use some form of above-ground TSS rather than a below-ground system. The following studies suggest that root ball anchoring is less detrimental to trunk development than staking or guying and provides sufficient stability for newly-transplanted trees.

Schuch and Kelly (2004) found that root ball anchored velvet mesquite (*Prosopis velutina* Woot.) developed significantly more taper after six months than trees that had been staked with two 2.4 m (8 ft.) stakes, two 50.8 cm (20 in.) stakes, or a single 2.4 m (8 ft.) stake. The trees had been transplanted from 15 gallon containers. Root ball anchoring consisted of driving two 0.9 m (3 ft.) steel rods through the root ball into undisturbed soil at a 45 degree angle. The least taper developed in trees that were staked with two 2.4 m (8 ft.) stakes.

Twelve different above and below-ground TSS systems were tested on field-grown, 5 cm (2 in.) diameter Bradford pears (*Pyrus calleryana* Dcne. 'Bradford') transplanted to an experimental field site (Appleton and Beatty 2004). After one year, non-stabilized trees and trees staked with two wooden stakes and ArborTie® showed the greatest increase in trunk diameter measured 15 cm (6 in.) above the ground. Trees staked with two wooden stakes and wire-covered hose and trees root ball anchored with Tree Staple™ showed the smallest increase in trunk diameter 15 cm (6 in.) above the ground. No trees, including non-stabilized trees, were leaning or damaged one year after installation, despite a category two hurricane passing through the area six months after planting.

At a nearby study site, field-grown, 5 cm (2 in.) diameter Chinese elm (*Ulmus parvifolia* Jacq. 'Allee') were also evaluated by the researchers. The elms received one of six treatments, which included non-stabilized, four above-ground systems, and one root ball anchoring system. Two weeks after installation, 60% of the root ball anchored trees were leaning "considerably" and had to be re-stabilized. All non-stabilized trees were leaning or lying flat on the ground after the category two hurricane. The other treatments had "minor" leans both after the hurricane and one year later. No significant differences in trunk diameter measured 15 cm (6 in.) above the ground were detected after one year.

Appleton (2006) later tested six of the same above- and below-ground systems and three additional systems on container-grown, 5 cm (2 in.) diameter red maple (*Acer rubrum* L.'Red Sunset'). After one year, there were significant differences in diameter measured 76 cm (30 in.) above the soil, but not measured 15 cm (6 in.) above the soil. After two years, there were no significant differences in diameter at either height. No significant injury to trees was observed after one year, but after two years, three systems caused significant trunk damage and several systems began to fall apart, such as the rubber guying and ArborTie® guying which had both broken.

Empirical Research on TSS – Mechanical Strength

When stabilizing trees, it is important for the system to provide the maximum possible strength with the materials used so that failure under high wind conditions or vandalism can be minimized. Smiley et al. (2003) determined the force required to extract wooden stakes commonly used to anchor guy lines. 3.5 cm by 2.2 cm by 40 cm (1.4 in by 0.9 in. by 15.7 in.) wooden anchors driven straight into the soil required more than twice the amount of extraction force compared to anchors driven into the soil at a 45 degree angle. The authors concluded that driving anchors into the soil at an angle causes soil disturbance that weakens the anchor point.

Eckstein and Gilman (2006) measured the force required to pull container-grown, 7.6 cm (3 in.) diameter live oak (*Quercus virginiana* P. Mill.'Cathedral') to a 20 degree angle. After transplanting, the oaks were stabilized with one of four root ball anchoring systems, with one of five above-ground systems, or remained non-stabilized. Trees with TSS required twice the amount of force required by non-stabilized trees to reach a 20 degree angle. The Terra Toggle™ root ball anchoring system, the 5 cm by 5 cm (2 in. by 2 in.) generic root ball anchoring system, and Brooks Tree Brace™ guying system (Brooks Tree Brace Systems, Inc., Lake Worth, FL) required significantly more force than the other systems to reach a 20 degree angle.

Summary

Tree stabilization systems are commonly installed on landscape trees to provide anchorage and aid in tree establishment, to provide trunk support for trees that cannot stand upright on their own, and to provide protection from injury caused by machinery, animals, and people. General recommendations exist for the design, installation, and maintenance of TSS. Most tree care authorities agree that TSS should only be used when there is a clear need, flexible staking is favored over rigid staking, tie materials should be smooth and nonabrasive, attachment points for stakes and guys should be kept low to permit some trunk movement, and systems should be removed within one year in most situations. Few specific recommendations exist for TSS use due to a lack of scientific knowledge and the multitude of factors that affect landscape tree stability. As a result, tree stabilization is one of the few tree care practices for which standards have not been established. Lack of standardization may be contributing to the overuse and misuse of TSS in the landscape. When TSS are not installed or maintained properly or removed in a timely manner, tree injury can result from trunk girdling, abrasion, or breakage.

Even when TSS are used properly, tree development can be negatively impacted. By reducing a tree's ability to sway in the wind, TSS can inhibit the necessary morphological changes that enable a tree to withstand high winds and support its own weight. Studies comparing guyed, staked, or mechanically stimulated trees to non-stabilized trees have shown that trunk and root development can be negatively affected by stabilization. Other studies have shown that systems that allow for the greatest trunk movement have the least detrimental effect on tree development. Limited research has been conducted on root ball anchoring systems or on the mechanical strength of TSS components. These aspects of TSS warrant further investigation to enhance TSS knowledge and improve TSS applications in the landscape.

Chapter 3 – METHODOLOGY

Study Site

This study was conducted at the Virginia Tech Urban Horticulture Center in Blacksburg, Virginia. The Center was established in 1989 and serves as a research facility for Virginia Tech faculty and graduate students. According to the Southeast Regional Climate Center (2007), average maximum temperature for Blacksburg is 28.1°C (82.6°F), while average minimum temperature is -6.3°C (20.6°F). Average annual precipitation is 103 cm (40.6 in.). The site is located in USDA Plant Hardiness Zone 6a (U.S. Department of Argiculture 1990). The soil at the Center is Groseclose silt loam (clayey, mixed, mesic Typic Hapludult). The average soil bulk density within the planting rows used for experimentation was 1.42 g/cm^3 (SE = 0.01) measured at the 5 – 7.5 cm (2 – 3 in.) depth interval.

A weather station located on site recorded wind speed every fifteen seconds throughout the duration of this study. From the beginning of May through the end of December 2006, average daily wind speed averaged 1.6 m/sec (3.6 mph) and maximum daily wind speed averaged 6.8 m/sec (15.3 mph). The maximum wind gust experienced by the short-term trees was 12.2 m/sec (27.4 mph) on July 4, 2006. The maximum wind gust experienced by the long-term trees was 17.1 m/sec (38.2 mph) on December 1, 2006.

Study Installation

Tree Description

The trees used in this study were 6.4 cm (2.5 in) diameter white ash (*Fraxinus americana* L. 'Autumn Purple'). Sixty trees were obtained from Waynesboro Nurseries, Inc., a wholesale nursery located in northern Virginia. The field-grown trees were harvested and balled in burlap in late March 2006 and delivered to the study site in mid April 2006. The trees were stockpiled and irrigated daily with an overhead sprinkler until planting.

From the sixty trees, fifty-four uniform and defect-free specimens were selected for experimentation.

The physical dimensions of each tree were measured at the time of planting (Table 3.1). These measurements provided baseline data for experimental analysis.

Table 3.1 – Mean physical dimensions of 6.4 cm diameter balled-and burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') used in the TSS Experiments. Measurements were taken directly before or after planting. Standard error are in parentheses, (*n*=48).

Physical Dimension	Value
Angle of trunk orientation, X	-1° (0.46)
Angle of trunk orientation, Y	-1° (0.50)
Lower trunk diameter	60.4 mm (0.41)
Crown radius	0.87 m (0.03)
Root ball diameter	70 cm (0.54)
Root ball moisture	16.9 % (0.75)
Root ball volume	0.059 m^3 (0.00)
Trunk taper	12.4 mm/m (0.39)
Tree height	4.8 m (0.06)
Whole tree mass	187 kg (1.66)

Total tree mass was measured using a 2268 kg capacity digital dynamometer (ED Junior 5K, Dillon/Quality Plus Inc., Kansas City, MO) suspended from the bucket of a skid-steer loader (Bobcat® S185, Bobcat Co., Gwinner, ND) (Figure 3.1). Root ball radius and height were measured with a cloth tape and root ball volume was estimated using the formula for the volume of a cone.

Trunk diameter was measured at two locations using a digital caliper. The first measurement was taken 15.2 cm (6 in.) above the top of the root ball and the second measurement was taken 15.2 cm (6 in.) below the lowest lateral branch. Two perpendicular measurements were taken at each location and averaged. Trunk taper was calculated using the two diameter measurements. Upper trunk diameter was subtracted from lower trunk diameter and then divided by the distance between the two measurements. This value was then multiplied by 1000 to obtain a value for trunk taper in mm/m. The location on the trunk where diameter measurements were taken was permanently marked for repeat measurements.

Tree height was measured using a height pole and recorded to the nearest 0.1 m (0.33 ft.).

Crown radius was measured in two perpendicular planes from the trunk to the tip of the longest live limb in the plane. These two measurements were averaged to obtain one value.

Initial tree lean or trunk orientation was measured using an angle gauge (Johnson 700 Magnetic Angle Locator, Johnson Level & Tool Mfg. Co., Mequon, WI) placed directly against the trunk (Figure 3.2).

Figure 3.1 – Total tree mass of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') was measured using a 2268 kg capacity digital dynamometer (ED Junior 5K, Dillon/Quality Plus Inc., Kansas City, MO) suspended from the bucket of a skid-steer loader (Bobcat® S185, Bobcat Co., Gwinner, ND). Trees were weighed prior to planting in field beds for experimentation.

