EVALUATION OF LANDSCAPE TREE STABILIZATION SYSTEMS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
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To all those tree hugging dirt worshipers, and my parents

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First and foremost, I thank Dr. Gilman, for his wisdom and experience has proven to be invaluable throughout the course of this experimental process. I would also like to give special thanks Chris Harchick and the University of Florida Tree Unit Staff for their generous help and support. To my committee members, Dr. Reinhardt Adams and Dr. Masters, I greatly appreciate your perspective and opinions helping to keep me focused throughout this experience. The Great Southern Tree Conference and the Tree Fund were instrumental in providing support for this project and a debt of gratitude is owed to them as well. The manufacturers of the stabilization systems included in this study also deserve special thanks for donating their systems to the project for testing. Lastly, I would like to thank my friends and family for helping me get through this challenging, but enormously rewarding, experience.

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EVALUATION OF LANDSCAPE TREE STABILIZATION SYSTEMS

By

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We conducted pull tests on newly planted 7 cm (2.7 in) caliper container grown *Quercus virginiana* 'SDLN' PP#12015, Cathedral Oak® to evaluate wind loading on nine commonly used landscape tree stabilization systems. Maximum force required to rotate the root ball 20° was used to compare systems. Terra Toggle™, Brooks Tree Brace®, and 2x2s anchoring the root ball withstood the largest forces. T-stakes, dowels, and Tree Staple™ performed no better than non-staked controls. The three guying systems tested, Arborbrace®, Duckbill®, and rebar & ArborTie® were statistically similar and required more force to failure than controls but less than the group that withstood the largest forces. Direction of pulling had no influence on force to failure for any stabilization system tested.

CHAPTER 1
INTRODUCTION

Despite 30 years of research showing that tree stabilization systems (TSS) can adversely affect tree development (Harris et al. 1976; Stokes et al. 1995; Mayhead and Jenkins, 1992), the practice of post-installation tree staking[1] continues to grow. Cost predominantly drives this decision; it is more expensive for a worker to return to the site and stand the tree back up after it has deflected than it is to install a TSS at the time of planting.

The TSS available on the market today are more sophisticated than the old “wire-in-garden hose” technique (Fig. 1-1). The low cost and ease of installation of this stabilization method made it the standard TSS for half a century, and likely is the reason TSS are collectively referred to as tree “staking” systems despite whether or not stakes are actually involved. The popularity of the “wire-in-hose” is evident by its preference even to this day. While still commonly used as a reliable tree stabilizer by homeowners and municipalities alike, the “wire-in-hose” method has been proven to hinder growth and development of the tree (Harris et al. 1976).

A major disadvantage of TSS is the potential risk of causing damage to the tree; therefore post-installation inspection is necessary. To avoid trunk girdling, TSS inspection generally occurs six to twelve months after installation. Aboveground TSS, such as guying systems that wrap around the trunk, are especially vulnerable to girdling the trunk, which physically restricts the flow of nutrient and water resources. Many of the aboveground TSS on the market attach to the trunk with guylines that wrap around the trunk above the first major limb. When left installed, the guylines act as a physical barrier to cambial growth. Trunk growth is then forced around the barrier enclosing the guyline within the trunk, which seriously jeopardizes the survival of the already stressed newly planted tree.

Literature Review

Physiological Impacts

Harris et al. (1976) showed that staking trees can hinder development of trunk taper which, in extreme cases, can result in trees that are sometimes unable to stand upright without support. The proper development of trunk taper involves periodic loading from natural wind force events or feathering. Trunk feathering initiates reaction wood growth, which counteracts forces in tension (produced by angiosperms) or compression (produced by conifers). Thus, mechanical restriction of trunk movement prohibits feathering and ultimately hinders trunk taper development by interfering with natural processes.

Leiser et al. (1972) showed experimentally that mechanical restriction of trunk movement reduces trunk caliper and taper while increasing tree height. The upright position of the tree eventually becomes dependent on the mechanical restriction of the trunk as a means of artificial support. As a result of dependency, resources allocated to trunk caliper and taper growth (for stability) decrease, and the source-sink relationship of the tree shifts. Growth in height then increases, as a result of increased resource availability from the shifted source-sink relationship. A similar response was produced by the use of tree shelters (Leiser et al. 1972). While tree shelters can protect trees in the urban environment, their use can produce trees that are too tall (Burger et al. 1996) with slender, untapered trunks that need support (Burger et al. 1991). Mayhead and Jenkins (1992) also reported reduced trunk caliper and taper and increased tree height from tree shelters and stabilization systems that limited trunk movement.

Stokes et al. (1995) found that the restriction of trunk movement also negatively impacts root development. The root system of a tree is a belowground physiological structure that uptakes water and nutrients from the soil. Tree roots also aid in supporting the tree upright by anchoring it to the ground, providing stability. Artificial support of the tree reduces the gravitational force load placed on the tree and increases the stability of the trunk. Providing artificial support to the trunk changes the allocation of resources within a tree; the priority of the root system, providing tree stability, is decreased and root growth is retarded in favor of other structures.

Svihra et al. (1999) conducted a study to compare three aboveground TSSs to examine the influence on trunk taper. The trunk taper of staked trees were found to be less than unstaked counterparts, and increasing the rigidity of the staking system was also shown to exacerbate this condition. The results provided by Svihra et al. (1999) are consistent with the results of earlier experiments (Harris et al. 1976; Burger et al. 1991; Burger et al. 1996), further supporting the argument against using a TSS unless necessary.

Product and Method Research

Prior research involving landscape TSSs has primarily concentrated on the resultant physiological impacts, with little focus on comparing or determining the effectiveness of them. Leiser and Kemper (1968) determined that landscape trees should be staked no higher than two-thirds of the tree height, and that trees should ideally be staked no higher than necessary. To determine the height on the tree to stake no higher than necessary, they recommend holding the trunk in one hand at increasing heights moving up the trunk until a position is found where the tree is able to support itself upright on its own. Attaching at this position on the trunk allows for maximum trunk feathering while maintaining an upright orientation of the tree.

Smiley et al. (2003) showed that extraction forces of wooden guying anchors differed among the three directions they were driven. They determined that wooden guying anchors were the most effective when they were driven straight down into the soil. Anchors oriented in this manner required the most amount of force for extraction from the soil. Anchors driven at an angle either towards or away from the guyline were only able to withstand half the amount of

force required to extract the anchors driven straight down. The wooden guying anchors included in the study would more appropriately be referred to as wooden guying stakes.
When installed, a guying stake remains slightly above-grade so that guylines can be attached. Guying anchor refers to an anchor that is driven completely below-grade at installation. The most popular guying systems available now follow a similar design concept. First, the anchor is driven to a depth of about 45-60 cm (18-24 in) below ground level. Guying anchors are designed with an orientation that produces the least amount of resistance during installation, minimally disrupting the soil profile as well as making installation easier. Once driven, pulling the guyline attached to the anchor causes a reorientation to a position that is designed so that the anchor produces the maximum amount of resistance within the soil profile.

One of the most comprehensive series of TSS experiments conducted by Appleton (2004), examined several above ground and below ground systems. Caliper change at two levels on the trunk and qualitatively assessed trunk damage were observed. Considerable differences among systems in trunk caliper at both levels for the staked trees were found. She also reported slight trunk damage from the above ground staking after one year.

Wind Load Stresses on Trees

Wind-induced stresses on a tree result from complex dynamic pressure fields that shift as the tree interacts with the wind. Forcing is difficult to accurately characterize, however several theories have been proposed through the literature attempting to model these stresses. Static loads placed on trees can be calculated with greater confidence than dynamic loads because they are constant, unlike an ever-changing dynamic load. Niklas and Spatz (2000) suggest that wind-load stresses in the crown depend on trunk taper and crown size and shape. This view is supported by Peltola et al. (1993) who found that tree swaying is not directly correlated to wind speed.

Simulating Wind

Several attempts have been made over the years attempting to simulate natural wind loading of a tree (Gilman et al. 2006a & 2006b; Niklas and Spatz, 2000). Due to limited availability and costs associated with machines capable of generating hurricane force winds, other techniques are used to simulate wind loading. Pulling tests are a commonly accepted means of simulating wind forces (Peltola et al. 2000). Conducting pulling tests reduces the complexity of dynamic forces from wind loading to a static force, which is easier to measure, calculate, and comprehend. Pulling tests are a practical, cost effective, and scientifically acceptable way to simulate wind forces.

Rationale of Pulling Tests

Pulling tests are used as a means to simulate wind load forces on trees. The tests are conducted by pulling on a cable or rope (pulling line), attached to the trunk of a tree, with a pulling device. A measuring device positioned in-line of the pulling records the amount of force that is exerted on the tree during the test. Pulling devices vary from experiment to experiment, but pulling with a tractor or winch and pulley systems are the most common. The height from ground level to where the pulling line attaches to the trunk also differs among experiments, depending on the nature of the research, but typically the center of mass (COM) is used.

Forestry researchers first pioneered pulling tests on trees. Today pulling tests are generally considered an acceptable means for testing the stability of trees. The advantage of pulling tests is that it allows researchers to place a known controlled load on a tree to examine a particular response of the tree. A disadvantage of pulling tests is that they use a static load to simulate dynamic forces, potentially oversimplifying wind force loading.

Research Objectives

Motivation for this study was supported by the lack of available published research on stabilization of landscape trees. Providing further incentive was a complete absence of previous research comparing the response of TSSs when induced with a controlled load. With an ever-increasing number of landscape TSSs becoming available on the market, it was clear that an evaluation of the most commonly used systems was necessary. The largest natural force a tree in the landscape will encounter comes from wind loading of the crown, and it was therefore determined that an evaluation of landscape TSSs was to be conducted using response to wind loading. Evaluation of stabilization system response to wind loading allowed strength of the systems to be quantified for comparison, which had never been done before in the published literature. With minimal direction from previous research, a multidisciplinary approach was taken to conduct a study involving mechanical and horticultural factors. The goal of this experiment was to evaluate how nine commonly used TSSs react to wind loading. This was accomplished by subjecting the stabilization systems to pulling tests.

The benefit to installing a TSS is the increased stability, and to a lesser extent as theft prevention. The drawbacks of TSS are the negative physiological impacts. Decision to install a TSS occurs when the benefits are determined to outweigh the drawbacks. However, the physiological impacts differ between aboveground TSS and root ball anchoring TSS. Aboveground TSS limit feathering by restricting trunk movement while root ball anchoring TSS allow more natural movement. Considering root ball anchoring TSS allow more feathering than aboveground TSS, they can be incorporated into a standard protocol for tree plantings without concern for hampering tree growth and development. The results of pulling tests help determine which root ball anchoring TSS can withstand the largest forces and how they compare to aboveground TSS.

1-1. “Wire-in-hose”. Photograph of a wire-in-hose tree staking application. Notice that the wire girdled the tree despite being shielded with a section of garden hose.

CHAPTER 2
MATERIALS AND METHODS

Tree Stabilization Systems

Nine stabilization systems were evaluated, four that anchored the root ball and five that stabilized the trunk, plus a control with no stabilization (Fig. 2-1). Each system presented two angles of orientation, so each was pulled from both directions (Fig. 2-2).

2x2s

The 2x2s stabilization system is a root ball anchoring method that is “homemade”, requiring the use of a saw to section the wood into appropriate lengths (Fig. 2-1A). Two untreated pine 2x2 wood braces [3.8 cm x 3.8 cm (1.5 in x 1.5 in)] were placed parallel to each other on top of the root ball 7.6 cm (3 in) away from the trunk. Horizontal braces were cut 7.6 cm (3 in) longer than the root ball diameter [45.7 cm (18 in)]. Four 1.2 m (4 ft) long vertical 2x2s were cut to a point and driven into the backfilled soil against the side of the root ball with approximately 7.6 cm (3 in) remaining above ground surface. The horizontal 2x2s were secured flush to vertical 2x2s with one 7.6 cm (3 in) #8 Phillips head screw. Two 0.24 cm (0.1 in) pilot holes were drilled through both braces to prevent wood from splitting. The braces were oriented so that screws were driven parallel to the wood rays where practical.

