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A Review of Factors That Affect the Static Load-Bearing Capacity of Urban Trees

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Abstract. Over the last 30 years, researchers have begun to employ biomechanical principles to understand the stability of urban trees. This review concentrates on literature pertaining to trees in temperate urban landscapes, but also includes relevant work from other disciplines and climates as appropriate. The load-bearing capacity of a tree depends on its size and shape and the material properties of its wood. As the trunk and branches increase in diameter, their load-bearing capacity increases. Material properties (e.g., moduli of elasticity and rupture) describe intrinsic wood stiffness and strength, which influence deflection under load and load-bearing capacity, respectively. In wood, material properties vary in relation to a variety of factors, including the direction of loading, moisture content, and tree age. Wood decay reduces a tree's load-bearing capacity. Although practitioners have developed guidelines to assess its effect, existing guidelines should be investigated, refined or rejected on the basis of rigorous scientific testing. Static load tests have been developed to address this question, as well as investigate the likelihood of uprooting, which accounts for up to 35% of tree failures. While much has been learned, many questions remain about the static load-bearing capacity of trees growing in urban landscapes.

Key Words. Allometry; Biomechanics; Decay; Literature Review; Material Properties; Modulus of Elasticity; Modulus of Rupture; Soil-Root Plate; Static Load Tests.

Biomechanics is the study of biological organisms from a mechanical perspective. Several monographs describe the literature on plant biomechanics (Niklas 1992; Vogel 1996; Niklas and Spatz 2012), and biomechanical investigations of plants are common in many basic and applied sciences (e.g., botany, ecology, evolutionary biology, forestry, and horticulture). Plant biomechanics seeks to understand how growth and development leads to a structurally stable plant that can withstand environmental and gravitational loading over its life span. Plant biomechanics applies well-known mechanical theories that were developed for engineering structures that use uniform materials, like steel and concrete. When these theories are applied to biological materials, some simplifying assumptions are used that may not always apply to the architecture of plants (Niklas 1992; Niklas and Spatz 2012). Authors readily acknowledge this limitation. Common and acknowledged simplifying assumptions include:

- Using equations that assume wood in living trees is homogeneous and isotropic, like engineering materials (e.g., steel or concrete) (Niklas 1992; Niklas and Spatz 2012)
- Using equations that are valid only for small deflections when regular geometric shapes are loaded (Niklas 1992; Niklas and Spatz 2012)
- Using static equations for wind load analysis (Hale et al. 2010)

Using simplifying assumptions is often necessary in the absence of more sophisticated analytical and measuring techniques or in the absence of knowledge of the species or situation in question. The geometry and material properties of engineered structures do not substantially change over time or in response to external stimuli, excepting material degradation due to fatigue or structural failure. In stark contrast, biological structures adapt material properties and morphology over their life span and in response to external stimuli

(Jaffe 1973; Telewski and Jaffe 1986a; Telewski and Jaffe 1986b; Jaffe 2002; Telewski 2006; Dahle and Grabosky 2010b), as well as changing due to formation of different kinds of wood (e.g., callus or woundwood) (Kane and Ryan 2003).

The focus of this review is arboricultural biomechanics. Researchers primarily reviewed studies published in the last 30 years but included older sources and studies from other disciplines where appropriate. Biomechanical investigations in applied disciplines, like arboriculture and forestry, study the applied loads and load-bearing capacity of a tree; the focus for this review is on the latter. Loads and structural responses are often categorized as "static" or "dynamic," describing the duration of the load or structural response. Static implies a relatively long duration, where loads might be considered relatively constant (Peltola 2006). Self-weight and loads due to snow or ice are considered static loads. Dynamic implies a relatively short duration; the magnitude and direction of the load and structural response change quickly (James et al. 2006). Wind-induced tree sway is an example of dynamic load and structural response. While trees must continuously resist self-weight, Niklas (2000) suggested that wind is likely the most common cause of tree failure. In a companion manuscript (James et al. 2014), researchers reviewed the biomechanics literature that focused on tree dynamics.