Trunk orientation measurements were taken 76 cm (30 in.) above ground line. Tree pulling tests would later be conducted to simulate strong wind loads. Two initial trunk orientation measurements per tree were recorded – the angle of trunk orientation parallel to the plane of pulling (X), and the angle of trunk orientation perpendicular to the plane of pulling (Y). A positive X value designated a lean towards the direction of pull, while a negative X value designated a lean away from the direction of pull. A positive Y value designated a lean towards the north, while a negative Y value designated a lean towards the south. The location on the trunk where angle measurements were taken was permanently marked for repeat measurements.

Volumetric water content of the root ball was measured at planting and again during experimentation using time-domain reflectometry (TDR) (Trase 6050X1, Soil Moisture Equipment Corp., Santa Barbara, CA). Measurements were taken 15.2 cm (6 in.) from the trunk to a depth of 15.2 cm.

Figure 3.2 – Trunk orientation (in X and Y planes) of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') was measured using an angle gauge (Johnson 700 Magnetic Angle Locator, Johnson Level & Tool Mfg. Co., Mequon, WI) placed directly against the trunk 76 cm above ground line.

Planting Method and After Care

On May 17 and 18, 2006, twenty-four trees were planted for the long-term TSS experiment ("long-term trees"). On June 7 and 8, 2006, twenty-four trees were planted for the short-term TSS experiment ("short-term trees"). The trees were planted in 3 m (10 ft.) wide beds in a staggered fashion with 2.1 m (7 ft.) spacing between each tree. Trees were staggered in the bed to minimize soil disturbance during planting and experimentation. Planting holes were dug with a 61 cm (24 in.) diameter tractor-mounted auger and then widened to 106.7 cm (42 in.) diameter using a shovel. The depth of each planting hole was 45.7 cm (18 in.). Pendimethalin pre-emergent herbicide was applied to each row prior to planting followed by spot treatment with glyphosate post-emergent herbicide throughout the growing season.

Trees were planted according to ISA Best Management Practices (see Watson and Himelick 2005). Each tree was moved to its planting hole using a skid-steer loader. The tree was gently lowered into the planting hole and oriented so that the trunk was vertical and that the top of the root ball was slightly above ground level. Burlap, rope, and wire basket were removed from the top half of the root ball. The planting hole was backfilled with the excavated soil, lightly tamped, and watered thoroughly. Root ball anchored trees were not backfilled until after the systems were installed. A 91.4 cm (3 ft.) radius mulch ring was created around each tree. Mulch was applied 5.1 – 7.6 cm (2 – 3 in.) deep and was kept away from the trunk. Wood chips were spread on the rest of the planting bed to provide additional weed control. A drip irrigation system, consisting of two emitters per tree, was installed and trees were irrigated during the experiment when rainfall was less than 2.5 cm (1 in.) per week.

TSS Construction and Installation

TSS were installed on both the short-term and long-term experimental trees immediately after planting. A description of each system is provided in Table 3.2. All systems were constructed of untreated wooden components, and 1.3 cm (0.5 in.) polypropylene, woven fabric strapping (ArborTie®, Deep Root Partners LP., San Francisco, CA) was used for guys and stake attachments (Figure 3.3 and Appendix A). The wooden components of the root ball anchoring systems were constructed using 5 cm (2 in.) # 10 wood screws. These materials were selected for constructing the TSS because they are readily available from hardware retailers and commonly used by landscape contractors.

For the staking systems, strapping was attached to the trunk at a height of 109 cm (3 ft. 7 in.) above ground level. For the guying systems, strapping was secured on each tree by looping the strap around the trunk above the lowest sturdy branch, which varied in height from 137.2 cm (4 ft. 6 in.) to 180.3 cm (5 ft. 11 in.) above ground level. Strapping was attached to the stakes and guy anchors using a clove hitch backed with a half hitch. It was attached to the trunk using a bowline loop. About 5 cm (2 in.) of space was left between the knot and the trunk to minimize abrasion. Straps were hand adjusted for firm, consistent tension. Straps on some guyed trees were re-tensioned a few days after installation due to soil and root ball settling. At the same time, about half of the root ball anchors had to be driven further into the soil. No adjustments were necessary for the staked trees.

Table 3.2 – Description of the generic staking, guying, and root ball anchoring systems installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') experimental trees at the study site.

TSS	Description
Staking	Three 5cmX5cmX183cm wooden stakes driven 61cm into the soil equidistantly around tree and secured to trunk using ArborTie®. Stakes were placed 76.2 cm from the trunk.
Guying	Three 2.5cmX5cmX91.4cm wooden anchors driven 61cm into the soil equidistantly around tree and secured over lowest branch crotch using ArborTie®. Anchors were placed 76.2 cm from the trunk.
Root Ball Anchoring	Four 5cmX5cmX76.2 cm wooden anchors driven vertically into soil to a depth flush with the root ball. Anchors were directly against root ball with two 2.5cmX5cmX91.4 cm wooden horizontal crosspieces drilled into the vertical anchors.

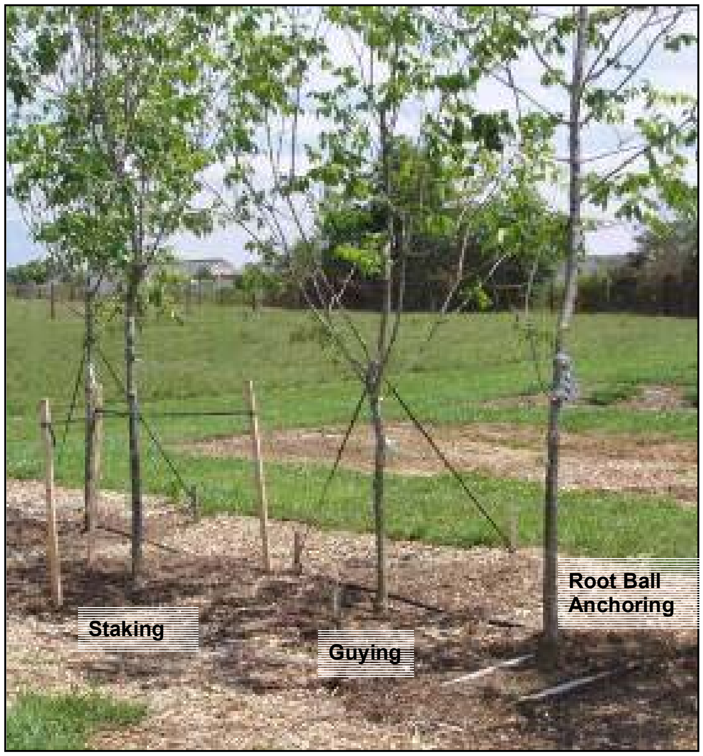

Figure 3.3 – Staking, guying, and root ball anchoring systems installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') experimental trees at the study site.

Experimental Design

This study consisted of three separate experiments. There was one wind-loading experiment and two TSS experiments: one long-term and one short-term. There were six wind-loaded trees, twenty-four long-term trees, and twenty-four short-term trees used in the experiments. The TSS experiments used a completely randomized design. One of four TSS treatments – staking, guying, root ball anchoring, or non-stabilized – was randomly applied to each long-term tree and each short-term tree at the time of planting. There were six replications of each TSS treatment in the long-term and short-term experiments.

Three 3 m (10 ft.) wide planting beds were used for the experiment. Eighteen short-term trees were planted in bed B8 (Figure 3.4). Eight long-term trees were planted in bed A6. Bed A7 contained the remaining sixteen long-term trees. The trees were staggered in the beds so that disruption to the soil was minimized during the pull tests.

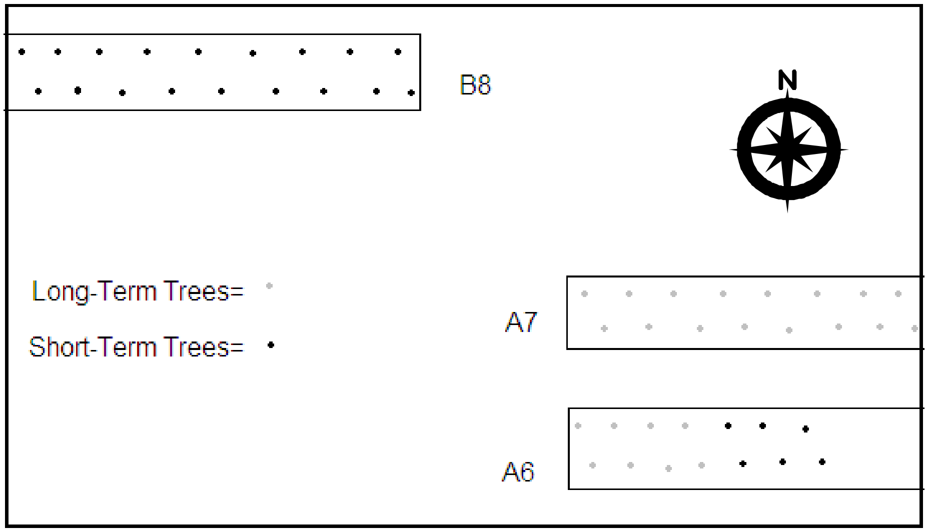

Figure 3.4 – Experimental lay-out of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') at the Urban Horticulture Center. Placement of 24 long- and 24 short-term trees within planting beds B8, A7, and A6 is indicated.

Wind-Loading Experiment

The wind-loading experiment was conducted to quantify the force exerted on the test trees by high-speed winds. This step was necessary to calculate an appropriate wind-simulating force to impose on the TSS experimental trees during tree pulling tests. It should be noted that we did not calculate the actual wind drag on the trees. Drag is the force that resists movement of a solid object through a liquid or gas and is composed of forces parallel and perpendicular to the object's surface. To minimize drag, a tree canopy will reconfigure its branches and leaves to minimize surface area and become more streamlined. Calculation of drag was beyond the scope of this experiment. The wind-loading experiment was conducted to assure that the wind-simulating forces imposed on the TSS experimental trees were representative of the wind stress that these ash trees might experience in the landscape.