Arborbrace®

The Arborbrace® (ATG-R Arborbrace Tree Guying Kit with hardened Nylon Anchors, Arborbrace, Miami, FL) TSS is an aboveground guying system (Fig. 2-1B). Three polypropylene guylines wrapped around the trunk on top of the first major limb were secured with cam-lock quick tensioning metal buckles. The hardened nylon anchors [7.6 cm (3 in) long] were driven into the ground according to the manufacturers specifications at an angle inline with the guyline to a depth of 61 cm (24 in). The distance from ground surface to the tie-in point on the trunk was equal to the distance from the trunk to the point where the anchors penetrated the soil. This ensured that the anchors were at a 45° angle relative to the trunk. The anchors were equidistant from each other at angles of 120° apart.

Brooks Tree Brace®

Brooks Tree Brace® (Model BTB-2SA, Brooks Tree Brace, Lake Worth, FL) is an aboveground TSS, consisting of three telescoping metal braces to secure the trunk (Fig. 2-1C). The braces were extended to their maximum length of 1.7 m (5.5 ft). The rubber pads, hinged at one end of the brace, were placed on the trunk at a height so that the distance from ground level to the attachment point on the trunk was the same as the distance from the base of the trunk to the base plate, hinged at the other end of the brace. This put the braces at a 45° angle relative to the trunk. Two polypropylene straps were threaded through the three rubber pads, securing the braces snuggly around the trunk. Metal base plates were secured to the ground by driving the provided 45.7 cm (18 in) long stakes through the slotted base plate, into the soil. Braces were positioned equidistant from each other, 120° apart.

Dowels

The wooden dowel TSS is a root ball stabilization method, completely below grade when installed (Fig. 2-1D). Three 1.2 m (4 ft) long, 1.9 cm (0.75 in) diameter untreated pine wooden dowels were driven through the root ball, into the soil below. Dowels were cut to a sharp point and driven through the root ball until flush with the surface. Dowels were driven into the root ball 15.2 cm (6 in) away from the trunk, equidistant from each other.

Duckbill®

The Duckbill® (Model 40DTS, Foresight® Products LLC, Commerce City, CO) TSS is an aboveground guying system (Fig. 2-1E). The kit included three metal anchors, each rated at 135 kg (300 lb) capacity in normal soil and attached to a wire cable guyline. The anchors were driven into the soil according to manufacturers directions to a depth of 61 cm (24 in), at an angle inline with the guyline. Anchors were driven into the soil at a distance away from the bottom of the trunk equal to the distance from ground level to the tie-in point above the first major limb, creating a 45° angle. Anchors were positioned 120° apart making them equidistant around the trunk. The wire-cable guylines were threaded through the provided 45.7 cm (18 in) long plastic tubing, where they wrapped around the trunk on top of the first major limb. Guylines were secured using the provided U-bolt cable clamps.

Rebar & ArborTie®

The rebar & ArborTie® (AT5W ArborTie White, Deep Root Partners, L.P., San Francisco, CA) TSS is an aboveground guying system consisting of three rebar anchors and ArborTie® polypropylene guylines (Fig. 2-1F). Three ArborTie® guylines, rated at 1,135 kg (2,500 lb) tensile strength, were wrapped around the trunk on top of the first major limb and secured by tying the end to the guyline with a no-slip knot. The 1.2 m (4 ft) long, 9.5 mm (0.375 in) diameter rebar were driven into the soil straight down. Rebar had a 90° bend, 5.1 cm (2 in) away from the top end. The distance from the tree to where the rebar was driven into the ground was equal to the distance from ground level to the tie-in point. The three pieces of rebar were equidistant from each other at 120° apart. Rebar were driven flush with ground level, and the guylines were wrapped around the 90° bend and secured with a no-slip knot.

Terra Toggle™

The Terra Toggle™ (Terra Toggle™ Tree Anchor System, Accuplastics, Inc., Brooksville, FL) TSS is a root ball anchoring system (Fig. 2-1G). Two 3.8 cm x 8.9 cm [1.5 in x 3.5 in (2x4)] untreated pine braces (not included) were placed on the root ball 5.1 cm (2 in) from the trunk on opposite sides. Lumber was cut the same length as the width of the root ball [53.3 cm (21 in)] and were positioned parallel to each other. The Terra Toggle™ earth anchors, rated at 225 kg (500 lb) breaking strength, are plastic anchors driven to a depth of 1.2 m (4 ft) into the ground, in accordance with the manufacturer's specifications. Anchors were driven into the ground with a driving tool, provided by the manufacturer, at an angle away from the tree. The manufacturer recommends installation of the anchors using the water-jet driving tool but the anchors can be installed using an auger and driving rod. The water-jet driving tool is a steel pipe 1.2 m (4 ft) long and 1.2 cm (0.5 in) diameter, with a ball valve and threaded garden-hose fitting attached at one end and a notch at the other end of the pipe secures the anchor during installation. The anchors were attached to low-stretch plastic strapping. As water pressure is supplied, the driving rod, with the anchor affixed at the driving end, is pushed into the soil. The water flowing through the end of the driving tool saturates the soil, washing away soil in the path of the anchor, which allows the anchor to be installed with less resistance. Lumber was placed so the strapping ran parallel to the rays. Four total anchors attached to straps were used per tree. Two straps were connected with a metal buckle, and the slack between the two was removed with a strapping tool, provided by the manufacturer. Excess strapping was removed.

Tree Staple™

The Tree Staple™ (TS 36 Tree Staple Stabilizers, Tree Staple, Inc., New Providence, NJ) TSS is a below grade root ball stabilization system (Fig. 2-1H). Two 91.5 cm (36 in) long Tree Staples™ were used to anchor the root ball. Tree Staples™ were driven so the longer of the two prongs was driven into the soil below the root ball as it rested against the side of the root ball. The shorter prong was driven into the top of the root ball. The Tree Staples™ were positioned so the shorter prong was driven halfway between the trunk and the opposite side of the root ball. Tree Staples™ were driven straight down until they were flush with the top of the root ball.

T-Stakes

Two T-stakes were driven into the undisturbed landscape soil 20.3 cm (8 in) outside of the backfilled soil (Fig. 2-1I). The 1.8 m (6 ft) long T-stakes were positioned 180° apart with notches facing away from the tree to prevent strap slippage. The T-stakes were driven in the ground 61 cm (2 ft). Support straps were made of 5 cm (2 in) wide polyester webbing, also known as seat belt material, and were cut in 1.5 m (5 ft) long sections. The straps were tied to the T-stake, wrapped around the trunk, and secured to the strapping on the other side with a no-slip knot.

Tree Specimens

One hundred clonally propagated live oak (Quercus virginiana, 'SDLN', PP#12015) Cathedral Oak® were randomly selected from a larger group with similar height [3.8 m (12.5 ft; S.D. = 0.8)] and caliper [6.6 cm (2.6 in; S.D. = 0.2)]. This tree species was selected for the experiment because it is commonly planted in the landscape. Trees were originally planted as liners in a 6.4 cm (2.5 in) diameter round propagation pot May 2003 and pruned to a central leader. Trees were container grown in #3, then #15 and finally in #45 Accelerator® (Nursery Supplies Inc., Fairless Hills, PA) pots at the University of Florida Environmental Horticulture Teaching Lab in Gainesville, FL (USDA, 1990 hardiness zone 8b), and were in #45 containers at time of testing. Root balls were 40.6 cm (16 in) in height and 53.3 cm (21 in) in diameter at the top. Selected trees showed consistency in their root ball development and presence of circling roots (Gilman, 2006).

Data Collection

Two instruments were used to collect data during pulling tests to measure force (load cell) and angle (inclinometer). The 900 kg (2,000 lb) capacity load cell (SSM-AF-2000, Interface Force, Inc., Scottsdale, AZ) was placed in-line of pulling to measure the amount of force exerted on the tree by the pulling test (Fig. 2-3). The ±70° inclinometer (Rieker N4 Inclinometer, Rieker

Inc., Aston, PA) measured rotation of the root ball during pulling tests, and was mounted to a fabricated steel plate [5.1 cm x 7.6 cm (2 in x 3 in)] with 15.2 cm (6 in) long spikes that were pushed into the top of the root ball (Fig. 2-4). The inclinometer was positioned 7.6 cm (3 in) above the root ball and parallel to the direction of pulling. Data from the load cell and inclinometer was collected by a Data Acquisition System (Compact Fieldpoint, National Instruments Corporation, Austin, TX) and recorded on a laptop (Fig. 2-5). Data was collected from both instruments at a rate of 2 Hz (2 samples/sec). Data collected from the instruments was displayed in real-time during pulling tests on the laptop running Labview (Labview Ver. 7.0, National Instruments) software. Equipment was powered in the field using an inverter generator (Honda EU3000*is* Inverter Generator, American Honda Power Equipment Division, Alpharetta, GA). The inverter generator produced power with minimal fluctuations.

Pulling Equipment

A concrete pillar was poured as a stationary pulling point. First a 1.5 m x 1.5 m x 1 m (5 ft x 5 ft x 3 ft) pit was dug by hand. Then a 30 cm (1 ft) high form was constructed around the pit, and then rebar and 9-gauge wire were positioned within the pit to serve as concrete reinforcements. Four cylindrical concrete forms [1.5 m (5 ft) long x 25 cm (10 in) diameter] were connected lengthwise and centered in the pit, extending 1 m (3 ft) above grade. Positioned in the center of each of the four concrete forms was a 45 cm (18 in) length of 1.25 cm (0.5 in) diameter threaded rod. Finally, 4.5 m^3 (6 yd^3) of concrete was poured into the four cylindrical forms and the pit below.

Bolted to the pillar was a winch (K-2250 Work Winch, W.W. Grainger, Inc., Lake Forest, Ill.) and two-sheave pulley (RP124, CMI Co., Franklin, WV) mounted on a custom fabricated steel plate (Fig. 2-6). The load cell was connected to the tree at one end with a clevis and a U-bolt, the other end was connected to another two-sheave pulley (Rock Exotica™ Omni-block®, Thompson Manufacturing, AU) using a clevis. No-stretch rope (AM Steel®, Samson Rope Technologies, Inc., Ferndale, WA) 0.6 cm (0.25 in) in diameter was tied to the pulley on the tree, threaded through the sheaves of both pulleys, and then through the winch.

Experimental Design

Each experimental block in the field contained two of each of the nine TSSs and two controls (with no staking) for a total of 20 trees per block. Each stabilization system was pulled once in both directions in each of the five blocks, for a total of 100 trees (10 systems x 2 directions x 5 blocks = 100 trees). Blocking was used to account for changes in environmental conditions between repetitions and growth of the trees during the experiment.

Each tree was pulled at the same rate until the inclinometer read 20° or the trunk snapped in half. With a root ball rotation of 20° a tree must be manually straightened and thus, the TSS has failed. Force to failure for this experiment was defined as the maximum amount of force recorded by the load cell before the inclinometer measured 20°.

Experimental Procedure

Planting

Each block, with the systems in random order, was planted in a 35 m (120 ft) diameter semi-circle around the pillar (Fig. 2-7). Trees were planted in 41 cm (16 in) deep holes dug prior to testing with a 61 cm (24 in) diameter auger for consistency in depth and width. This positioned the top of the root ball and the root flare even with the landscape soil. Trees were placed in the center of the hole, before adding backfill. Backfilled site soil was uniformly compacted by having one person walk on the soil around the tree 20 times.

Tree Stabilization System Installation

A new TSS was installed for every repetition and no system was used more than once. To precisely orient the TSSs at installation, a reference line was strung from the pillar to the tree.

The stabilization system was then installed, in the predetermined orientation (direction 1 or 2), according to the manufacturers directions. Great care was taken to ensure consistent installation and symmetrical positioning, relative to the pillar, of stabilization systems among repetitions.

Irrigation

It was determined that soil moisture could potentially impact performance of the TSSs. To minimize the influence of soil moisture and maintain its consistency, the soil surrounding each plot was brought to field capacity. To determine the field capacity of the site's soil, the Alachua County soil survey was used. The soil survey provided data on soil characteristics specific to the geographic location of the site. Calculations were made using the soil survey data, giving the amount of water to add [881 L (200 gal)] and the amount of time to wait (6 hours) to bring a 2.4 m x 2.4 m (8 ft x 8 ft) plot, 1.2 m (4 ft) deep, around each tree to field capacity for testing. The actual amount of water added [1321.5 L (300 gal.)] was 1.5 times the actual amount needed [881 L (200 gal.) x 1.5=1321.5 L (300 gal.)], ensuring soil saturation consistency. Water was applied thru watering stations made from PVC and low-profile sprinkler heads, and were controlled by battery-operated timers (Fig. 2-8). Water was supplied to the watering stations through 2.5 cm (1 in) diameter polyethylene irrigation tubing. Each tree was pulled 6-6.5 hours after the end of the irrigation cycle.