This review focuses on urban trees in temperate climates and the intrinsic biomechanical factors that affect their static load-bearing capacity. This approach was chosen because arborists use biomechanics to estimate the likelihood of tree failure when assessing tree risk. Researchers organized the manuscript into the following sections: material properties of wood (strength, elasticity, ontogenetic changes); tree form (allometry and growth response); decay and the loss in load-bearing capacity; assessing the load-bearing capacity using static load tests; and root architecture and stability of the soil-root plate.

MATERIAL PROPERTIES

The material properties of wood determine its load-bearing capacity. The two most commonly measured material properties of wood are the elastic modulus (E) and modulus of rupture (MOR), which describe a material's stiffness and maximum load-bearing capacity, respectively (Table 1).

Wood is an anisotropic material, and its material properties are different in the longitudinal, radial, and tangential directions (Figure 1). An example of how Young's modulus (E) values vary can be found with balsa wood: in three directions are longitudinal (in compression), E_L = 3.12 GN/m^2; radial, E_R = 0.144 GN/m^2; and tangential, E_T = 0.0468 GN/m^2 (Niklas 1992). Wood from trees growing in temperate climates is typically twice as strong in tension as compression in the longitudinal direction (Kretschmann 2010). Gordon (1991) suggests that there can be a difference as high as three or four times.

Depending on the line of action of a force, different types of stress develop in trees, including tension, compression, bending, shear, and torsion. The material properties of wood can be complex to describe (Table 1), and sometimes wood is considered to be orthotropic, with E and MOR varying longitudinally, tangentially, and radially. Differences in material properties can influence the failure mode of a tree, which has implications for assessing the likelihood of failure. Niklas (2002) points out that the literature on plant materials rarely provides elastic moduli for each direction, and studies frequently refer to a single E value. Unless otherwise stated, this literature review refers to longitudinal E and MOR values.

E and MOR are often directly proportional to wood density in stems and branches (van

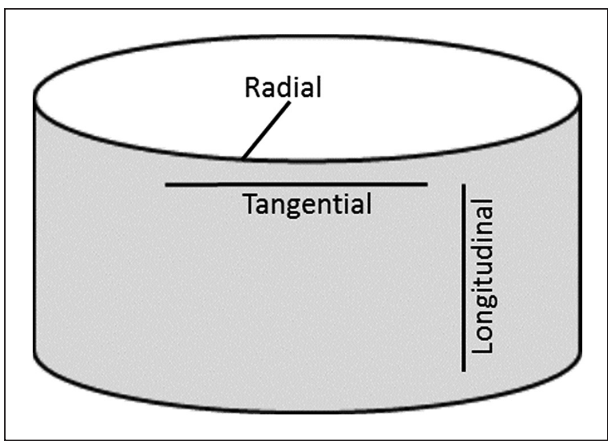

Figure 1. An example of Young's modulus (E) of wood (balsa) in three directions. Longitudinal (in compression) E_L = 3.12 GN/m^2, radial E_R = 0.144 GN/m^2 and tangential E_T = 0.0468 GN/m^2 (adapted from Niklas 1992).

Table 1. Mechanical terms used in tree biomechanics adapted from Hibbeler (2005), Burgert (2006), and Kretschmann (2010).