A custom-made, steel-framed sled equipped with a digital dynamometer and mounted in the bed of a full-size, pick-up truck was used to measure the load imposed on experimental trees at progressively increasing wind speeds (Figure 3.5). The wind-loading experiment was conducted under fair, calm weather conditions on June 30, 2006.

Trees were in full leaf. The experiment was performed on a rural road near the research center where there was a low volume of traffic, a high speed limit, and flat, straight terrain. Six balled and burlapped ash trees were randomly selected from the lot of experimental trees, covered, and transported to the experiment site in a pick-up truck.

To prepare each tree for the wind-loading test, the tree was severed from its root ball and a hole was drilled through the base of its trunk. A13 mm (0.5 in.) diameter steel bolt was inserted through the hole and the tree was secured to the sled. To prevent foliage wilting, trees were not severed from their root balls until directly before they were mounted in the sled. A prusik cord was tied around the trunk at a height of 83.8 cm (2.75 ft.) and attached to a 1.83 m (6 ft.) section of 0.6 cm (0.25 in.) extra-high-strength steel cable using a steel carabiner and microascender. The horizontally-oriented cable was attached to the dynamometer, which was then secured to the front rack of the sled. The tree was prevented from falling forward in the sled by securing it to a 5 cmX5 cmX122 cm (2 in.X2 in.X48 in.) metal beam mounted to the rear in the truck's hitch receiver.

Once the tree was secured in the sled, the truck was driven at progressively increasing speeds up to 24.6 m/sec (55 mph). As the truck was driven, one person sat in the bed video recording the screen of the dynamometer. The truck was accelerated to 6.7 m/sec (15 mph) and held at that speed for a few seconds. At that moment, the driver yelled out the truck speed, which was recorded by the video recorder. In this manner, the truck speed could be accurately correlated with the wind force by reviewing the video and noting the dynamometer reading at the moment the driver yelled the speed. It was assumed that the speed that the truck was being driven was the same as the wind speed acting on the tree. This procedure was repeated at speeds of 11.2, 15.6, 20.1, and 24.6 m/sec (25, 35, 45, and 55 mph). The truck was then brought to a stop and turned around to make a second run on the same stretch of road. For each tree, two runs were made and the force values were averaged for each wind speed interval. This minimized the impact of any unidirectional, ambient winds and any curves or bumps in the road. Once the wind-loading experiment was performed on the six replicate trees, average wind force values were calculated for each of the speeds.

Figure 3.5 – A custom-made, steel-framed sled equipped with a digital dynamometer (ED Junior 5K, Dillon/Quality Plus Inc., Kansas City, MO) mounted in the bed of a full-size, pick-up truck was used to measure the wind load imposed on 6.4 cm diameter white ash (*Fraxinus americana* L. 'Autumn Purple') trees driven at progressively increasing speeds.

TSS Experiments

Tree Pulling Procedure

Tree pulling tests were used to simulate wind-loading and to evaluate the experimental TSS. All trees were pulled at 1.8 m (6 ft.) above the ground in order to more accurately simulate wind. This is the minimum height that would allow us to pull all trees above the staking or guying attachment point. Pulling some trees above and some trees below the attachment point would create different forces within the trees and therefore alter our results.

Because the trees were pulled at a height different from the one at which they were driven during the wind-loading tests, the wind force values observed at 83.8 cm (2.75 ft.) first needed to be converted to wind force values that would have been observed at 1.8 m (6 ft.). This was accomplished by using a simple formula for bending moment. When applying a static force like that of the pull tests, it is assumed that trees fail when the applied bending moment exceeds the maximum resistive moment of the tree, which, depending on their relative strengths, is either the maximum resistance of the tree trunk to breakage or the maximum resistance of the root system to overturning (Peltola 2006).

Applied bending moment = Applied force * Distance between applied force and ground

BM= P*L

Once the predicted wind force values at 1.8 m (6 ft.) were calculated, a 12-volt, electric winch (XD 9000i, Warn Industries, Inc., Clackamas, OR) attached to a skid-steer loader was use to impose these wind-simulating forces on the experimental trees (Figures 3.7 and 3.8). The winch was attached to the bucket of the skid-steer loader using a custom-made hitch receiver and wired into the loader's electrical system. The loader was parked on the centerline of the planting row 4.6 m (15 ft.) from the experimental tree and the bucket was elevated to 1.8 m (6 ft.) above the ground. A 10 cm (4 in.) diameter pulley was attached to the trunk of the experimental tree with a nylon strap 1.8 m (6 ft.) above the ground. The winch cable was passed through the pulley and attached to the dynamometer, which was then secured to a bracket on the hitch receiver.

The winch was remotely operated with a hand-held controller which was used to steadily increase the winch cable tension until the target force was observed on the dynamometer display. At that point, the cable tension was released immediately by reversing the winch motor. Each pull lasted 5-10 seconds. The winch cable was then unhooked from the tree and the angle gauge was used to measure the trunk orientation 76.2 cm (30 in.) above the ground. The winch cable was then reattached to the tree and subsequent pulls were conducted. Once all pulls were completed, the tree was pulled from the ground, TSS components were dismantled, and the procedure was repeated on the next tree.

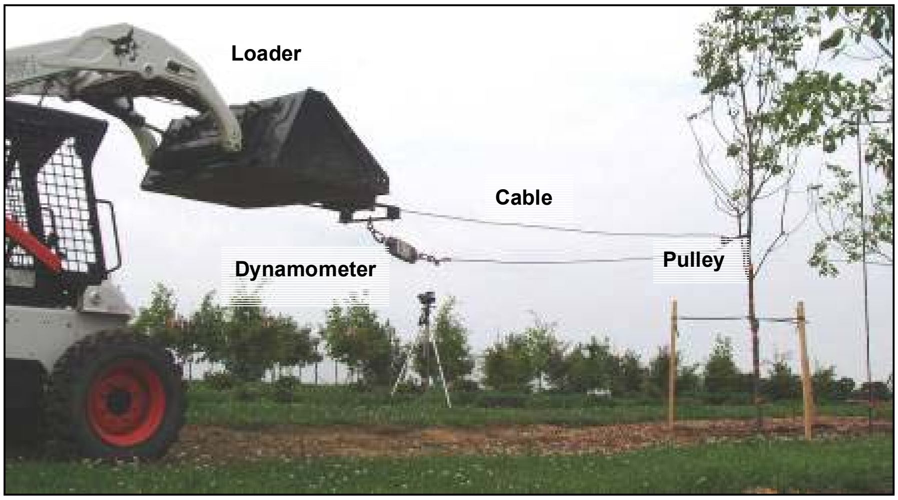

Figure 3.6 – A cable winch (XD 9000i, Warn Industries, Inc., Clackamas, OR) attached to a skid-steer loader (Bobcat® S185, Bobcat Co., Gwinner, ND) was used to impose wind-simulating forces on 6.4 cm diameter white ash (*Fraxinus americana* L. 'Autumn Purple') during tree pulling tests.

The experimental trees were pulled in a consistent direction. Staked trees were pulled so that two stakes were on the leeward side (near loader) and one stake was on the windward side (away from loader). Guyed trees were pulled so that two anchors were on the leeward side and one anchor was on the windward side. Root ball anchored trees were pulled so that the horizontal crosspieces were perpendicular to the plane of pulling.

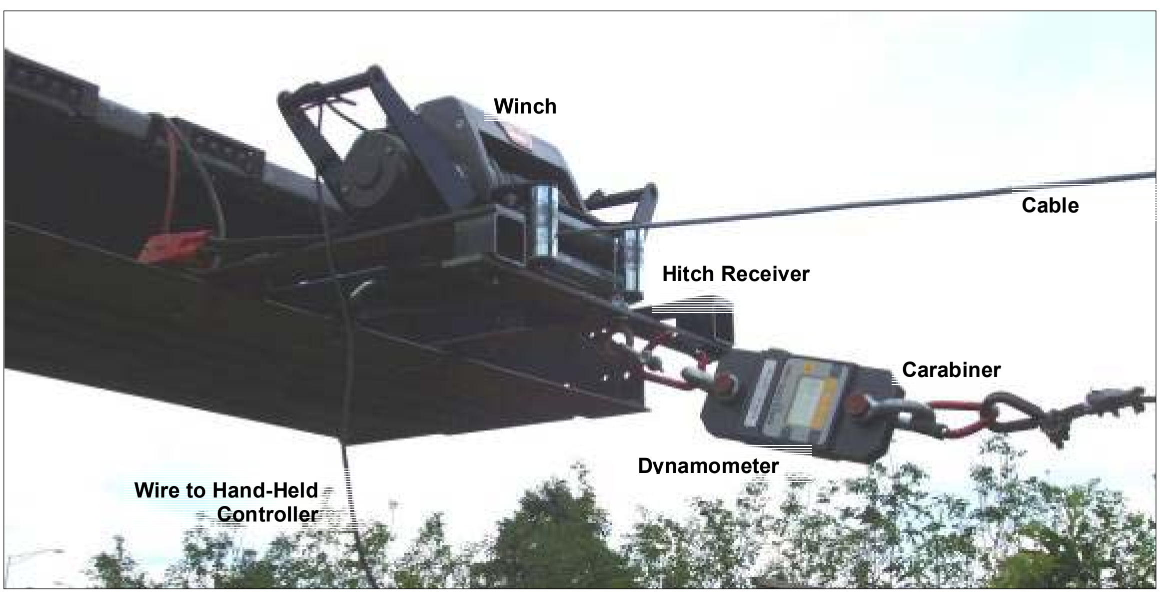

Figure 3.7 – The 12-volt electric winch (XD 9000i, Warn Industries, Inc., Clackamas, OR) used in the tree pulling tests was attached to the bucket of skid-steer loader (Bobcat® S185, Bobcat Co., Gwinner, ND) using a custom-made hitch receiver and was wired into the loader's electrical system. The winch cable was passed through a pulley and attached to a digital dynamometer (ED Junior 5K, Dillon/Quality Plus Inc., Kansas City, MO), which was then secured to a bracket on the hitch receiver. The winch was remotely operated with a hand-held controller.