Pulling Test

The center of mass was used as the attachment point on the trunk for the pulling tests. To calculate center of mass, six trees were randomly selected from a group of 100 to estimate the center of mass. Branch diameter was the average of two perpendicular diameter measurements taken on every primary branch [>2.5 mm (0.1 in)] just beyond the collar; the distance from the media surface to just below the branch collar was recorded for all primary branches. Average branch diameter was used to calculate the cross-sectional area of each primary branch; these areas were summed for all primary branches on the tree. The center of mass on each of the six trees was estimated as the point on the trunk where half the branch cross-sectional area was above and half was below. Mean center of mass [1.9 m (6.2 ft)] was calculated by averaging center of mass from all six trees (Table 2-1). The mean center of mass value was the height at which all trees were connected to the winch and pulley system for pulling tests.

All trees were pulled within two days of planting to minimize the effects of rooting-in. Trees were pulled by hand cranking the winch (1 revolution/sec) until the inclinometer on the top of the root ball measured 20°, or the tree broke. Maximum force measured by the load cell up to 20° from horizontal was used for comparison among the systems. Once all 20 trees in the block were pulled, the next block was planted.

Statistical Rationale

The general linear model (GLM) of the Statistical Analysis Systems software (SAS Ver. 9, SAS Institute, Inc., Cary, NC) was used to analyze data. A two-way analysis of variance (ANOVA) was used to compare differences between the TSSs (treatments). Treatment means were compared for statistical similarities using Duncan's multiple range test. To test the significance of direction of pull interaction for the TSSs (trt x dir), Tukey-Kramer adjustments for multiple comparisons were used ($P = 0.05$).

Table 2-1. Center of Mass Data

Sample Tree	Center of Mass[z] (mm^2)	Center of Mass Height[y] [m (ft)]
1	23271	1.8 (5.8)
2	1913	1.8 (5.9)
3	3089	2.1 (7.0)
4	2108	1.7 (5.7)
5	2571	1.9 (6.4)
6	3445	2.1 (6.8)
Mean Center of Mass Height:		1.9 (6.3)

[z]Half of total cross-sectional area of all primary branches. [y]Height whereupon cross-sectional area of primary branches is equal above and below.

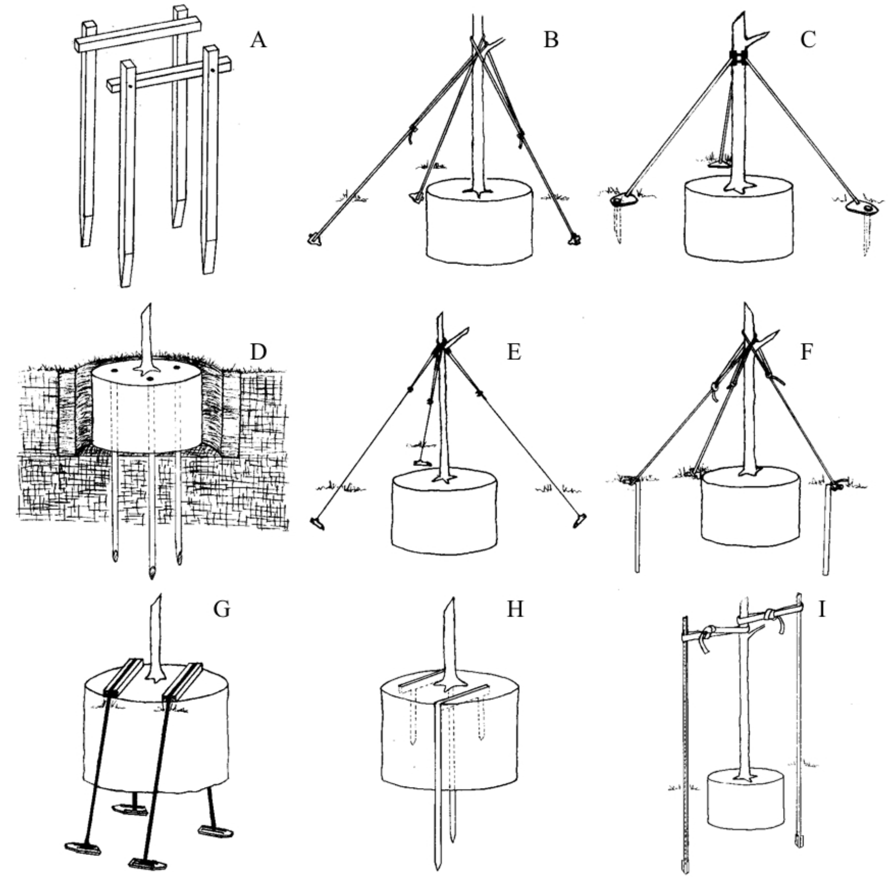


Figure 2-1. Tree stabilization system illustrations. A) 2x2s, B) Arborbrace®, C) Brooks Tree Brace®, D) Dowels, E) Duckbill®, F) Rebar & ArborTie®, G) Terra Toggle , H) Tree Staple , and I) T-stakes.

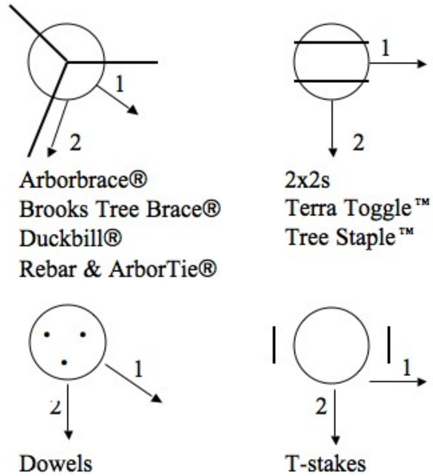


Figure 2-2. Diagram showing the two directions each TSS was pulled during the pulling tests. There is no significance to the designation of direction 1 and 2 for the TSS, they were determined arbitrarily.

Figure 2-3. Load cell positioned in-line of pulling.

Figure 2-4. Photograph showing the inclinometer fixed on the root ball via the fabricated mounting plate.

Figure 2-5. Data acquisition system and laptop computer.

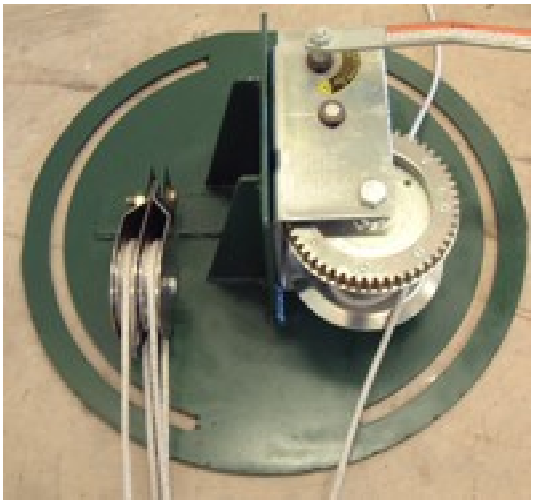


Figure 2-6. Winch and pulley fastened to the fabricated mounting plate.

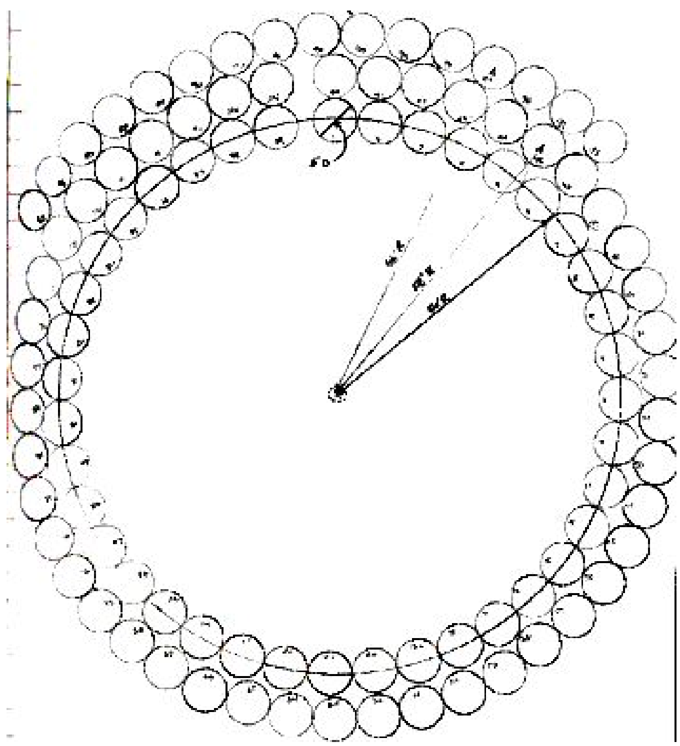


Figure 2-7. Diagram illustrating the location of the experimental plots, centered around the concrete pillar.

Figure 2-8. Watering station made of PVC and low-profile sprinkler heads, shown here with the Arborbrace® stabilization system.

CHAPTER 3
RESULTS AND DISCUSSION

Data Analysis

Results from the ANOVA (Table 3-1) showed that force to failure differed among TSSs (Table 3-2, P $\leq$.0001). However, analysis also revealed that direction of pull was not statistically significant for any individual stabilization system tested (Table 3-3). Therefore, stabilization systems were compared averaged over both directions (Table 3-2). TSS effectiveness was determined to be the amount of force it was able to withstand.

The Terra Toggle™, Brooks Tree Brace®, and 2x2s withstood the largest forces of all stabilization systems tested. There was no difference in force to failure between the Terra Toggle™ and Brooks Tree Brace® (Table 3-2); and these two systems had the highest force to failure means of all systems tested. The amount of force the 2x2s withstood [181 kg (399 lb)] was statistically similar to Brooks Tree Brace® [212.7 kg (468.9 lb)], but less than Terra Toggle™ [233.7 kg (515.3 lb)].

Of the three guying systems, the rebar & ArborTie® withstood the most amount of force and was statistically no different than the 2x2s. The Duckbill® [129.8 kg (286.2)] was also similar to rebar & ArborTie® [143.6 kg (316.7 lb)] but not the 2x2s. Force to failure on the third guying system, Arborbrace® [99.5 kg (219.3 lb)], was statistically similar to the Duckbill®, but lower than rebar & ArborTie®.

The Tree Staple™, dowels, and T-stakes mean force to failure values were statistically no greater than controls [29.5 kg (65 lb)]. The Tree Staple™ [67 kg (147.8 lb)] and dowels [61.4 kg (135.4 lb)] were also statistically similar to the Arborbrace®. The T-stakes [50.3 kg (111 lb)] TSS had the lowest force to failure mean of all the systems tested.

Mode of Tree Stabilization System Failure

From observation during the pulling tests, it appeared as though system design and direction of pulling both influenced system failure. During testing the above ground TSSs, including Brooks Tree Brace® and the three guying systems, and would typically only allow the tree to bend above where they attached to the trunk. Trunk bending was minimal for the T-stakes, the other above ground stabilization system, because it could not provide enough support to do so.

Ease of installation appeared to correlate with the effectiveness of the root ball stabilization systems. Of the four root ball stabilization systems tested the 2x2s and the Terra Toggle™ were the two most labor intensive and time consuming systems to install, but they were very effective at supporting trees during testing . The dowels and the Tree Staple™ took the least amount of effort and time for installation of all the systems tested, they were also statistically no different than no staking at all (control).

The Terra Toggle™ did not break any trees in half but cracked the trunk at the base on the side that was in compression (facing direction of pull). None of the Terra Toggle™ earth anchors came out of the ground during testing and the plastic strapping never broke. The strapping would usually slice into the lumber supports approximately 15.2 cm (0.5 in), preventing it from sliding off the top of the wood. Occasionally, as tension on the straps increased, a lumber support would become displaced, and the strapping would cut into the root ball. This did not appear to impact strength of the system.