Member	A structural component of a tree that is under consideration; e.g., a stem, a branch, a root.
Force	Force is a quantity that causes a mass to accelerate. F = m * a (Newton's second law of motion). A force may act in many ways, e.g., Pulling – tensile force Pushing – compressive force Sliding – shearing force
Modulus of Rupture (*MOR*)	A measure of maximum load-bearing capacity of a member, before it fails. For wood, *MOR* is usually measured in a bending test, so *MOR* may be taken as the bending strength of wood. *MOR* is an acceptable measure of strength, yet is not a true measure as the calculation is only valid in the elastic limit.
Modulus of Elasticity symbol (*E*)	A measure of a member's resistance to elastic deformation, which is typically determined from the slope of the line in the linear portion of the stress-strain diagram. Also called Young's Modulus, or stiffness of the material.
Flexural stiffness symbol (*EI*)	The resistance of a member (usually a beam) in bending. Stiffness depends on a material's modulus of elasticity (*E*) and its size and shape, which determines its moment of inertia (*I*).
Moment	A twisting or bending that causes a rotation about a point. Usually considered as a combination of a force acting at a distance to cause rotation about a point. For example, a wind force on a tree canopy pushes at a height (distance) above the base of the trunk to create a moment at the base and the tree tends to rotate about this point. Moments have the same unit as torque (e.g., N*m).
Moment of inertia symbol (*I*)	A geometrical property of a beam or member. Moment of Inertia, (also called second moment of area) reflects the cross-sectional size and shape of a beam. It must be specified with respect to a selected axis (see Figure 6).
Moment of inertia (circle); I_{Circle}	$0.25\pi r^4$ for bending if the member is circular.
Moment of inertia (ellipse); $I_{Ellipse}$	$0.25\pi r{y}^3 r_x$ for bending about the x-axis if the member is elliptical.
Shear strain symbol (γ)	Change in angle between two line segments that were originally perpendicular.
Strain symbol (ε_{normal})	Change in length divided by original length, expressed as a percentage or fraction. Strain can be: positive – elongation under tension, or negative – contraction under compression.
Strength	A measure of the ultimate stress in a member, often measured at the point of failure.
Stress symbol (σ)	A measurement of force per unit area $\sigma = F/A$
Axial stress symbol (σ_{Axial})	Stress created during axial loading.
Bending stress symbol (σ_{Bend})	Stress created during bending.
Torsional stress symbol (τ)	Stress created during a twist.

Gelder et al. 2006; Anten and Schieving 2010; Niklas and Spatz 2010; Onoda et al. 2010). Specific gravity (SG) is the density of a material relative to the density of water and is often considered as a surrogate measure for wood properties, including *E* and *MOR* (Williamson and Wiemann 2010; Spatz and Pfisterer 2013). Use of SG as a surrogate measure, however, must be considered carefully to avoid introducing error (Williamson and Wiemann 2010).

The literature describing wood properties is extensive, reflected in numerous textbooks, some of which have multiple editions (Panshin and De Zeeuw 1980; Haygreen and Bowyer 1982; Kollman and Cote 1984; Bodig and Jayne 1993). Most of this work, however, was undertaken on clear, defect-free specimens to understand wood properties of lumber used in engineered structures. Reference books provide mean values of wood properties for many species (Jessome 1977; Lavers 1983; Wessolly and Erb 1998; Kretschmann 2010). Applying these values to living trees presents challenges because of the inherent variability due to a wide range of natural and anthropogenic causes (Zobel and van Buijtenen 1989). Even using material properties of branches and trunks of urban trees, as Lundström et al. (2007) suggest, presents problems. Branches and trunks failed at smaller values of *MOR* measured on specimens taken from the branches (Kane 2007) or trunks (Kane and Clouston 2008).

Material properties of wood vary with age, growing conditions, genetics, moisture content (MC), and location in an individual (Figure 2). For example, variation in mean values of *E* and *MOR* ranges from 16% to 60% (Clair et al. 2003; Woodrum et al. 2003; Dahle and Grabosky 2010b; Kretschmann 2010). Wood properties measured on "dry" specimens [i.e., moisture content less than fiber saturation point (FSP)—between 30% and 35%] are typically greater (Figure 2) than when measured on "green" wood (i.e., MC > FSP) (Cousins 1976; Cousins 1978; Cannell and Morgan 1987; Kane 2007; Kane and Clouston 2008; Kane 2014).

Values of *E* and *MOR* are not uniform within an individual tree. Small specimens are taken from a trees to determine material property values and these specimens are typically (i) defect-free and straight-grained, and (ii) sampled from near the base of the trunk (ASTM 2014). Assuming such values apply to wood higher along the trunk or branches is problematic because *E* and *MOR* decrease axially with trunk height (Milne and Blackburn 1989; Yoshida et al. 1992; Niklas 1997a; Niklas 1997b; NIklas 1997c; Brüchert et al. 2000; Rowe and Speck 2005; Spatz et al. 2007; Lundström et al. 2008; Speck and Burgert 2011) and branch length (Cannell and Morgan 1987; Dahle and Grabosky 2010b). *E* also increased branch nodes to help bear loads in twigs (Caringella et al. 2014).