Short-Term Experiment

The short-term TSS experiment was conducted five weeks after planting and TSS installation. This experiment was conducted shortly after planting to assess TSS performance before the back fill soil had fully settled and before roots had grown out of the root ball. This is the period of highest risk for tree destabilization. The purpose of the short-term experiment was to evaluate TSS efficacy under ambient site conditions, to evaluate TSS efficacy under wind-load simulating conditions, and to evaluate the failure force of TSS components.

Tree Stability Measurements

Trunk orientation of the short-term trees was measured five weeks after planting and TSS installation. Trunk orientation measurements were taken in the X and Y planes on July 13, 2006. To determine change in trunk orientation, initial trunk orientation measurements were subtracted from five week trunk orientation measurements and the absolute value was recorded.

Tree pulling tests were conducted on the short-term trees on July 13,14, and 17, 2006. To evaluate TSS efficacy under high wind conditions, the maximum force observed at 24.6 m/sec (55 mph) during the wind-loading experiment was imposed on the short-term trees. Wind speeds of 24.6 – 28.2 m/sec (55 – 63 mph) are characterized by the World Meteorology Organization as a "storm," and by the U.S. National Weather Service as a "whole gale" (Cullen 2002). Greater than 32.6 m/sec (73 mph) is categorized by both organizations as a hurricane (Cullen 2002). A higher wind speed was not chosen for our experiment because such events occur infrequently and safety considerations would have been an issue during the wind-loading experiment.

Using the formula for bending moment, the maximum force observed during the wind tests, 823 N (185 lb.), was multiplied by the height of the dynamometer attachment above the base of the severed tree trunk, 0.838 m (2.75 ft.), to obtain a value of 690 Nm (509 ft-lb.), which is the bending moment. 690 Nm (509 ft-lb.) was then divided by 1.828 m (6 ft.) to obtain a predicted wind force value of 377 N (85 lb.). 377 N (85 lb.) was therefore our target force applied during the short-term TSS experiment in order to simulate a 24.6 m/sec (55 mph) wind.

Failure Force of TSS Components

Following the 24.6 m/sec (55 mph) wind-loading simulation, the short-term trees were pulled a second time to evaluate the failure force of the TSS components. The second pull imposed an increasing amount of force on the tree until the TSS failed. The peak force required to cause TSS breakage was recorded. The components of the TSS that broke first were noted.

Long-Term Experiment

The second TSS experiment was conducted seven months after planting and TSS installation. The purpose of the long-term experiment was to evaluate the durability of TSS components following exposure to ambient conditions and to assess the effect of TSS on tree growth, establishment, and stability after one growing season.

Tree Growth Measurements

Tree growth measurements were taken December 14 and 16, 2006. Tree height, lower trunk diameter at 15.2 cm (6 in.), and trunk taper were measured and calculated in the same manner as the initial tree measurements. To determine the change in height, diameter, and taper, initial measurements were subtracted from seven month measurements.

Prior to pulling, four shoot elongation measurements were taken per tree at cardinal locations in the tree canopy. Shoot elongation was measured December 15, 2006. The terminal portion of first-order branches was sampled, making sure to exclude any injured or broken branches.

Root Growth Measurements

Tree establishment was assessed by collecting soil cores to quantify root growth into the backfill soil during the seven months after planting. Three soil cores per tree were taken

40.6 cm (16 in.) from the trunk on December 16, 2006. The largest root ball diameter measured prior to planting was 78.7 cm (31 in.), so all cores were taken just outside the root ball in the backfill soil. A 61 cm (24 in.) section of metal conduit with a 10.2 cm (4 in.) inside diameter was manually driven into the soil at each sampling location to a depth of 15.2 cm (6 in.). The soil core was extracted and emptied into a plastic bag, which was labeled and refrigerated at 4°C (39°F) until further analysis.

Roots were manually extracted from the soil cores. The soil was spread on a large piece of white paper and roots were collected by rummaging through the soil sample. Each root sample was then placed into a plastic bag containing a 50-50 solution by volume of water and ethanol and refrigerated to preserve roots.

Root morphology and architecture were assessed using the WinRHIZO PRO digital image analysis system (Regent Instruments, Inc., Quebec, Canada). The roots from each sample were carefully washed in a tub of water and then placed into a clear plastic tray filled with distilled water. Care was taken to make sure that roots did not overlap when placed into the tray. The tray was then placed on the surface of a flatbed scanner interfaced with a desktop computer. The scanner created a digital image of the root sample that was then analyzed by the WinRHIZO software. Once scanning was completed, each root sample was placed into a paper envelope, oven-dried at 40°C (104°F), and weighed using a digital balance.

Tree Stability Measurements

Tree stability was assessed by measuring trunk orientation, by conducting wind-loading simulations, and by quantifying the broken roots observed on the leeward side of the root ball void following destabilization.

Trunk orientation was measured in the same manner as initial trunk orientation in both the X and Y planes. Trunk orientation measurements were taken December 14, 2006. Initial measurements were subtracted from seven month measurements and then the absolute value was taken to determine the change in trunk orientation.

Long-term trees were pulled on December 18-20, 2006, seven months after planting and TSS installation. Immediately before pulling, staking and guying attachments and the horizontal crosspieces of the root ball anchors were removed. To avoid soil disturbance, stakes and anchors were not removed from the ground until after the trees had been pulled.

To evaluate TSS efficacy under high wind conditions, slightly more than the predicted maximum force at 24.6 m/sec (55 mph), 400 N (90 lb.) rather than 377 N (85 lb.), was the target force imposed on the long-term trees. Three subsequent pulls were conducted on each tree with target forces of 800 N (2x), 1600 N (4x), and 2400 N (6x). After each pull, trunk orientation was measured and any root ball lifting or trunk breakage was noted.

Once pull tests were completed, the tree was pulled completely out of the ground using the skid-steer loader. Loose soil in the root ball void was then carefully excavated by hand to expose broken roots. A tally was made of the number of broken roots exposed on the windward side of the root ball void that were greater than 2 mm (0.08 in.) in diameter. If a large root had broken and rootlets leading into that root were exposed and visible, the individual rootlets were tallied. Broken roots were counted to provide an indication of the tree's root anchorage which in turn affects its stability.

Practical Evaluation of TSS

The cost and installation time of the experimental TSS and the durability of TSS components were also evaluated. Because transplant material costs, transplant time, and follow-up maintenance costs all increase when TSS are utilized, it was important to see how each of the systems in our study compared with one another. Appleton et al. (2007) have found that manufacturers consider rapid and easy installation and ease of product removal to be the most important criteria when developing or selecting TSS.

TSS Material Costs

The cost of each TSS component was calculated. From this, the total cost of materials per tree for each system was calculated. The cost of staking, guying, and root ball anchoring were then compared to see which were the most expensive and least expensive systems.

TSS Installation Time

The time required to install each system was also calculated. TSS were installed by two able-bodied people. A third person timed how long it took to install each system using a stop watch. Installation time included the time it took to drive in stakes and anchors, tie strapping on guyed and staked trees, and fasten the root ball anchors with screws and an electric drill. Installation time did not include the time required to cut stakes to the correct length and cut a point on one end, the time required to gather materials and lay them out, or rest time. The time required to cut a stake to the correct length and cut a point on one end using a hand saw was timed separately.

Durability of TSS

The durability of TSS, or how well systems had held up for the extent of time they were installed, was assessed after one growing season on December 14, 2006. Notes were taken on the condition of each system installed on the long-term trees. It was recorded whether systems remained intact, attachment ties had loosened or caused trunk injury, anchors had cracked, or screws on root ball anchors had loosened.

Statistical Analysis

All statistical analyses were performed using SAS 9.1 (SAS Institute, Cary, NC) or JMP IN 5.1 (SAS Institute, Cary, NC). Main treatment effects on dependent variables were assessed using one-way analysis of variance. Multiple comparisons of the treatments were conducted for each significant dependent variable using Tukey-Kramer's HSD procedure. Main treatment effects and treatment comparisons were tested against the null hypothesis at the $\alpha=0.05$ significance level.

Chapter 4 – RESULTS

Wind-Loading Experiment

The mean wind force recorded by the dynamometer at each speed was calculated from the average of the two runs for all six trees. It was found that as vehicle speed increased, the force exerted by the wind on the trees also increased. Mean force observed during the wind tests ranged from 82 N (18 lb.) at 6.7 m/sec (15 mph) to 715 N (161 lb.) at 24.6 m/sec (55 mph).

Because the trees were driven during the wind tests at a height different from the one at which they were pulled, the wind force values observed at 0.84 m (2.75 ft.) needed to be converted to wind force values that would have been observed at 1.8 m (6 ft.). Mean predicted wind force values at 1.8 m (6 ft.) for the various speeds were calculated using the formula for bending moment and are shown in Figure 4.1.