Brooks Tree Brace® in direction 2 (Fig. 2-2) broke all five trees at the same spot, just above where the rubber pads attached to the trunk. Brooks Tree Brace® in direction 1 (Fig. 2-2) was also unique; as the tree was being pulled the front two braces in the direction of pull acted as lever arms because they were tightly secured around the trunk, and began to lift the root ball out of the ground. The root ball remained above ground level even after the tension from the pulling rope was removed. The plastic plate connecting the rubber pads to the metal brace showed the only visible signs of damage from pulling tests, and was deformed beyond possible further use three times.

The 2x2s in direction 1 (Fig. 2-2) broke two trees approximately 15.2 cm (6 in) from ground level. The most common mode of failure for 2x2s in direction 1 was when the vertical braces were forced up on the tension side (opposite direction of pull) as the root ball rotated. This reduced the amount of downward force applied to the top of the root ball, allowing it to rotate more freely. The 2x2s in direction 2 (Fig. 2-2) failed when the horizontal brace on the side of the direction of pull broke as the trunk of the tree was forced down into it.

The Duckbill® stabilization system failed seven times because the wire cable snapped between the U-bolt cable clamp and the soil surface, and the anchors came out of the ground three times. The U-bolt cable clamps that came with the Duckbill® failed to secure the cable under high forces, allowing the cable to slip periodically despite being tightened adequately.

The Arborbrace® guying system was similar to the Duckbill® conceptually. However, the Arborbrace® anchors never came out of the ground like the Duckbill® anchors, and the ArborBrace® polypropylene guylines never snapped the way the Duckbill® cable guylines snapped. ArborBrace® failed when the guylines stretched and cut through the soil, allowing the tree to bend more and the root ball to rotate. The ArborBrace® cam-lock metal tensioning buckle securely fastened the guyline and no slipping occurred. The difference between the Duckbill® and ArborBrace® was that the amount of force it took to stretch ArborBrace®'s polypropylene guylines was less than the breaking strength of Duckbill®'s wire cables. Therefore, as the tree was pulled ArborBrace®'s polypropylene guylines stretched, allowing the root ball to rotate. Meanwhile, the wire cables of Duckbill had little or no stretch but suddenly broke, or the anchor was pulled out of the ground.

The third guyline system tested was rebar & ArborTie®. Rebar pulled out of the ground and/or bent as the tree was pulled during each repetition, but the ArborTie® never snapped. From pulling test observations, it appeared as though the rebar slipped out of the ground more in direction 1 than direction 2. Pulling the rebar & ArborTie® stabilization system in direction 1 provided the tree with the support of only one guyline, whereas resistance was supplied by two guylines when pulled in direction 2. Rebar & ArborTie® in direction 2 broke one tree [299.3 kg (659.8 lb)] at the tie-in point on the trunk.

The dowels root ball anchoring system failed to provide enough resistance to adequately support the tree, given the relatively low mean force to failure mean. Trunk bending was minimal during the dowel stabilization system pulling tests. As the trees were pulled, the root ball typically slipped along the dowels and several of the wood dowels broke as well. The exact number of dowels that broke as a result of the pulling tests is unknown because retrieval of the dowels without further damage was not feasible.

The Tree Staple™ root ball stabilization system sliced into the top of the root ball approximately 15 cm (6 in) deep as trees were pulled in direction 1. The horizontal section of the Tree Staple™, connecting the shorter prong penetrating the root ball and the longer prong driven into the backfilled soil, was 0.6 cm (0.25 in) wide where in contact with the root ball. The Tree Staple™ sliced through the root ball because the narrow horizontal section, having a low amount of surface area, concentrated forces from pulling to a confined area, like a blade. Bending of Tree Staple™ braces from pulling tests in direction 1 was minimal. All Tree Staple™ braces from pulling tests in direction 2 were bent to some extent, and roughly half were bent beyond possible future use. Bending occurred along the horizontal section of the Tree Staple™ because it was torqued, with the two prongs being forced in opposite directions during pulling tests.

The T-stake stabilization system provided the least amount of resistance from the pulling tests and system failure was consistent, regardless of direction, based on observations made in the field. Pulling tests forced the T-stakes through the soil towards the direction of pull. The narrow edge of the steel T-stake [0.6 cm (0.25 in) thick] concentrated pulling forces on a small surface area, allowing the T-stake to move almost freely with the tree. No problems were encountered with the polyester webbing support straps as they adequately attached the T-stakes to the tree trunk.

Table 3-1. Analysis of variance table.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	19	2560441.824	134760.096	13.96	<.0001
Error	80	772189.319	9652.366		
Corrected Total	99	3332631.143			

R-Square	Coeff Var	Root MSE	Force Mean
0.768294	36.87037	98.24646	266.4645

Source	DF	Type I SS	Mean Square	F Value	Pr > F
trt	9	2216074.335	246230.482	25.51	<.0001
dir	1	53692.721	53692.721	5.56	0.0208
trt*dir	9	290674.768	32297.196	3.35	0.0016

Table 3-2. Force to failure for each tree stabilization system.

Stabilization System	Mean[z] Force [kg (lb)]
Terra Toggle	233.7 (515.3)a[y]
Brooks Tree Brace®	212.7 (468.9)ab
2x2s	181.0 (399.0)bc
Rebar & ArborTie®	143.7 (316.7)cd
Duckbill®	129.8 (286.2)de
Arborbrace®	99.5 (219.3)ef
Tree Staple	67.0 (147.8)fg
Dowels	61.4 (135.4)fg
T-stakes	50.4 (111.0)g
Control	29.5 (65.0)g

[z]Average of two pulling directions (N=10). [y]Means with the same letter are not significantly different (P≤0.05, Duncan's MRT).

Table 3-3. Force to failure by direction for each tree stabilization system.

Stabilization System (Direction)	Mean[z] Force [kg (lb)]
Brooks Tree Brace® (2)	260.9 (575.3)a[y]
Terra Toggle™ (1)	247.0 (544.5)ab
Terra Toggle™ (2)	224.9 (495.9)ab
2x2s (1)	212.2 (467.8)ab
Rebar & ArborTie® (2)	193.3 (426.2)abc
Brooks Tree Brace® (1)	164.4 (362.4)abcd
Duckbill® (2)	158.7 (349.8)abcd
2x2s (2)	149.8 (330.2)bcde
Duckbill® (1)	101.0 (222.6)cdef
Arborbrace® (1)	99.7 (219.8)cdef
Arborbrace® (2)	99.3 (218.9)cdef
Rebar & ArborTie® (1)	94.0 (207.2)cdef
Tree Staple™ (2)	86.1 (189.9)def
Wood dowels (1)	61.8 (136.3)def
Wood dowels (2)	61.0 (134.4)ef
T-stakes (2)	50.4 (111.1)f
T-stakes (1)	50.3 (110.9)f
Tree Staple™ (1)	48.0 (105.9)f
Control	29.5 (65.1)f

[z]Average of one pulling direction (N=5), except the control (N=10). [y]Means with the same letter are not significantly different (P≤0.05, Duncan's MRT).

CHAPTER 4
CONCLUSIONS

Of the three superior performing systems tested, Brooks Tree Brace® required the least amount of time to install but was also the most expensive. The Terra Toggle™ was the cheapest but the recommended installation method required a water source to drive the anchors. And lastly the 2x2s could be made "in-house" but installation was the most labor intensive. The rebar & ArborTie®, Duckbill®, and Arborbrace® guying systems were similar, considering cost and their effectiveness relative to the other systems tested, and installation was time consuming but not labor intensive. The dowels, T-stakes, and Tree Staple™ were among systems that required the least amount of effort to install and, probably not coincidentally, the three least effective systems.

Tree Stabilization System Design Improvement Suggestions

2x2s

Although the 2x2s root ball anchoring system was one of the top three stabilization systems tested, there are some features that could be modified to make the system more effective. When the 2x2s system was pulled in direction 1 the vertical braces, driven into the backfilled soil along the side of the root ball, on the windward side were prone to slipping up and out of the soil. Slipping of 2x2s vertical braces could be reduced by using longer [> 1.5 m (5 ft) sections of lumber. Driving the vertical braces further away from the tree into undisturbed soil, as opposed to the looser backfilled soil, would also reduce brace slipping and increase the effectiveness of the stabilization system. Driving of the vertical braces for the 2x2s system was time consuming and extremely labor intensive. Mechanization of vertical brace driving would reduce the amount of human effort and time needed, and thus cost, to install the 2x2s stabilization system, making it more suitable for applications involving multiple installations.

Arborbrace®

The Arborbrace® stabilization system was the least effective of the three guying systems tested because the polypropylene guylines stretched when placed under a load. The only other two components of the system, the plastic anchors and the cam-lock tension buckles, never contributed to system failure during testing. Replacement of the polypropylene guylines with a material with less capacity for stretching, such as the polyester webbing type of material used with the T-stakes stabilization system, would greatly increase the force to failure for the Arborbrace® system.

Brooks Tree Brace®

The Brooks Tree Brace® stabilization system was a very effective system, especially in direction 2, as all trees tested in this direction broke before root ball rotation or system failure. Brooks Tree Brace® effectively supported trees during testing by firmly securing the trunk allowing minimal movement, which has been shown to negatively impact tree height (Leiser et al. 1972; Mayhead and Jenkins, 1992), taper (Svihra et al. 1999), and root growth (Stokes et al. 1995), at least in the short term. In this regard, Brooks Tree Brace® stabilization system could be improved for the wellbeing of the tree by not having the rubber pads attach directly to the trunk, allowing some degree of natural trunk movement.

Dowels

The dowels root ball stabilization system was among the three most ineffective systems tested because the smooth surface of the wooden dowels failed to provide enough resistance against the root ball. Replacing the dowels with rebar or larger diameter [≥ 2.5 cm (1 in)] dowels would increase stability while still maintaining a relatively low cost and minimal amount of effort to install the system. Another improvement that could be made to the dowels stabilization system would be to attach a flange at the end of the dowel on top of the root ball to further prevent the root ball from slipping.

Duckbill®

Failure of the Duckbill® stabilization system was fairly inconsistent as the wire cables snapped during some repetitions, while anchors pulled out of the ground or U-bolt cable clamps failed on other occasions. Individual Duckbill® anchors were rated at 135 kg (300 lb) capacity, which was close to the observed mean force to failure of 129.8 kg (286.2 lb) from the pulling tests. System failure inconsistency between repetitions could be attributed to individual components of the system having similar load capacities. This suggests that upgrading to the Duckbill® (Model 68DTS) rated for trees up to 15 cm (6 in) in caliper would provide more support than the system used in the experiment (Model 40DTS) rated for trees up to 7.5 cm (3 in) in caliper. As for design improvements, the provided U-bolt cable clamps were difficult to use because of their small size, and could be replaced with hardware that is easier to handle and less prone to cable slipping. Lastly, the Duckbill® wire cables wrap around the trunk through sections of plastic tubing, which closely resembles the “wire-in-hose” method now known to be ineffective at protecting the trunk from narrow attachment materials. To prevent girdling, wider straps should be substituted for the wire cable through tubing provided with the Duckbill® system.

Rebar & ArborTie®

The rebar & ArborTie® stabilization system was the most effective guying system tested. The system showed consistency between directions in the way it failed, with the rebar slipping out of the ground every time. Rebar was driven straight down into the soil, which was shown to be the orientation that required the most amount of force for extaction (Smiley et al. 2003). The

ArborTie® was never the cause of failure for the guying system. Therefore, improvements to the rebar & ArborTie® stabilization system should concentrate on improving the holding capacity of the rebar in soil. Use of rebar greater than 9.5 mm (0.375 in) in diameter would require more force to extract from the soil and increase the strength of the stabilization system.

Terra Toggle™

The Terra Toggle™ stabilization system was the most effective at supporting trees during the pulling tests of all root ball anchoring systems. The biggest drawback was that the recommended installation method required the use of a water-jet driving tool, necessitating a nearby water source with adequate pressure. The alternative installation method to the water-jet driving tool was the use of a drill and auger bit, which would have required special equipment including a drill and auger bit, as well as a nearby power source for the drill. Improvements to the Terra Toggle™ stabilization system could be made to eliminate the need for such specialized tools for installation, making the system more practical for applications in remote areas. Simplifying the installation process would also make the system more appealing to those without the required installation tools at their disposal. Installation could be simplified by using a driving rod to drive the anchors into the soil, similar to installation of the Arborbrace® and Duckbill® anchors.