Wood properties are also influenced by cambial age, and hence, radial position in the cross section (Figure 3). On smaller branches, the greater proportion of juvenile wood can also influence *E* and *MOR*. The effect of juvenile wood may not apply to large branches, except in the case of topped or pollarded trees, which often produce large watersprouts with a large proportion of juvenile wood (Dahle et al. 2006). Juvenile wood is located near the pith and is produced early in the life of a trunk or branch, but the transition to mature wood is usually gradual, occurring over several years. The cells tend to be shorter with thinner cell walls than in mature wood (Read and Stokes 2006). Juvenile wood typically has lower values of *E* and *MOR* than mature wood (Lindström et al. 1998; Lichtenegger et al. 1999; Evans et al. 2000; Pruyn et al. 2000; Plomion et al. 2001; Thibaut et al. 2001; Groom et al. 2002a; Groom et al. 2002b; Mott et al. 2002; Woodcock and Shier 2002; Woodrum et al. 2003; Pilate et al. 2004; Kern et al. 2005; Read and Stokes 2006; Dahle and Grabosky 2010b). *E* was found to be up to 75% greater in mature wood than in juvenile wood of *Acer platanoides* (Dahle and Grabosky 2010b). This makes sense, as more flexible distal tree parts facilitate crown reconfiguration in the wind, increasing safety factors of smaller trees (Niklas 2002), and more rigid proximal tree parts resist self-weight and wind-induced bending and torsional moments (Dahle and Grabosky 2010b). As wood matures, the radial variation in *E* decreases in both trunks (Clair et al. 2003) and branches (Dahle and Grabosky 2010b).

Values of *E* and *MOR* for ornamental or introduced species are not always included in references (Jessome 1977; Lavers 1983; Wessolly and Erb 1998; Kretschmann 2010). Assuming values of wood properties from other regions may be problematic, given the effect of growing conditions on wood properties. Wood properties can also vary between cultivars and hybrids (Pruyn et al. 2000; Kern et al. 2005), which are not usually included in references (Jessome 1977; Lavers 1983; Wessolly and Erb 1998; Kretschmann 2010). Some work has modeled *E* and *MOR* in trunks (Lundström et al. 2008) and branches (Dahle and Grabosky 2010b), but very little work has considered the values for root wood (Coutts 1983; Pratt et al. 2007) and woundwood (Kane and Ryan 2003).

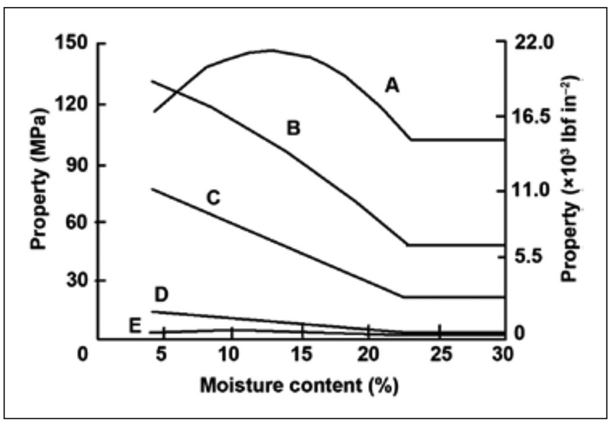

Figure 2. Effect of moisture content on wood strength properties. A, tension parallel to grain; B, bending; C, compression parallel to grain; D, compression perpendicular to grain; and E, tension perpendicular to grain. Courtesy of Kretchmann (2010).