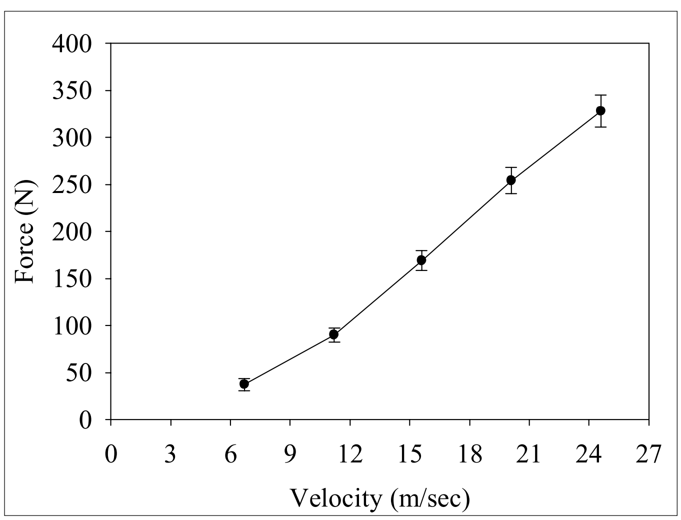

Figure 4.1 – Mean predicted wind force at 1.8 m for 6.4 cm diameter white ash (*Fraxinus americana* L. 'Autumn Purple'). These values were calculated from observed values of wind force at 0.84 m when ash trees were driven at progressively increasing speeds, (n=12).

The *maximum* force observed during the wind tests, 823 N (185 lb.), was used to calculate the target force applied during the pull tests to simulate a 24.6 m/sec (55 mph) wind. The calculated target applied force was 377 N (85 lb.).

Gravity also influences the mechanical stability of a tree when under a static load. The total bending moment due to wind-loading is therefore a sum of the applied bending moment and the force of gravity multiplied by the horizontal displacement of the trunk from vertical (Peltola 2006). When a sample of tree above-ground weight was taken, it was found that mean above-ground weight was only 13.6 kg (30 lb.). The force of gravity acting on the tree trunk and crown was minimal compared to the applied bending moment and it was therefore not factored into our calculations.

TSS Experiments

It should be noted that the actual forces applied during the short- and long-term pull tests were somewhat different from the target applied forces. Consistently applying the exact same values across treatments was difficult because there was a slight delay in the hand-held controller on the winch when the cable was released. As the target applied force increased, the actual applied force varied even more (Table 4.1). Although a more precise method of applying wind-load simulation forces would reduce variability in tree destabilization measurements, we believe that valid and significant conclusions can still be reached using this data.

Table 4.1 – Target applied force and mean actual applied force for short-term and long-term tree pulling tests conducted on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple'). Trees were stabilized with one of four tree stabilization system (TSS) treatments – staking, guying, root ball anchoring, or non-stabilized. The difference in target and actual forces was due to a delay in the cable winch used to destabilize trees. Standard error are in parentheses, (*n*=24).

TSS Experiment	Target Force (N)	Actual Force (N)
Short-Term	377	439 (10.5)
Long-Term, X	400	456 (9.4)
Long-Term, 2X	800	903 (26.4)
Long-Term, 4X	1600	1807 (36.5)
Long-Term, 6X	2400	2642 (28.2)

Short-Term Experiment

Tree Stability Evaluation

Under ambient site conditions, TSS treatment had no significant effect on tree stability during the five weeks after planting and TSS installation (Table 4.2). On average, trunk orientation across treatment groups changed only 1 – 4 degrees. This was not surprising given that wind gusts did not exceed 12.5 m/sec (28 mph) during this period. When the trees were visually assessed, it was observed that a lean of less than 5 degrees was imperceptible, a lean of 5 degrees was barely perceptible, and a lean of 10 degrees was noticeable. A lean greater than 10 degrees would be readily noticeable by most individuals and might be considered aesthetically undesirable. Across all treatment groups, only one tree had a change in trunk orientation of 10 degrees. Two trees had a change in orientation of 5 or 6 degrees. All other trees had a change in orientation of 4 degrees or less.

Table 4.2 – Mean change in trunk orientation (X and Y planes) of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') five weeks after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (n=6).

TSS Treatment	Δ X (°)	Δ Y (°)
Non-stabilized	2 (0.33)	3 (0.99)
Staking	2 (0.33)	2 (0.43)
Guying	1 (0.33)	2 (0.61)
Root Ball Anchoring	1 (0.48)	4 (1.36)
	P=0.2133	P=0.3502

TSS treatment had a marginally significant effect (P=0.0727) on tree stability when a 24.6 m/sec (55 mph) wind-simulating force was applied to the trees (Figure 4.2). On average, the trunk orientation of non-stabilized trees changed 16 degrees, while stabilized trees changed only 1 – 2 degrees. No significant differences in tree stability were observed among the stabilized treatment groups.

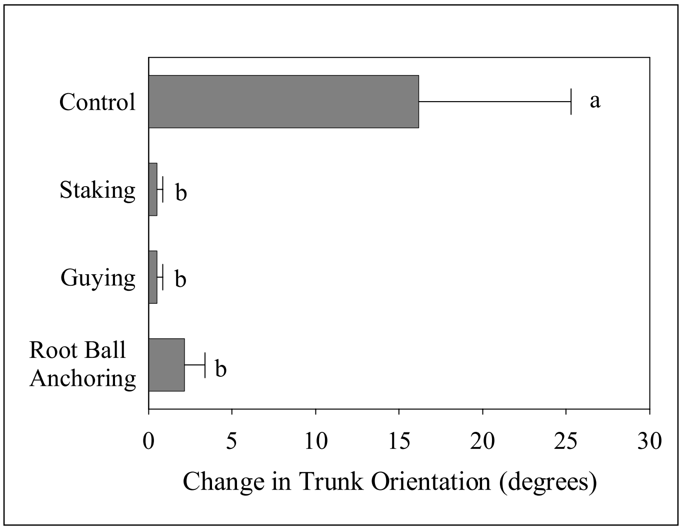

Figure 4.2– Mean change in trunk orientation after applying a 24.6m/sec wind-simulating force to 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') five weeks after planting and installation of tree stabilization system (TSS) treatments, (P=0.0727, *n*=6). Means followed by the same letter are not significantly different at the 0.05 alpha level using Tukey-Kramer's honest significant difference multiple comparison procedure.

Failure Force of TSS

Guyed trees endured significantly more force before failure than staked or root ball anchored trees (P=0.0007) (Figure 4.3). The mean failure force of staked, guyed, and root ball anchored trees was 675 N (152 lb.), 1675 N (377 lb.), and 942 N (212 lb.), respectively. There was no significant difference in failure force between root ball anchored trees and staked trees. For two-thirds of guyed trees, the initial point of failure was the windward guy anchor (on the side of the tree away from the loader). For one-third of the guyed trees, the initial point of failure was the lower trunk region. Most root ball anchored trees failed when the windward crosspiece separated from the two vertical root ball anchors into which it had been screwed. One root ball anchored tree failed when the roots pulled out of the root ball, which suggests that the root ball was defective or damaged prior to planting. For all staked trees, the initial point of failure was the windward stake. In the majority of cases, guy anchors and stakes broke at or near the soil line.

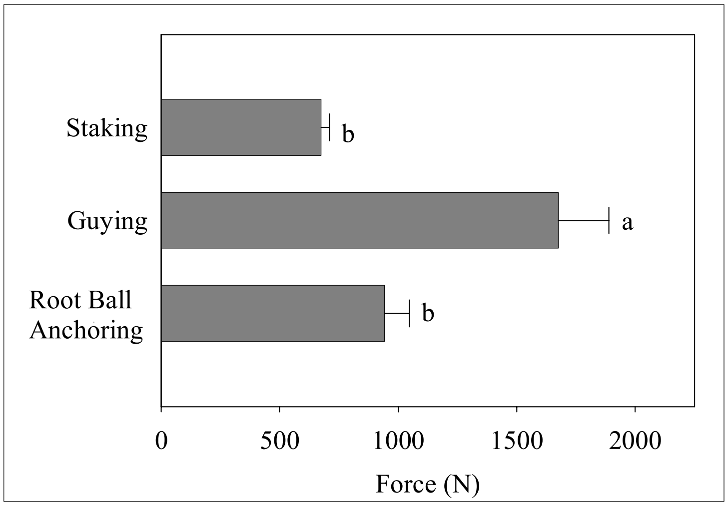

Figure 4.3 – Mean peak failure force of generic staking, guying, and root ball anchoring systems installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple'). Trees were pulled five weeks after planting and installation of tree stabilization systems (TSS), (P=0.0007, *n*=6). Means followed by the same letter are not significantly different at the 0.05 alpha level using Tukey-Kramer's honest significant difference multiple comparison procedure.

Long-Term Experiment

Effect of TSS on Tree Growth and Root Growth after One Growing Season

TSS treatment had no significant effect on tree height growth during the first growing season after planting and TSS installation (Table 4.3). The greatest increase in height of a single tree was only 0.2 m (8 in.). Staked trees had the smallest increase in lower trunk diameter growth. Their diameter growth was significantly less than guyed or root ball anchored trees, but not non-stabilized trees (P=0.0037) (Table 4.3). There was no significant difference in diameter growth among non-stabilized, guyed, and root ball anchored trees. Overall, trunk diameter increases were very small across treatment groups; guyed trees, which had the greatest increase in diameter, grew on average only 2.5 mm (0.1 in.).

TSS treatment had a marginally significant effect on change in trunk taper (P=0.0629) (Table 4.3). Staked trees decreased in trunk taper over the course of the growing season while trees in the other treatments increased in taper. Across treatment groups, only staked and guyed trees significantly differed in change in trunk taper.

Table 4.3 – Mean change in tree height, lower trunk diameter, and trunk taper of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') seven months after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (n=6). Means followed by the same letter are not significantly different at the 0.05 alpha level using Tukey-Kramer's honest significant difference multiple comparison procedure.