Tree Staple™

The Tree Staple™ root ball stabilization system cut into the top of the root ball when pulled in direction 1. Increasing the surface area of the horizontal section of the Tree Staple™ would prohibit the system from slicing into the root ball, the downside would be that visibility of the system would increase which may be undesirable depending on the application. Pulling tests in direction 2 on the Tree Staple™ caused bending of the horizontal section of the system.

Reinforcing this portion of the stabilization system would require more force to damage the Tree Staple™, making it a more effective TSS. The Tree Staple™ could also be improved by increasing the number of Tree Staples™ to stabilize the root ball so that all sides of the tree are supported equally.

T-Stakes

The T-stakes stabilization system was the most ineffective system tested, providing minimal support for the tree. From observation direction did not seem to influence method of failure, as the system supported the tree so inadequately that it appeared as though no support was provided by the system during pulling tests. Sandy soil at the test site could have contributed to the inability of the T-stakes to remain upright, however this effect would be constant for all systems tested. The T-stakes would likely provide more support in more compact soil than what was observed in the site's sandy soil. The polyester webbing support straps never attributed to the failure of the T-stakes stabilization system. The T-stake stabilization system could be improved by using longer [≥ 2.5 m (8 ft)] stakes so that more of the support was in the ground. The T-stakes could also be replaced with lodgepole pine polls for added rigidity.

Limitations of the Research

The most limiting factor of the research is that the results of the experiment are restricted to the TSSs that were tested, and only for trees that are of similar size as those used in the experiment. In addition, site-specific soil characteristics further limit the applicability of the results.

Another limitation of this experiment was the low sample size that was available to test for interaction of treatment and direction (N=5). Aided by a larger number of repetitions (N=10), significant differences between treatments were found. Field observations of TSS mode of failure differences by direction of pull suggests that significant differences could be proven experimentally, given a large enough sample size (N=10).

Future Research

Correlating Pulling Forces to Wind Speeds

Results of the pulling test produced force versus angle values that were used as a reference to compare systems included in the study. However, making inferences on the effectiveness of a particular stabilization system becomes difficult when wind speed is the preferred unit of measure. In order to make the results more practical, and comprehendible to industry professionals, it is essential that pulling force be correlated to wind speed. To correlate wind speed to force experimentally, another experiment needs to be conducted.

Blowing trees, installed with the nine stabilization systems, with a wind machine would produce wind speed versus angle results. Using the wind speed versus angle curve generated from the blowing test, and the force versus angle curve generated from the pulling tests, a third curve of force versus wind speed could be created. The force versus wind speed curve would be extremely useful allowing for the conversion of pulling forces to wind speeds, making results from the pulling tests more useful.

Creation of a force versus wind speed curve would be beneficial for a number of reasons. First, future pulling test results could immediately be converted into terms that translate more easily into the vocabulary of the general public, making results from pulling tests more useful. It is s a challenge reporting results, such as the effectiveness of a TSS, as a force when wind speed is a more appropriate unit of measure. The ability to convert pulling force to wind speed would also be beneficial because blowing tests could be substituted with pulling experiments. With confidence that results can be readily and accurately converted to the desirable units, the integration of pulling and blowing tests of trees would also save resources, as one person is capable of conducting a pulling test at a reasonably small cost, whereas blowing tests require multiple people and expensive machinery with very limited availability.

Over time, as blowing and pulling tests are integrated, the correlation between force and wind speed will become more accurate and precise. Replacement of blowing tests with pulling tests would not be appropriate for every circumstance, as some experiments would still require the use of a wind machine. For example, testing for differences in trunk movement based on pruning dose or treatment would necessitate a blowing test because the response is dependant on the crown. Pulling tests aren't capable of replacing blowing tests when the crown of a tree is involved with treatments because pulling tests are only able to test trunk movement. However, pulling tests are a great way to simulate wind when testing for differences in trunk movement as an effect of anything other than the crown.

Testing of Additional TSS and Different Tree Sizes and Species

The results of this experiment provide a catalyst for possible future research projects. A continuation of this experiment using different TSSs would be extremely valuable, as would a continuation of this study using the same systems on larger caliper trees. Testing other stabilization systems on similarly sized trees as those used in this experiment, using the same experimental protocol, would allow future results to be compared to the results of this experiment.

Further Testing on Influence of Direction

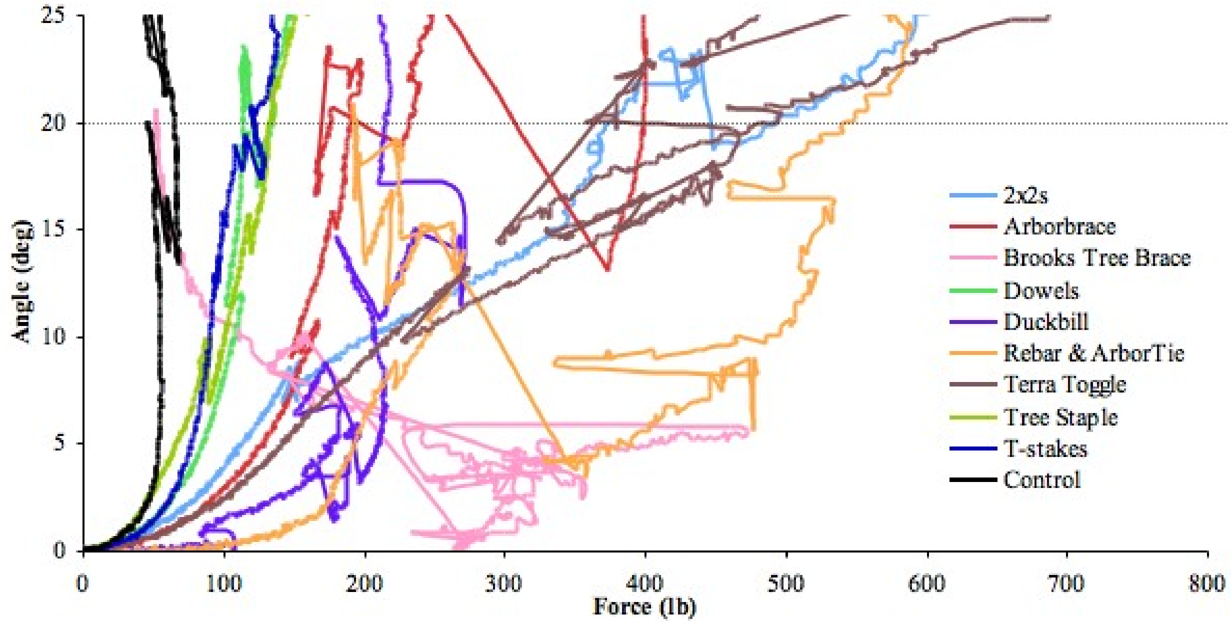
It is difficult to predict the direction that wind will blow from. It would therefore be preferred to install a TSS capable of withstanding equal amounts of force, regardless of direction. This supports the argument for further testing on the significance direction of pull has, if any, on the ability of TSS to sustain force loading. A retrospective power analysis (RPA) is useful for planning an experiment to determine the number of repetitions needed to find a significant difference, based on the results of previous research. An appropriate sample size will have a power value that approaches one while an insufficient sample size have a power value that approaches zero. Running a computer generated RPA (Lenth, R. V. 2006) shows that within a direction, five repetitions per TSS was insufficient (power = 0.301), and that ten (power = 0.917) would be more adequate to find significant differences, A continuation of this experiment aimed specifically at testing the significance of direction of pull, including a smaller number of TSS and at least ten repetitions per direction, would allow its influence to be proven experimentally. Studying the significance direction of pull has would also be valuable for determining weaknesses of TSSs and ways to improve them.

Final Recommendations

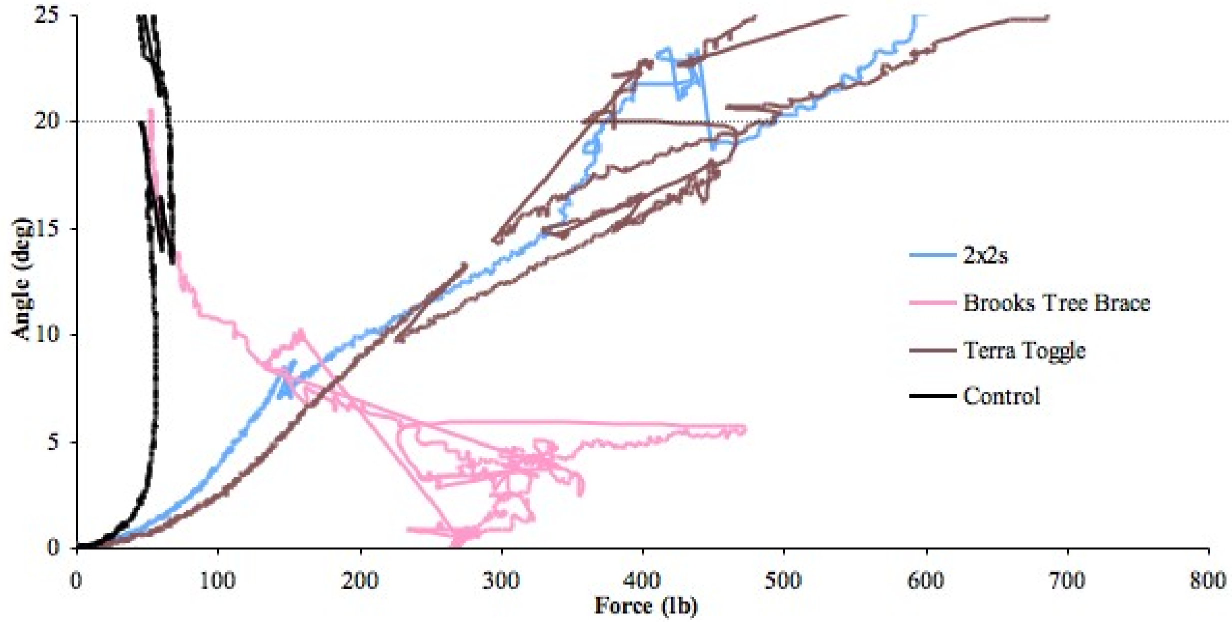
It has been shown numerous times that the natural process of trunk feathering promotes proper tree structure development, including trunk taper and caliper (Burger et al., 1991; Harris et al., 1976; Leiser et al. 1972). It can therefore be concluded that root ball anchoring TSS provide better performance over aboveground TSS because they allow the most amount of trunk feathering. Thus, it is recommended that the Terra Toggle™ and the 2x2s provide the most effective performance of all TSS tested because these TSS are root ball anchoring systems that withstood the most amount of force during pulling tests. However, occasionally the trunk of a tree is unable to stand upright without support and an aboveground TSS is necessary. Installation of the Brooks Tree Brace® or a guying TSS is recommended for aboveground applications because these TSS withstood the most amount of force of all aboveground systems tested.

It is important to remember that installation of a TSS should ideally be done only when necessary because of the negative influence on physiological growth and development. This is perhaps more applicable to aboveground TSS than root ball anchoring TSS because they allow the least amount of trunk feathering. This results in a dilemma; TSS should only be installed when a tree requires support to maintain an upright trunk, however aboveground TSS hinder further trunk development and the recommended root ball anchoring TSS do not provide the required support to the trunk. This dilemma can be avoided by installing only appropriate plant materials, which includes trees that are able to maintain an upright trunk, so that a root ball TSS can be installed if desired.