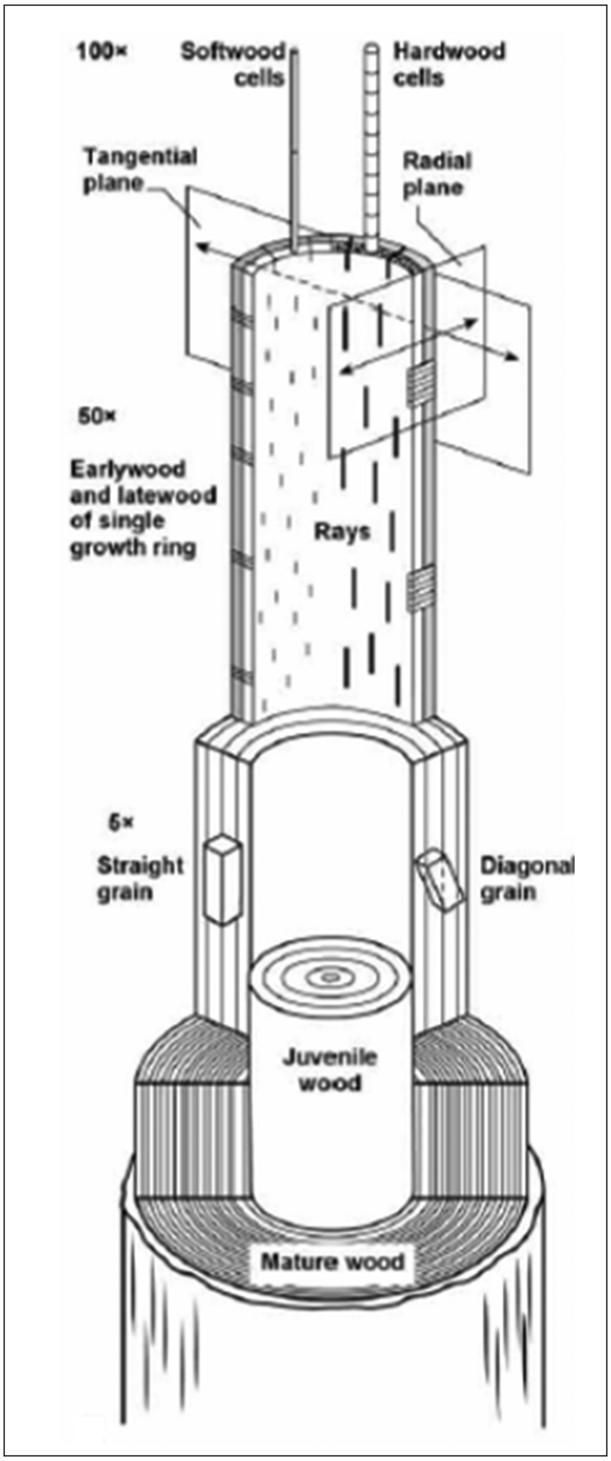

Figure 3. Depiction of a tree stem or branch, denoting the location of juvenile and mature wood. Courtesy of Wiedenhoeft (2010).

In summary, the two most commonly reported material properties in the tree biomechanics literature (*E* and *MOR*) are integral to understanding the static load-bearing capacity of trees. They are positively correlated with wood density and SG, and increase as MC decreases below FSP. In mature wood, *E* and *MOR* tend to be greater than in juvenile wood, which allows distal branch tips to bend more freely, while the stiffer and stronger wood at the base of trunks and branches provides the necessary structural support.

TREE FORM

The static load-bearing capacity of trees is also governed by their form—specifically, the length and diameter of the trunk and branches and the direction of loading (Figure 4). Length of trunks and branches affects the bending and torsional moments (also known as "torques") induced by loads. When subjected to the same load, longer branches and trunks endure greater torques than shorter ones. The load-bearing capacity of trunks and branches is related to their cross-sectional area and second moment of area, which is also known as the moment of inertia (or simply "*I*"). The effect of diameter on the load-bearing capacity of trunks and branches is non-linear: cross-sectional area and *I* are proportional to the square and fourth power, respectively, of diameter.

Since *I* is proportional to the fourth power of diameter, material farthest from the centroid of a cross-sectional area contributes disproportionately to *I*. Most of the "flexural stiffness" (the product of *E* and *I*, see Table 1) of a trunk or branch is conferred by the outer growth rings, even though it represents only a small proportion of trunk diameter (Mencuccini et al. 1997; Niklas 1997a; Niklas 1997b). Flexural stiffness, which affects deformation and deflection in a branch or trunk, may be most efficiently increased through increases in diameter, even if the wood is less stiff (Lavandjara and Müller-Lanndau 2010).