TSS Treatment	Δ Tree Height (m)	Δ Diameter (mm)	Δ Trunk Taper (mm/m)
Non-stabilized	0.0	1.6 ab (0.37)	0.9 ab (0.45)
Staking	0.0	0.7 a (0.33)	-0.3 a (0.32)
Guying	0.1	2.5 b (0.20)	2.1 b (0.72)
Root Ball Anchoring	0.0	1.9 b (0.26)	0.9 ab (0.74)
	P=0.5402	P=0.0037	P=0.0629

TSS treatment had no significant effect on shoot elongation, root dry weight, length, or diameter (Table 4.4). Root ball anchored trees had the greatest mean shoot elongation, 37.2 cm (14.6 in.), while guyed trees had the smallest shoot elongation, 29.9 cm (11.8 in). Root ball anchored trees had the greatest mean root dry weight, 914.5 g/m^3, while non-stabilized trees had the smallest mean dry weight, 468.3 g/m^3. Mean root length ranged from 616,601 cm/m^3 for non-stabilized trees to 710,221 cm/m^3 for root ball anchored trees. Root diameter was consistent across treatments, averaging 0.52 – 0.55 mm (0.020 – 0.022 in.).

Table 4.4 – Mean shoot elongation and root dry weight, length, and diameter of 5cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') seven months after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (n=6).

TSS Treatment	Shoot Elongation (cm)	Root Dry Weight (g/m^3)	Root Length (cm/m^3)	Root Diameter (mm)
Non-stabilized	32.7 (5.60)	468.3 (73.8)	616,601 (76,687)	0.52 (0.03)
Staking	32.6 (4.32)	600.0 (114.3)	572,632 (96,248)	0.52 (0.03)
Guying	29.9 (2.70)	677.1 (84.8)	649,141 (124,775)	0.55 (0.03)
Root Ball Anchoring	37.2 (7.06)	914.5 (184.0)	710,221 (83,487)	0.55 (0.02)
	P=0.7978	P=0.1161	P=0.7796	P=0.8979

Effect of TSS on Tree Stability after One Growing Season

Under ambient site conditions, TSS treatment had no significant effect on tree stability during the seven months after planting and TSS installation (Table 4.5). Across treatment groups, trunk orientation changed only 1-2 degrees during this period. The greatest change in trunk orientation for a single tree was 4 degrees. The maximum wind gust recorded at the site during the seven month period was 17.1 m/sec (38.2 mph) on December 1, 2006.

Table 4.5 – Mean change in trunk orientation (X and Y planes) of 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') seven months after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (*n*=6).

TSS Treatment	Δ X (°)	Δ Y (°)
Non-stabilized	2 (0.31)	2 (0.42)
Staking	2 (0.54)	2 (0.48)
Guying	1 (0.21)	2 (0.26)
Root Ball Anchoring	2 (0.49)	1 (0.62)
	P=0.8052	P=0.4996

Following removal of the tree stabilization systems, no significant differences were observed in tree stability when wind-simulating forces were applied (Table 4.6). Across all treatment groups, the mean change in trunk orientation was only 1 – 3 degrees when a 24.6 m/sec (55 mph) wind-simulating force was applied to the trees. When twice this force was applied, trunk orientation change was still only 5 – 6 degrees among the treatments. Trunk lean became progressively greater as the wind-simulating force was increased.

Table 4.6 – Mean change in trunk orientation after mean forces of 456, 903, 1807, and 2642 N were applied to 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') seven months after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (*n*=6).

TSS Treatment	Δ X after 456 N (°)	Δ X after 903 N (°)	Δ X after 1807 N (°)	Δ X after 2642 N (°)
Non-stabilized	2 (0.43)	5 (0.85)	10 (2.11)	18 (2.63)
Staking	3 (1.41)	6 (1.67)	15 (5.80)	19 (4.70)
Guying	1 (0.42)	5 (0.75)	9 (0.93)	11 (1.43)
Root Ball Anchoring	1 (0.33)	6 (0.89)	12 (1.54)	22 (4.61)
	P=0.5766	P=0.8907	P=0.5462	P=0.2292

At very high loads, the trees failed by either trunk breakage or lifting of the root ball. Most trees that snapped required a force of 2642 N (594 lb.) (Table 4.7). All others (except one tree) required a force of 1807 N (406 lb.). An anomalous tree that snapped at 903 N (203 lb.) had an internal trunk injury, not visible from the exterior that corresponded to the point at which the trunk broke. Lifting of the root ball was a much more gradual process that began with soil cracking on the windward side of the tree.

Table 4.7 – Percentage of each tree stabilization system (TSS) treatment installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple') that snapped at the specified force or failed by lifting the root ball when mean forces of 456, 903, 1807, and 2642 N were applied seven months after planting and installation of tree stabilization system (TSS) treatments, (*n*=6).

TSS Treatment	Snap at 903 N	Snap at 1807 N	Snap at 2642 N	Root Ball
Non-stabilized	-	33.3%	33.3%	33.3%
Staking	-	33.3%	33.3%	33.3%
Guying	-	-	50%	50%
Root Ball Anchoring	16.67%	16.67%	-	66.6%

TSS treatment had no effect on the number of broken roots (>2 mm diameter) observed on the windward side of the root ball void following tree removal (Table 4.8).

Table 4.8 – Mean number of broken roots for each tree stabilization system (TSS) treatment installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple'). The number of broken roots includes only those > 2mm in diameter observed on the windward side of the root ball void following tree removal seven months after planting and installation of tree stabilization system (TSS) treatments. Standard error are in parentheses, (*n*=6).

TSS Treatment	Number of roots
Non-stabilized	18 (2.46)
Staking	17 (2.95)
Guying	17 (3.32)
Root Ball Anchoring	19 (2.70)
	P=0.8920

Practical Evaluation of TSS

TSS Material Costs

Materials used to construct TSS were purchased from a local landscape supply dealer and a local home improvement retailer. Two spools, or 152 m (500 ft.), of 1.3 cm (0.5 in.) ArborTie® were purchased from Landscape Supply of Roanoke, VA, for a total of $85.14. Two bundles, or one-hundred, wooden anchors were also purchased from Landscape Supply for a total of $66.00. Eighty-five 5 cmX5 cmX2.4 m (2 in.X2 in.X8 ft.) untreated wooden stakes were purchased from Home Depot of Christiansburg, VA, for a total of $175.82. A box of fifty 5 cm (2 in.) #10 wood screws was purchased for $2.75.

At $7.03 per tree, staking was more than twice as expensive as guying or root ball anchoring (Table 4.9). The relatively high cost of staking was due to the cost of the 1.8

m (6 ft.) wooden stakes. The cost of guying and root ball anchoring systems was similar, costing $3.31 and $3.00 respectively.

Table 4.9 – Cost of materials and mean installation time per tree of tree stabilization systems (TSS) installed on 6.4 cm diameter balled-and-burlapped white ash (*Fraxinus americana* L. 'Autumn Purple'). Total cost of materials was calculated from the cost of each TSS component. TSS were installed by two able-bodied people. Standard error are in parentheses, (*n*=12).

TSS	Cost of Each Component	Total Cost of Materials	Installation time (min)
Staking	three 5cmX5cmX183cm wooden stakes= $6.21 three 147cm pieces of 1.3cm ArborTie®= $0.82	$7.03	5:30 (:10)
Guying	three 2.5cmX5cmX91cm wooden anchors= $1.98 three 239cm pieces of 1.3cm ArborTie®= $1.33	$3.31	5:59 (:15)
Root Ball Anchoring	four 5cmX5cmX76cm wooden anchors= $2.76 four 5cm screws= $0.24	$3.00	5:17 (:15)
			P=0.0996

<u>TSS Installation Time</u>

There were no significant differences in mean installation time of TSS (Table 4.9). All systems required between 5 and 6 minutes to install. Root ball anchoring systems were installed in the shortest amount of time (5:17 min), while guying systems took the longest (5:59 min). An additional 4 minutes was required to cut a single stake or anchor to the correct length and cut a point on one end using a hand saw. This might be necessary in the field if a stake or anchor unexpectedly broke.

<u>Durability of TSS</u>

After one growing season, all staking and guying systems remained intact. All stakes and guy anchors were still firmly in the ground and upright. However, all attachment ties were looser than when installed. Half of the staked trees and all guyed trees had at least one attachment tie that was "very loose," meaning that it was visibly slack. On one tree, one guy anchor had partially cracked but was still firm in the ground when pressure was applied by hand. All root ball anchoring systems also remained intact. However, the screws on the horizontal crosspieces had loosened on about half the trees and could be removed from the vertical anchors when pulled by hand. No girdling or trunk abrasion induced by TSS was observed on any of the trees.

Chapter 5 – DISCUSSION

Implications of TSS Experiments

Short-Term Experiment

Tree Stability Evaluation

With or without TSS, trees remained stable under ambient conditions during the five weeks after planting. Although short-term trees were exposed to actual wind gusts of 12.2 m/sec (27.4 mph), change in trunk orientation was imperceptible across treatments. Harris and Hamilton (1969) found that guyed trees frequently subjected to wind speeds of 6.7 – 11.2 m/sec (15 – 25 mph) remained straight and upright after guys were removed three months after installation.

However, after a 24.6 m/sec (55 mph) wind-simulating force was imposed, non-stabilized trees were significantly destabilized, while stabilized trees remained upright. Mean change in trunk orientation of non-stabilized trees was 16°, which produced a readily noticeable and potentially undesirable lean. Trunk orientation of the stabilized trees was not significantly impacted by the strong wind-simulating force. Eckstein and Gilman (2006) found that all trees with TSS required twice or more the amount of force required by non-stabilized trees to reach a 20° angle when pulled a few days after planting and TSS installation. We conclude that staked, guyed, and root ball anchored trees are significantly more stable than non-stabilized trees under strong wind conditions during the period immediately following transplanting. Furthermore, the generic staking, guying, and root ball anchoring systems used in this experiment are equally effective at maintaining the stability of small diameter, balled-and burlapped landscape trees.