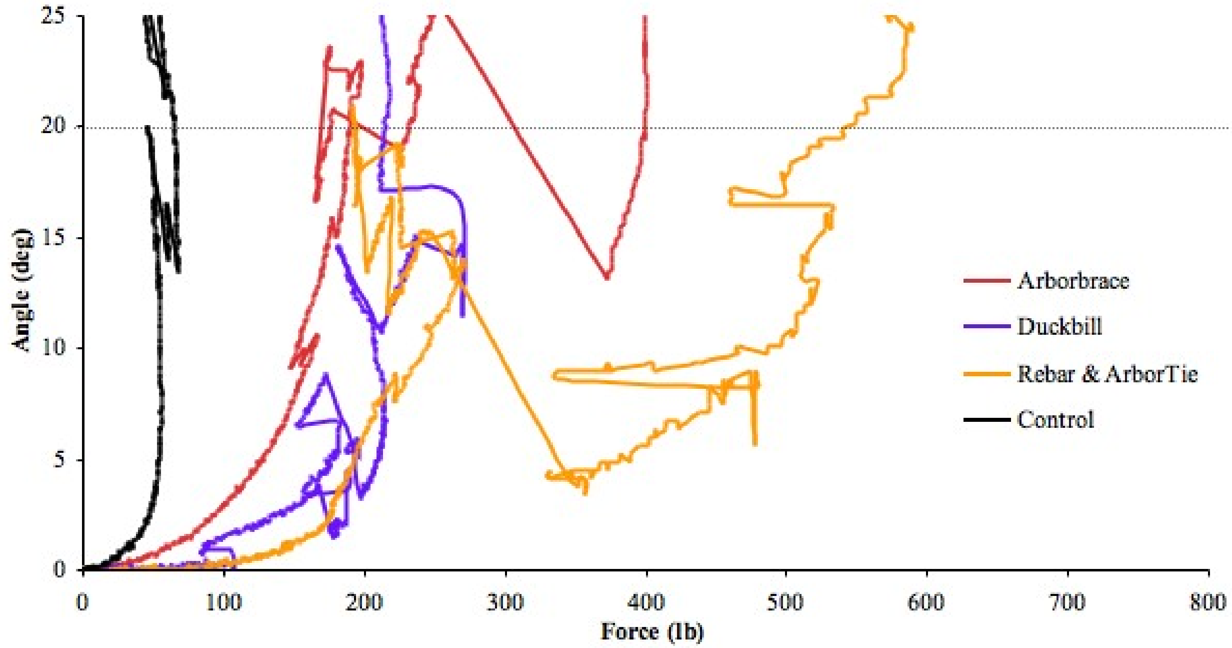
APPENDIX
TSS FORCE VS. ANGLE GRAPHS



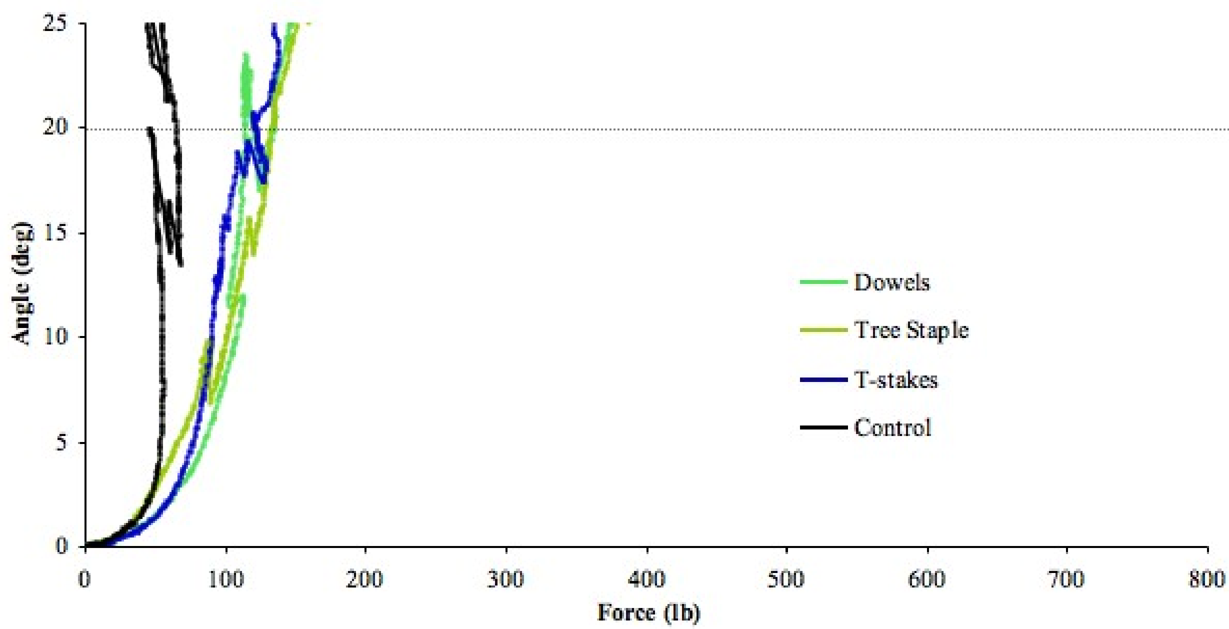
Force vs. angle graph of all tree stabilization systems tested plus the control. Each line represents an average of ten repetitions.



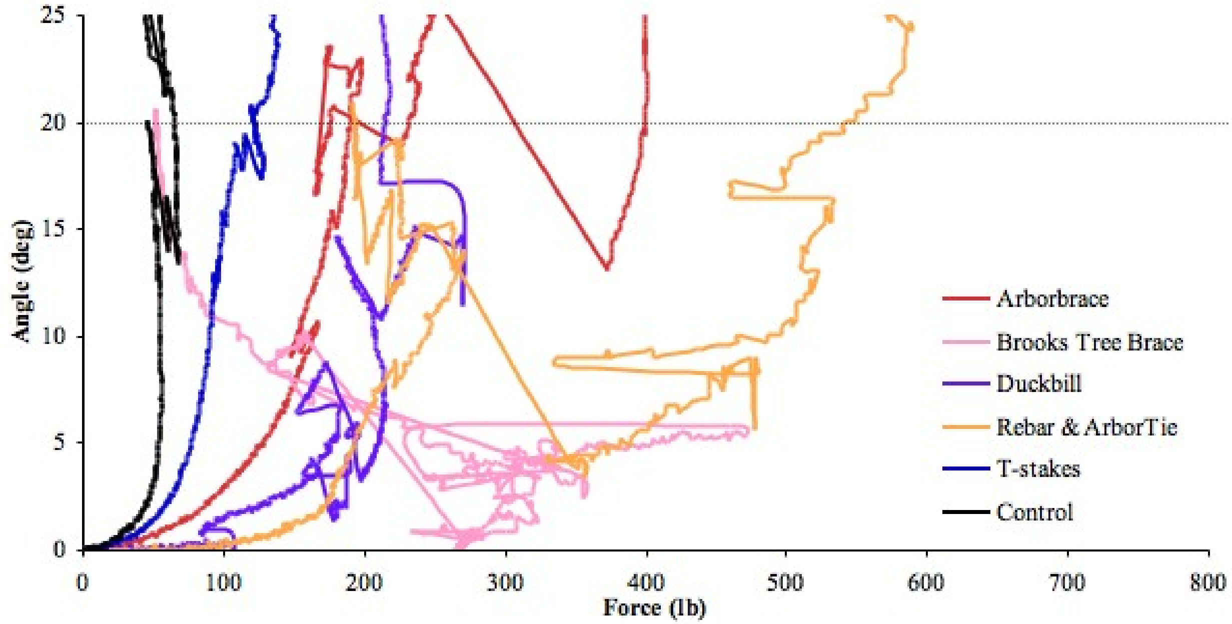
Force vs. angle graph of the three most effective tree stabilization systems tested plus the control. Each line represents an average of ten repetitions.



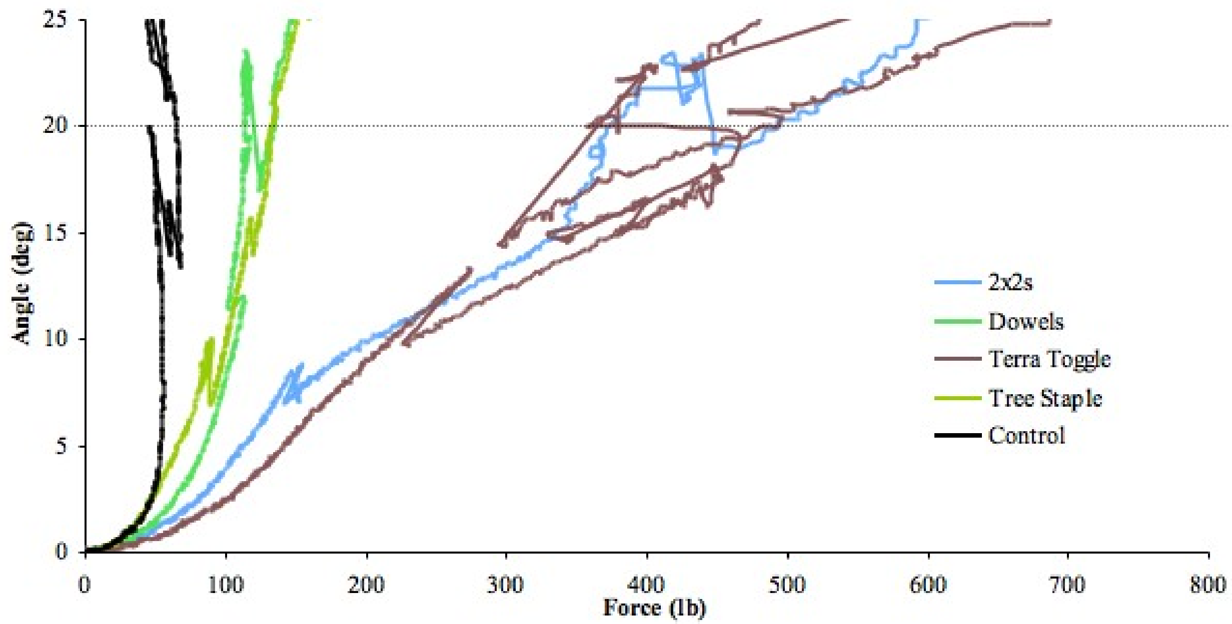
Force vs. angle graph of the three guying systems tested plus the control. Each line represents an average of ten repetitions.



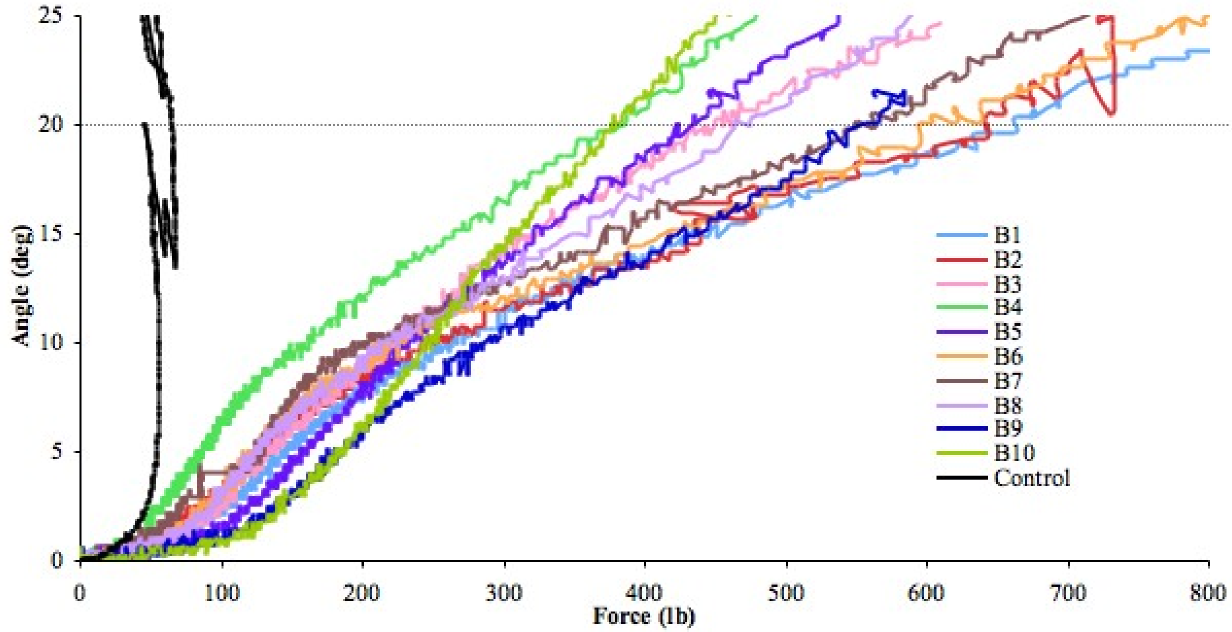
Force vs. angle graph of the three least effective tree stabilization systems tested plus the control. All treatments shown are statistically similar to the control. Each line represents an average of ten repetitions.