Investigators often consider the ratio of length to diameter, which is known as the slenderness (length/diameter) of a trunk or branch, and is considered to be a good predictor of stability (Rosłon-Szeryńska and Kosmala 2007). Foresters use slenderness to assess stability of residual trees after harvesting a stand. Slenderness values below 100 are typically considered stable for gymnosperm trees (Petty and Worrel 1981; Cremer et al. 1982; Petty and Swain 1985; Wang et al. 1998). Slenderness may be tied to life history.

Shaded trees often have high slenderness values (Osunkoya et al. 2007; Mattson and Putz 2008; Harja et al. 2012) as they grow to obtain more light, (Jaouen et al. 2010). In contrast, the slenderness of self-supporting *Tachigali melinonii* and *Dicorynia guianensis* trees did not exceed 100, even when staked (Jaouen et al. 2010).

Branch slenderness may also change over time (McMahon and Kronauer 1976; Bertram 1989; Dahle and Grabosky 2010a), approaching 100–125 in young branches that function as solar collectors (Bertram 1989; Dahle and Grabosky 2010a). Slenderness of mature branches, which are primarily structural, decreases when a branch reaches around three meters in length (Figure 5) (Dahle and Grabosky 2010a). Changes in slenderness are governed by a decrease in annual elongation and perhaps an increase in diameter growth. Such changes are important in the survival of neo-tropical rainforest saplings (Coutand et al. 2010) and young *Acer platanoides* branches (Dahle and Grabosky 2010a).

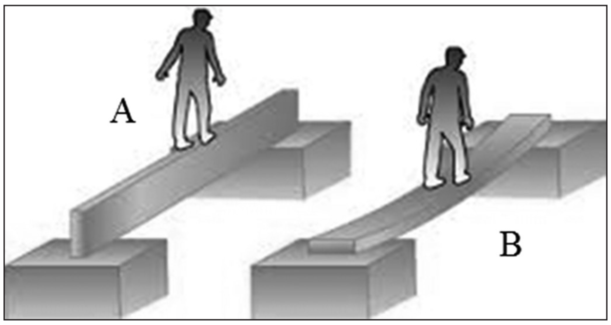

Figure 4. The orientation of a beam influences the resistance to the applied load. Both beams are the same size and subjected to the same loading. The vertically oriented beam (A) has a higher moment of inertia (*I*) parallel to the direction of loading and thus resists bending better than the horizontally loaded beam (B).

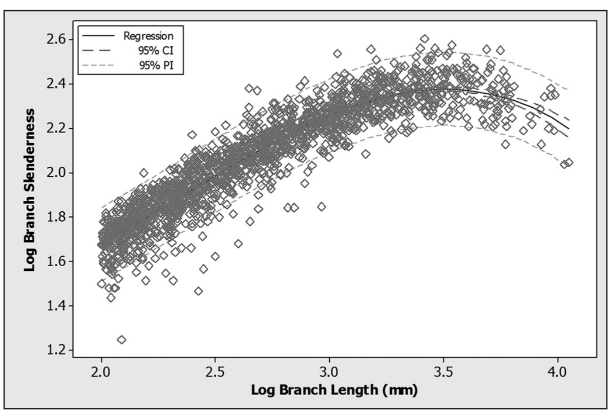

Figure 5. Branch slenderness (length / diameter) increases with length until around 3,000 millimeters. At which point slenderness begins to decrease as the branch transitions from a solar role to a structural role, where the moment of inertia (*I*) becomes more important. Courtesy of Dahle and Grabosky (2010a).

Allometry

Allometry has also been used to explore the relationship between length and diameter of trunks and branches. An early attempt came from Greenhill (1881), who investigated the critical buckling height of a tree, considered as a column, using the following formula:

$$[1] \qquad H_{critical} = C\left(\frac{E}{\rho}\right)^{\frac{1}{3}} r_s^{\frac{2}{3}}$$

where $H_{critical}$ = critical height, C = a proportionality constant (1.26 for cylinders and 1.96 for tapered cones), ρ = wood density, and r_s = radius of the column at its base.