Failure Force of TSS

In the direction that the force was applied (one stake or guy anchor windward and horizontal crosspieces perpendicular to the plane of pulling) guying was the most robust system with a mean failure force of 1675 N (377 lb.). Nevertheless, the least robust system (staking) was still able to endure 675 N (152 lb.) of force before breakage occurred, which was almost twice the amount of force associated with a 24.6 m/sec (55 mph) wind. We conclude that the staking, guying, and root ball anchoring systems used in this experiment are extremely robust and can endure very high destabilizing forces when installed on small diameter, balled-and burlapped landscape trees.

Long-Term Experiment

Effect of TSS on Tree Growth after One Growing Season

Staking, guying, and root ball anchoring had minimal effect on tree growth during the first growing season after transplanting. Although change in lower trunk diameter and trunk taper were significantly less for staked trees, the actual differences were very small and likely have few practical implications. While tension measurements were not taken, the staked trees appeared to be stabilized more rigidly than the other systems which may provide an explanation why staked trees experienced the least diameter growth. No significant differences were found among treatments for tree height growth or shoot elongation.

Other researchers have observed significant TSS effects on trunk diameter, taper, and height growth in transplanted, landscape-size trees (Harris and Hamilton 1969; Svihra et al. 1999; Schuch and Kelly 2004). Svihra et al. (1999) and Schuch and Kelly (2004) both used trees transplanted from 15 gallon containers that were shorter than our experimental trees – 3 m (10 ft.) tall rather than 4.8 m (15.7 ft.) tall. Harris and Hamilton (1969) also used almost 3 m (10 ft.) tall trees and used very tall, rigid stakes. Harris and Hamilton (1969) and Svihra et al. (1999) also had TSS installed for a longer period of time – two years rather than seven months. These differences in experimental design may perhaps explain why our experimental trees responded differently.

Appleton and Beatty (2004) and Gilman (2006) found significant differences in lower trunk diameter among stabilization treatments for some species but not for other species. Appleton (2006) did not find any significant differences in lower trunk diameter of various TSS treatments installed on 5 cm (2 in.) diameter container-grown red maple for two years.

Studies involving mechanical stimulation, seedlings, mature trees, and non-transplanted trees have found similar results – mechanically stimulated or non-stabilized trees had reduced height growth and increased diameter growth at the base of the tree, producing a more strongly tapered trunk and a smaller height to diameter ratio (Jacobs 1954; Larson 1965; Neel 1967; Leiser et al. 1971; Neel and Harris 1971; Burton and Smith 1972; Wrigley and Smith 1978; Holbrook and Putz 1989; Mitchell 2003). If TSS had been left installed for a longer period in our study, more pronounced effects on tree growth may have become apparent. We conclude that the staking, guying, and root ball anchoring systems used in this experiment have minimal effect on the growth of small diameter, balled-and burlapped landscape trees during the first growing season.

Effect of TSS on Root Growth after One Growing Season

Staking, guying, and root ball anchoring had no significant effect on root growth during the first growing season after transplanting. No significant differences in root dry weight, length, or diameter were found among all treatments. To our knowledge, no other studies have examined how different stabilization treatments affect the root growth of transplanted, landscape-size trees, nor have any studies specifically examined fine root production in response to stabilization treatments.

For Sitka spruce seedlings growing in the field, Mayhead and Jenkins (1992) found that the root system of staked trees had significantly less dry root mass than non-stabilized trees. The area, depth, and volume of soil occupied by roots ≥2 mm were also significantly less for staked trees. For containerized trees, Leiser et al. (1971) also found that the root system of staked trees tended to be smaller, but not significantly. Other studies involving mechanical stimulation or mature trees have found similar results – mechanically stimulated or non-stabilized trees produce more numerous, longer, and/or thicker roots (Jacobs 1954; Fayle 1976; Mickovski and Ennos 2003; Tamasi et al. 2005).

Although the trees used in this study were obtained from the same nursery and were carefully selected for uniformity in size and condition, non-visible differences such as stored energy reserves and number of roots within the root ball undoubtedly influenced new root growth and establishment. Mitchell (2003) notes that first-year growth after transplanting reflects the tree's condition at the time of planting. Within-treatment variability in tree and root growth may therefore have reflected variation in individual tree condition at the time of planting. In conclusion, we found no evidence that the tree stabilization systems used in this experiment negatively impact root growth of small diameter, balled-and burlapped landscape trees during the first growing season.

Effect of TSS on Tree Stability after One Growing Season

With or without TSS, trees remained stable under ambient conditions for the duration of the first growing season. Although the long-term trees were subject to actual wind gusts of 17.1 m/sec (38.2 mph), trunk orientation change was almost imperceptible across treatments. Similarly, Appleton and Beatty (2004) found that neither stabilized nor non-stabilized trees were leaning one year after installation. However, at a nearby study-site, the researchers found that root ball anchored trees and non-stabilized trees blew over or were leaning considerably more than trees stabilized with above-ground systems after a hurricane had passed through.

When TSS were removed after one growing season, all trees, including non-stabilized trees, were much more stable than had been anticipated. A force four times greater than that measured for a 24.6 m/sec (55 mph) wind was required to destabilize most trees. These results differ from those of Whalley (1982), who found that over 90% of trees that had been staked for three years with a heavy metal pole blew over when the systems were removed, while no non-stabilized trees blew over. The trees were rigidly staked for three years which may perhaps explain why our experimental trees responded differently. For non-stabilized trees, the force that had caused a readily noticeable lean when applied five weeks after planting produced no perceptible lean when applied after one growing season. Most trees were so well anchored in the soil that they failed by snapping at the trunk rather than uprooting when very high loads were applied. ISA Best Management Practices for tree planting were followed (Watson and Himelick 2005), including the removal of burlap from the sides of the root ball which may help explain why our trees were so well rooted. When the experimental trees were removed, similar numbers of broken roots were observed on the windward side of the root ball void in all treatments, which may explain why no significant differences in tree stability were observed after one growing season.

Implications of Practical Evaluation of TSS

TSS Material Costs and Installation Time

In a survey of landscape practitioners, 21% of respondents listed cost effectiveness as an important short-term criteria for selecting a stabilization system (Appleton et al. 2007). The total cost of a TSS is a function of its material costs, installation costs, maintenance costs, and removal costs. The most cost-effective system is one that uses inexpensive components, installs quickly, and requires no follow-up maintenance or removal. In this experiment, TSS did not significantly differ in their installation times, but there were differences in material costs and anticipated maintenance and removal costs. Based on these criteria, root ball anchoring was the most cost-effective system in this experiment because it used the least expensive materials and did not require removal at the end of its service life. The cost of guying materials was not much more than root ball anchoring, but the need for system removal adds additional maintenance costs. Staking materials were more than twice as expensive as root ball anchoring and guying materials. Staking systems must also be removed at the end of their service life.

It is recommended that all TSS be inspected periodically after their installation to make system adjustments and to ensure that they are not causing tree injury. While all of the experimental systems required adjustment shortly after installation, fewer staked trees required adjustment than guyed or root ball anchored trees. Therefore, the higher material costs of a staking system may be offset by lower maintenance costs. When selecting a TSS for use on a large-scale planting, practitioners should consider maintenance and removal costs as well as material costs since repetitive site visits will increase total system cost.

Durability of TSS

All TSS remained intact for the duration of the study. Stakes and guy anchors were still very firmly in the ground and upright. Horizontal crosspieces of the root ball anchoring systems were still intact but some could be pulled off relatively easily. Putting mulch over the crosspieces would easily hide them and potentially reduce the risk of vandalism. All attachment ties were looser seven months after installation, which may indicate that trees were able to move somewhat in the wind.

No systems visibly girdled or injured the trees during the first growing season. Appleton (2006) observed no significant injury to trees after one year, but after two years, several systems caused significant trunk damage and several were falling apart. Likewise, Svihra et al. (1999) reported that girdling was evident on trees that had been guyed for two years. Harris and Hamilton (1969) found that guying had caused no bark injury or girdling after three months, but when staked for an additional two years, bark injury occurred on several trees due to rubbing against the stake.

Conclusions

In conclusion, tree stabilization systems may not be necessary for small diameter, balled-and-burlapped landscape trees growing under similar site conditions. Maximum ambient wind speeds of 17.1 m/sec (38.2 mph) caused imperceptible changes in trunk orientation of both stabilized and non-stabilized white ash trees.

In locations that frequently have higher wind speeds, TSS may be necessary for trees similar to those in our study, but only for a very short period of time. Five weeks after installation, trees with TSS were significantly more stable than trees without TSS, but after only one growing season, these differences disappeared.

Staking, guying, and root ball anchoring were equally effective, very robust, very durable, caused no tree injuries, and did not impact tree growth or establishment. Practical considerations may therefore play a more important role when choosing which system to use. Although the time required for installation was similar for each system in this study, staking was more than twice as expensive as guying or root ball anchoring.

Limitations and Future Work

Limitations of Tree Pulling Studies

Tree pulling studies are a common and accepted method of investigating root anchorage and the response of trees to destabilizing forces such as wind. Nevertheless, tree pulling tests are an oversimplification of reality, and tree response to wind is a dynamic and extremely complex process. Wind storms produce gusts that are constantly changing in both speed and direction, which induce oscillating movement of the leaves, branches, and trunk causing tree sway (James et al. 2006). Windthrow involves the interaction between wind, crown, and trunk, wind turbulence, vibration of the tree, momentum of the tree, and root anchorage (Coutts 1986).

It has been found that less force is required to uproot trees during wind storms than is predicted from tree pulling tests (Milne 1988; Watson 2000; Peltola 2006). In a study of more than 1,200 trees following a category four hurricane, Francis and Gillespie (1993) found that windthrow and trunk breakage became an issue at wind gust speeds of about 33.5 m/sec (75 mph). Damage in the form of defoliation and minor branch breakage began at speeds of only 16.5 m/sec (37 mph). Tree pulling tests which apply a constant, unidirectional, static force cannot account for all the dynamic forces induced by wind storms.