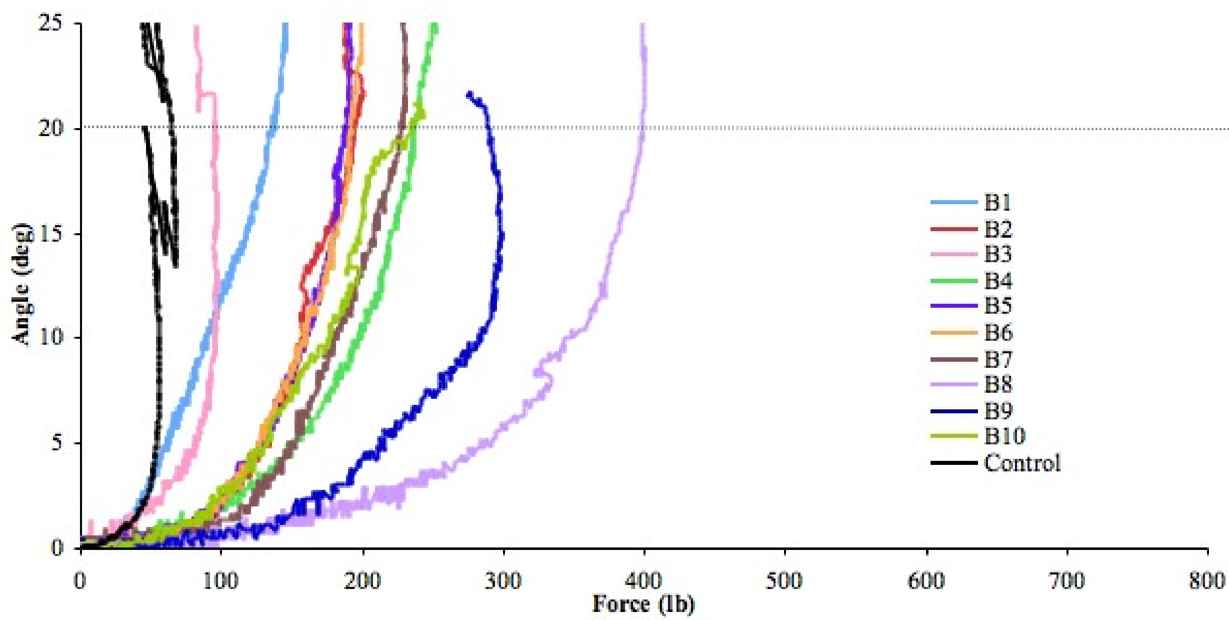
Force vs. angle graph of the five aboveground tree stabilization systems tested plus the control. Each line represents an average of ten repetitions.



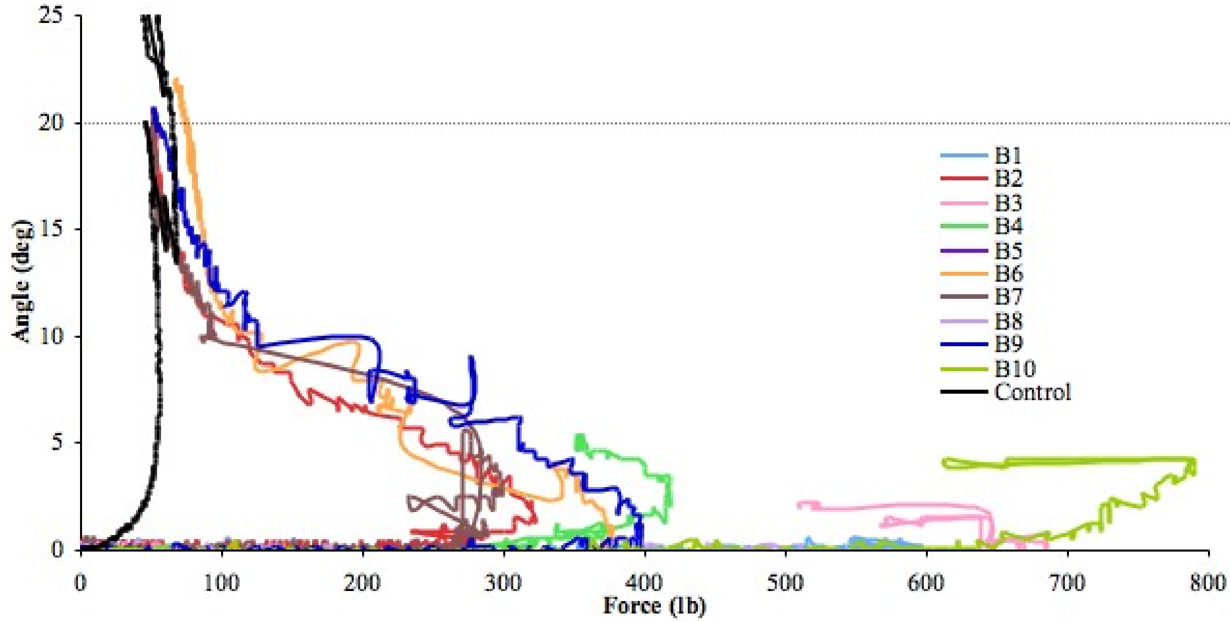
Force vs. angle graph of the four root ball stabilization systems tested plus the control. Each line represents an average of ten repetitions.



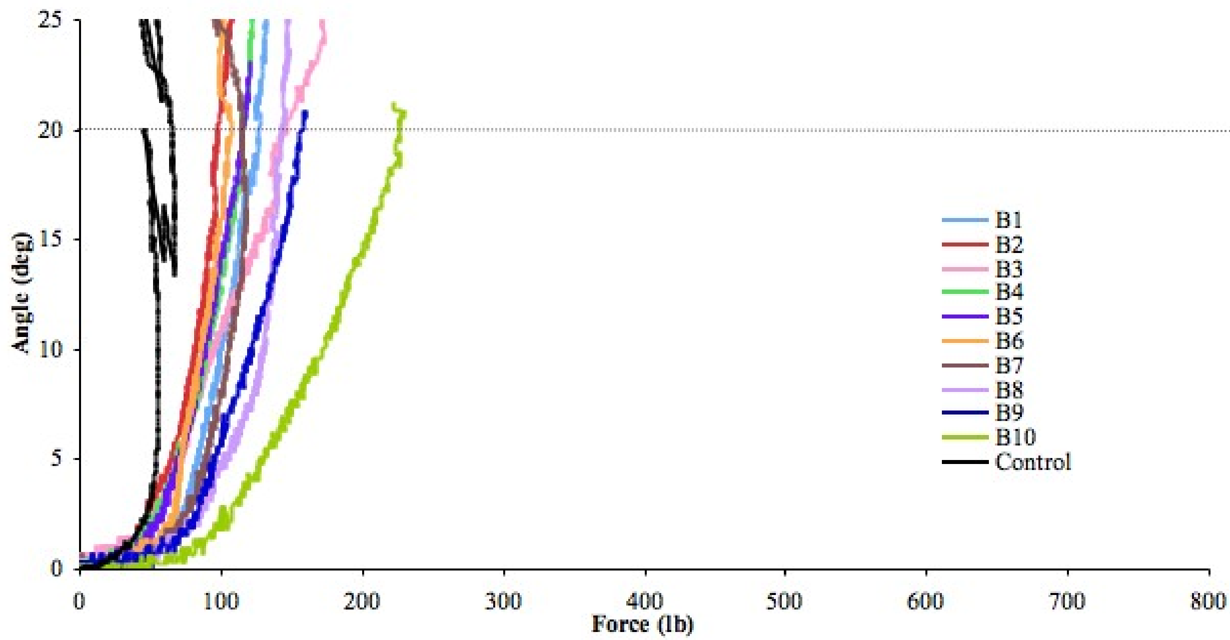
Force vs. angle graph of the 2x2s stabilization system ten repetitions, plus the control average.



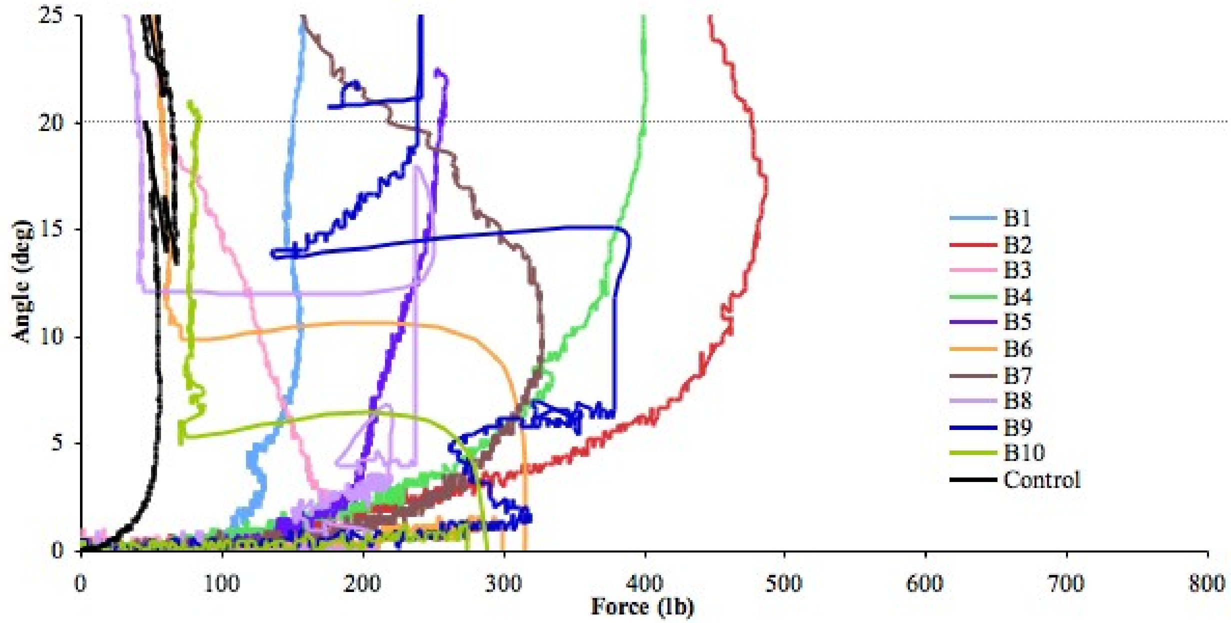
Force vs. angle graph of the Arborbrace® stabilization system ten repetitions, plus the control average.



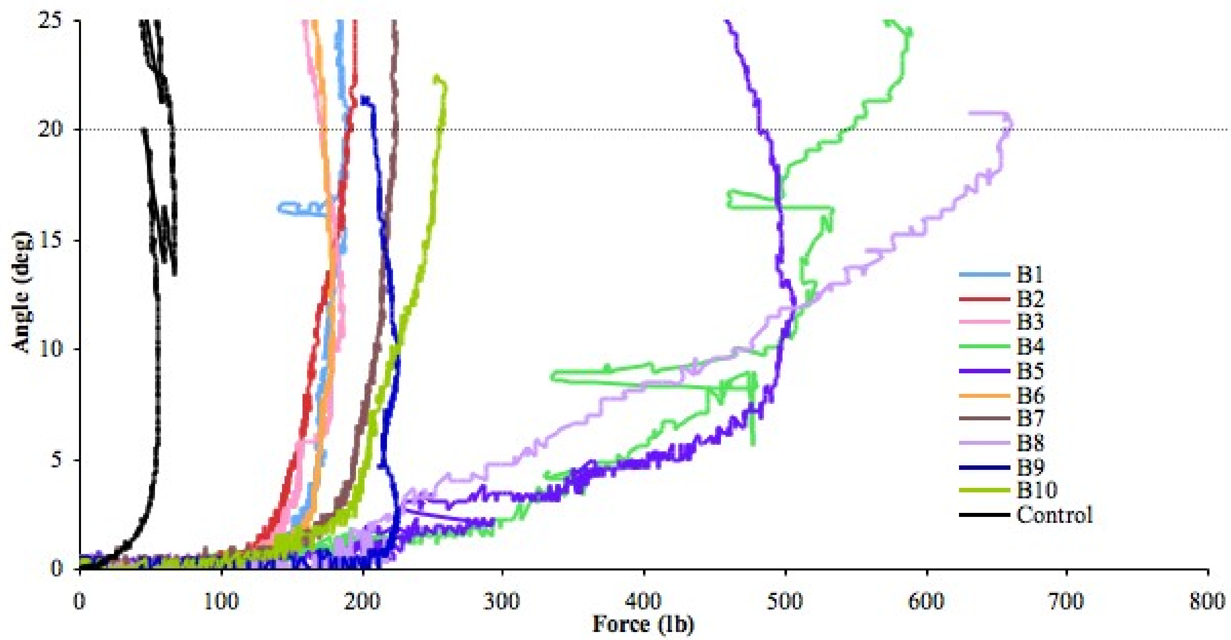
Force vs. angle graph of the Brooks Tree Brace® stabilization system ten repetitions, plus the control average.