Expanding this work, McMahon (1975) proposed three allometric models to describe the relationship between length (l) and radius (r) of a trunk or branch. In the elastic similarity model, $1 \propto r^{2/3}$; in the geometric similarity model, $1 \propto r^1$; and in the static stress similarity model, $1 \propto r^{1/2}$. Since Dahle and Grabosky (2009) reviewed these "power law" models, researchers limit the current discussion in this review. While no model has been found to fit all trees, a general pattern appears in the literature. The geometric similarity model applies to gymnosperms and understory trees in rainforests (Niklas 1994a; Osunkoya et al. 2007), the static stress model applies to mature pines (Dean and Long 1986; Mäkelä 2002), and the elastic similarity model applies to many angiosperms (King 1986; Rich et al. 1986; Niklas 1994b; O'Brien et al. 1995; King 1996).

Allometry changes over time, and trees might transition through two or all three of the power law models (Niklas 1994a; Niklas 1995; Osunkoya et al. 2007). The transition is due to a mechanical signal (Jaffe 1976; Telewski and Jaffe 1986a; Telewski and Jaffe 1986b; Braam and Davis 1990; Braam 2005; Telewski 2006; Coutand et al. 2008; Chehab et al. 2009; Coutand et al. 2010), such as the amount of longitudinal strain in *Prunus avium* saplings (Coutand et al. 2008) induced by a mechanical perturbation (Pruyn et al. 2000; Rowe and Speck 2005; King et al. 2009) that triggers a genetic or hormonal response. For example, an increase in low frequency loading was found to increase diameter growth in *Pinus taeda* (Telewski 1990) and *Prunus avium* (Coutand et al. 2008), and ethylene production is increased with loading (Telewski 1990; Telewski and Pruyn 1998). Researchers caution that while loading alters growth, little is known on what a typical daily loading regime might look like (Coutand et al. 2010), and therefore the extent of the induced growth response.

There are a number of signals to mechanical perturbation that trigger physiological responses [see Braam (2005) and Chehab et al. (2009) for reviews], yet the principal controller remains elusive. Research suggests that there may be a control at the genetic level (Rowe and Speck 2005), especially with TCH or touch genes (Braam 2005) that have been identified in thigmomorphogenetic responses (Braam 2005; Telewski 2006; Chehab et al. 2009; Coutand et al. 2010).

Modeling Growth

Mechanical stimuli can influence growth (Coutand et al. 2008), and the resulting allometric shifts as trees grow may limit computer models to predict tree growth. Growth models take different approaches, including the pipe model (Berninger and Nikinmaa 1997; Chiba 1998; Mäkelä 2002), fractals (Lindenmayer 1968; Berezovskava et al. 1997), power laws (Dean and Long 1986; King 1986; Rich et al. 1986; Niklas 1994b; O'Brien et al. 1995; Spatz and Brüchert 2000; Sposito and Santos 2001; Mäkelä 2002), or a combination of fractals and power laws (Pluciński et al. 2008), but all have important limitations. For example, many models assume plagiotropic growth, which is appropriate for young gymnosperms (Lindenmayer 1968; Berezovskava et al. 1997; Suzuki and Suzuki 2009), but may be inappropriate for mature conifers or many angiosperms that exhibit orthotropic growth. Neither have models explicitly considered for urban trees, which are of greatest interest to arborists.

Arborists must understand slenderness and allometry of trunks and branches to understand their load-bearing capacity. Non-linear relationships between diameter and load-bearing capacity show its relative importance compared to material properties. Allometry has been shown to change as trunks and branches become larger. Decreases in slenderness appear to be associated with a reduction in elongation, as the trunk or branch assumes primarily a structural rather than a light-gathering role.

DECAY AND STRENGTH LOSS

There are numerous defects that elevate the likelihood of tree failures, such as cavities, included bark, weak branch unions and codominant branches, cracks, splits, and decay (Dahle et al. 2014). While all of these are important, decay has received considerable attention in the literature. Decay is a natural process in which fungi decompose wood (Schwarze et al. 1997; Schwarze et al. 2000) and the loss of wood reduces the load-bearing capacity of a trunk or branch. The biomechanical relevance of decay in trees is important in tree risk assessment. Decay is often cited as a structural defect warranting tree removal (Terho and Hallaksela 2005) and even incipient decay can result in significant decreases in wood properties without significant loss of wood weight (Wilcox 1978; Zabel and Morrell 1992).