Peltola (2006) suggests that this discrepancy may be explained by the fact that in response to wind gusts, trees sway dynamically with consequent short-term vibration or oscillatory motion. Milne (1988) calculated that, due to tree sway and the build-up of momentum, repeated wind gusts will bend a tree from the vertical three times or more the amount bent by a constant, static force. Watson (2000) inferred that for a given change in trunk orientation, tree pulling tests predicted greater forces in the roots than were actually observed during wind events.

Wind tunnel experiments have also been used to empirically study tree stability, but they too apply a constant, unidirectional, static force. Peltola (2006) concluded that, "simulation of static loading alone by tree pulling is not enough to explain the mechanical stability of trees, although these real-size tree experiments are useful in stability research". James et al. (2006) recently introduced a new model that incorporates the dynamic structural properties of branches which act to reduce the sway motion of the tree trunk.

It is not known how TSS affect the dynamic loading of trees. It is possible that less force would have been required to destabilize the test trees during a wind event than that found during our tree pulling tests. However, this difference may have been less for stabilized trees than for non-stabilized trees because tree sway and the build-up of momentum would have presumably been reduced by the TSS. Tree pulling studies must be viewed as a means of providing information about tree stability and not as accurate replications of wind events. However, the static forces of tree pulling tests are more representative of the constant pull that vandals exert on a tree (Smiley et al. 2003).

Specific Limitations of Our Study

The methodology employed in this study worked well for testing our hypotheses. However, one of our most important concerns was that it was quite difficult to consistently apply the same value of force during the tree pulling tests. There was a slight delay in the hand-held controller on the winch when the cable was released, and an inconsistent amount of force was applied throughout the pull tests. A more precise method of applying wind-load simulation forces would reduce variability in tree destabilization measurements.

To most accurately simulate wind on a tree during the pull tests, the force would need to have been applied at the crown center of pressure, which occurs at half the crown height for elliptical and circular-shaped crowns (B. Kane personal communication, June 14, 2006). However, we did not pull at a mid-crown level, an average of 2.7 m (9 ft.), because the trunk was much thinner there and therefore more apt to break. Furthermore, we wanted to minimize the amount of trunk bending that would occur. Instead, all trees were pulled at 1.8 m (6 ft.) above the ground. This is the minimum height that would allow us to pull all trees above the staking or guying attachment point. Pulling some trees above and some trees below the attachment point would have created different forces within the trees and therefore confounded our comparisons.

It would have been beneficial to pull a duplicate set of trees in the opposite direction. For staked and guyed trees, only one stake or anchor would be on the leeward side and two on the windward side. For root ball anchored trees, the horizontal crosspieces would be parallel to the plane of pull rather than horizontal. Eckstein and Gilman (2006) note that the direction each TSS was pulled had a "major" impact on how much force was required to bring each tree to a 20° angle. This is because the direction of the applied force with respect to where the stake or anchor is attached will affect the force required to rotate the root ball and therefore destabilize the tree (B. Kane personal communication, April 25, 2006).

Future Work

Over the past decade, progress has been made on determining how TSS affect tree height, trunk diameter, and trunk taper and on how long TSS should remain installed. Characterizing the site and tree conditions that necessitate TSS use is an ongoing challenge. Our study provides some insight into what types of wind conditions may necessitate the use of TSS. Future research might also focus on how soil properties, nursery stock type, or season of planting affect the need for TSS. In the fall, soils are generally warmer and drier and energy levels in plant tissue are higher than in the spring, which affect establishment rates (Whitcomb 2006).

Much has also been learned over the past decade on structural root system adaptations to wind. Yet few studies have specifically focused on how wind and/or stabilization affects the development of small, absorbing roots. Since one of the primary objectives of TSS is to improve the growth of fine, absorbing roots and promote tree establishment, this is an important topic of additional research.

Our study tested three generic versions of staking, guying, and root ball anchoring, but many commercial varieties of TSS exist today and remain largely untested. Root ball anchoring in particular has received little attention, yet shows potential to be an effective alternative to traditional above-ground systems. More research is needed to investigate this promising stabilization technique.

Understanding the biomechanics of tree stability and anchorage is an interesting subject in and of itself, although it was not the objective of this study. To our knowledge, no research has quantified how different stabilization systems affect the bending moments and resistive forces acting on individual trees. This would also be an interesting and valuable topic of future research.

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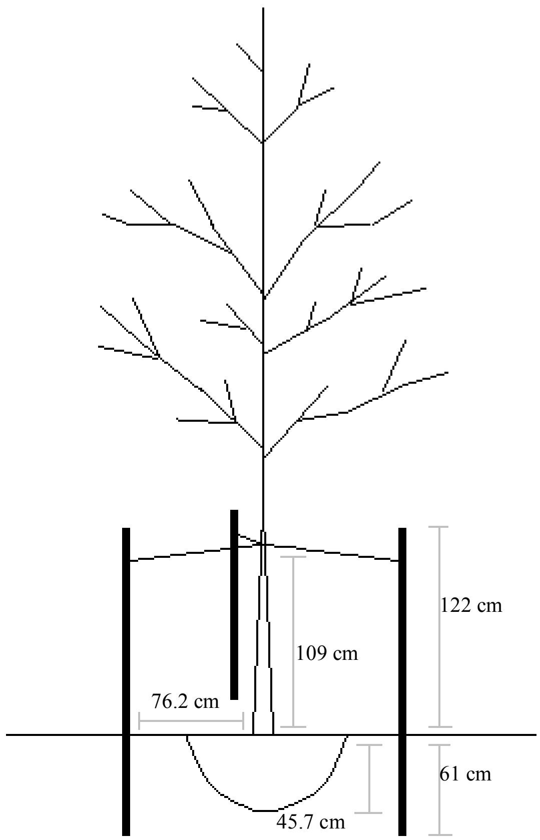
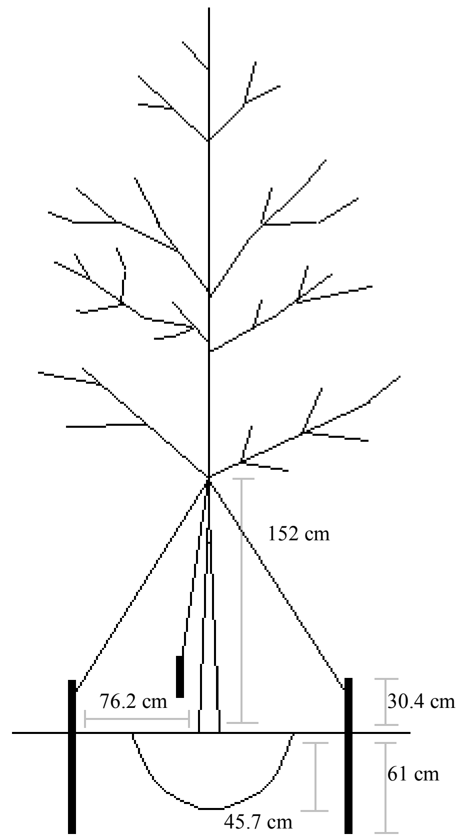
APPENDIX A – Diagrams of tree stabilization systems (TSS) installed on experimental trees.



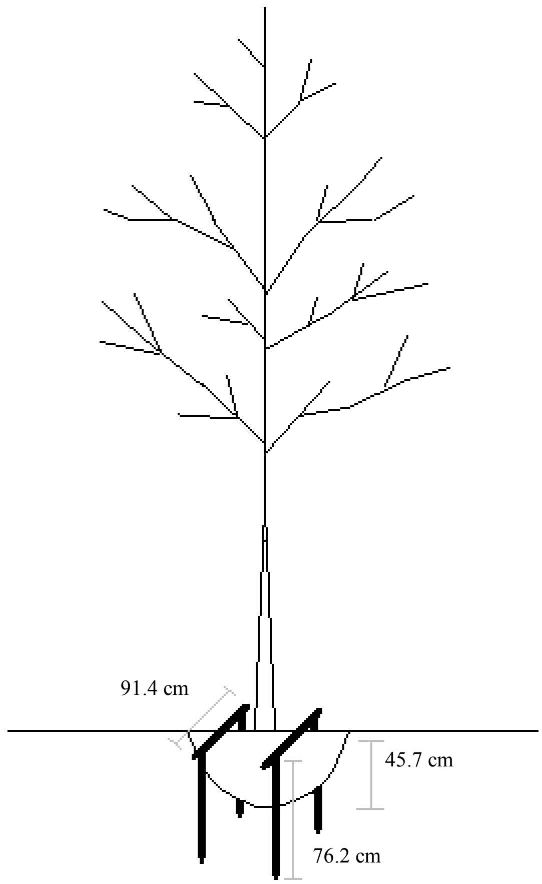
STAKING

Three 5cmX5cmX183cm (2”X2”X6’) wooden stakes driven 61cm (24”) into the soil equidistantly around tree and secured to trunk using ArborTie®. Stakes were placed 76.2cm (30”) from the trunk.



GUYING

Three 2.5cmX2.5cmX91.4cm (1”X2”X3’) wooden anchors driven 61cm (24”) into the soil equidistantly around tree and secured over lowest branch crotch using ArborTie®. Anchors were placed 76.2cm (30”) from the trunk.



ROOT BALL
ANCHORING

Four 5cmX5cmX76.2cm (2”X2”X30”) wooden anchors driven vertically into soil to a depth flush with the root ball. Anchors were directly against root ball with two 2.5cmX5cmX91.4cm (1”X2”X3’) wooden horizontal crosspieces drilled into the vertical anchors.