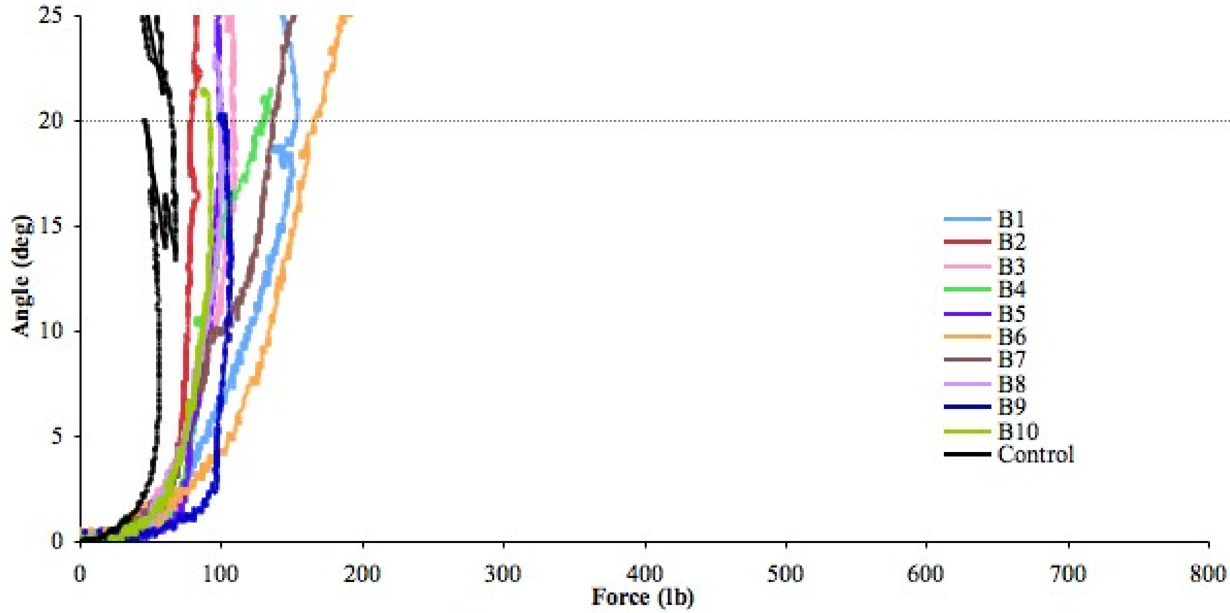
Force vs. angle graph of the dowels stabilization system ten repetitions, plus the control average.



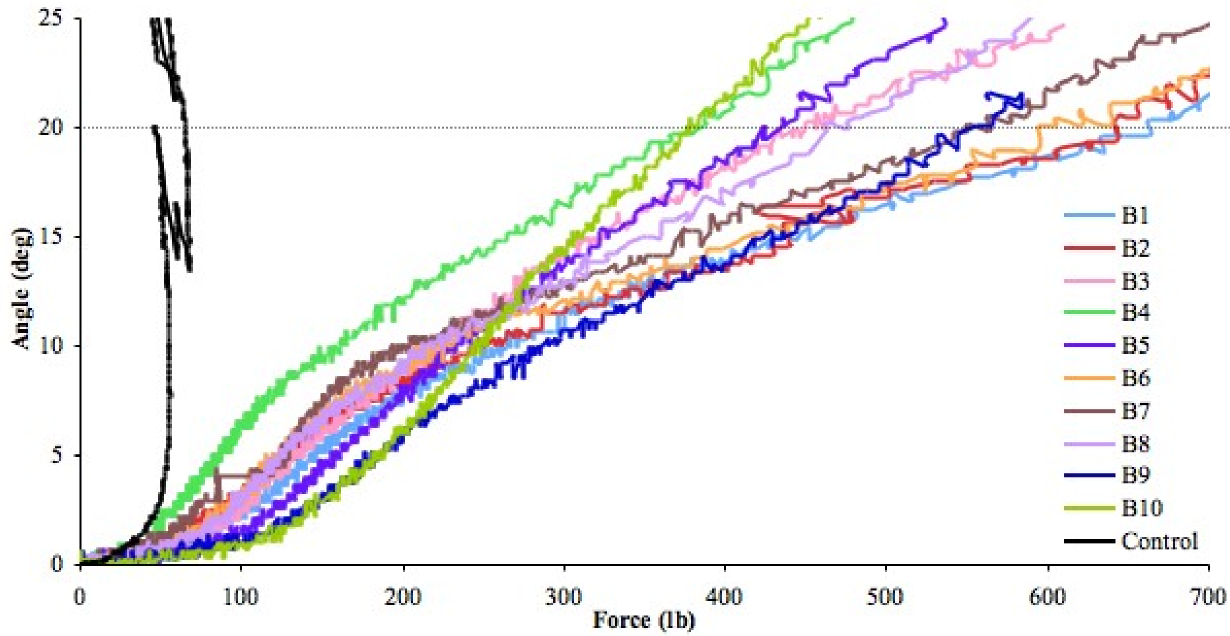
Force vs. angle graph of the Duckbill® stabilization system ten repetitions, plus the control average.



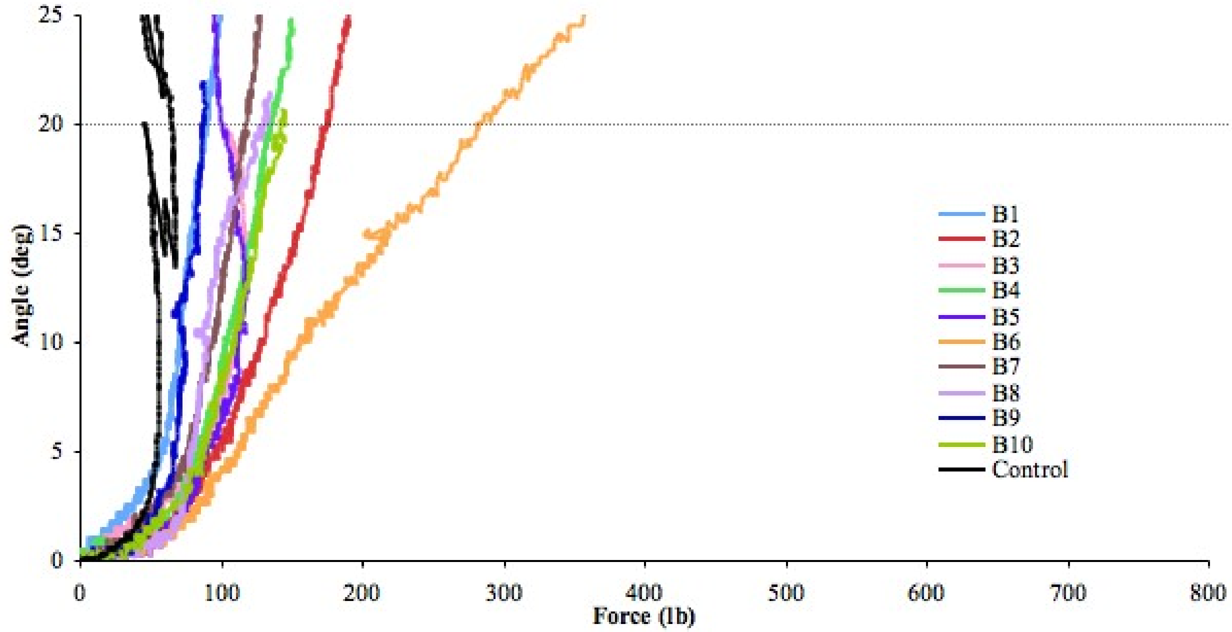
Force vs. angle graph of the rebar & ArborTie® stabilization system ten repetitions, plus the control average.



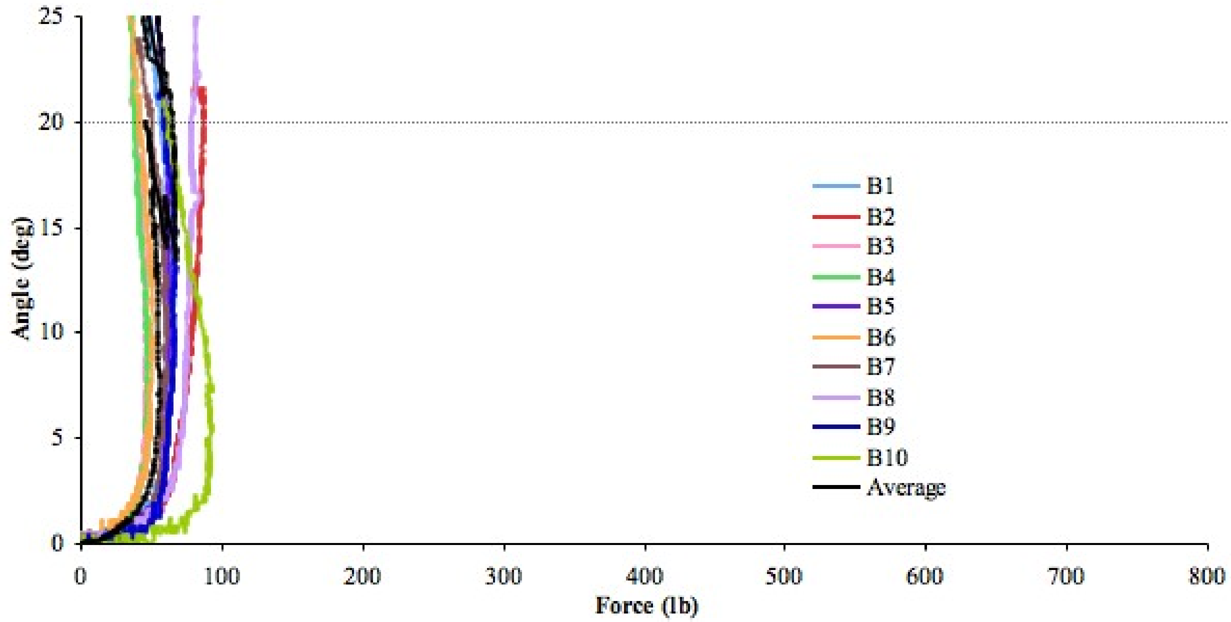
Force vs. angle graph of the T-stakes stabilization system ten repetitions, plus the control average.



Force vs. angle graph of the Terra Toggle™ stabilization system ten repetitions, plus the control average.



Force vs. angle graph of the Tree Staple™ stabilization system ten repetitions, plus the control average.



Force vs. angle graph of the ten control repetitions, plus the average.

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BIOGRAPHICAL SKETCH

Ryan J. Eckstein was born and raised in Clearwater, Florida. He earned a Bachelor of Science degree in environmental science and policy from the University of South Florida and began working in production and sales in the ornamental horticulture industry. He later accepted a graduate assistantship position in the Environmental Horticulture Department at the University of Florida, where he began working with Dr. Gilman toward a Master of Science degree. In August 2008, he received his Master of Science degree in horticultural science. While with the university, Eckstein presented his thesis research at the Great Southern Tree Conference (2005 & 2006), Trees Florida (2006), Roots Plus Growers Conference (2005), and the 83rd Annual ISA International Conference (2007). He was also the first recipient of the John P. White Annual Memorial Scholarship awarded by the Florida Chapter of the ISA (2006).