As bending stress is greater on the perimeter, the presence of decay does not necessarily indicate or elevate the likelihood of failure. For many years, a starting point to assess whether decay had significantly increased the likelihood of failure was based on Wagener's (1963) observation that conifers growing in the USA's Pacific Northwest region were more likely to fail when the trunk was 70% decayed (or hollow). Wagener (1963) cautioned that his observations should not be extrapolated to other areas or species, but his findings were largely supported by observations of failed and standing trees after a hurricane in North Carolina, USA (Smiley and Fraedrich 1992). Wagener (1963) developed the guideline with a formula into which practitioners could enter the diameter of a decayed (or hollow) cross section (d_i) and the trunk diameter at the point of decay (d_o):

[2] d_i^3 / d_o^3 (Wagener 1963)

Coder (1989) proposed a similar method of assessing the likelihood of failure of trunks with decay:

[3] d_i^4 / d_o^4

Recent work on small conifers questioned the reliability of predicting the effect of decay on trunk strength (Ruel et al. 2010), but the sample was limited to very few trees with more than 50% decay. Equations 2 and 3 show that loss in *I* of these trunks would be relatively small, unless the decay were off center or non-circular. When areas of decay are not concentric, Equations 2 and 3 become less accurate (Kane and Ryan 2004). Smiley and Fraedrich (1992) modified Equation 2 to account for cavities in the trunk; their modification reasonably predicted strength loss due to offset decay (Kane and Ryan 2004). Mattheck et al. (1993) developed a formula to predict failure from a similar criterion based only on the ratio of sound wood thickness (t) and trunk radius (R). As originally presented, their data appeared to show a clear demarcation between standing and failed trees in the low diameter range when $t/R > 0.30–0.32$ (Mattheck et al. 1993; Mattheck et al. 1994; Mattheck and Bethge 2000). With respect to predicting strength loss, this formula also reasonably accounted for offset decay (Kane and Ryan 2004), but the validity of the interpretation of the data has been called into question (Gruber 2008; Schwarze 2008). The value of strength loss at which Wagener (1963) and Smiley and Fraedrich (1992) suggested trees had a greater likelihood of failure was 33%, analogous to Mattheck et al.'s (1993) suggestion. Kane (2014) cut hollows into trees and found evidence to support this convention.

Calculations of *I* are based entirely on geometry, and the formulae reported above assume that cross-sectional areas are circular. For small deviations from a circular area, this assumption would not introduce meaningful error. As areas become more elliptical, however, simply adjusting Equations 2 and 3 to consider elliptical areas is problematic. For an asymmetrical area of decay, Mattheck et al. (1993) conservatively assumed that the area was inscribed in a circle, the radius of which was used to determine t/R. Koizumi and Hirai (2006) numerically calculated section modulus of irregular-shaped decay cross sections using high-resolution images. Ciftci et al. (2014) used a conservative approach to assess strength loss due to irregularly shaped areas of decay.

The adoption of advanced technological methods of measuring decay or determining strength promises to improve the understanding the likelihood of failure due to decay. The effectiveness of technologically advanced decay-detecting devices is still unclear (Nicolotti et al. 2003; Gilbert and Smiley 2004; Deflorio et al. 2008; Wang and Allison 2008; Butnor et al. 2009; Seifert et al. 2010). Improving the accuracy of such devices, as well as the images they produce, would facilitate the numerical evaluation of decayed cross sections.

Although considerable scholarly effort has been expended on evaluating decay-detecting devices [see Johnstone et al. (2010) for a review], the effect of decay on tree failure has been studied much less. Few studies have quantified the effect of decay on the likelihood of trunk (Kane 2014) and branch (Dahle et al. 2006) failure. And while many studies investigating parameters related to the failure of urban trees following windstorms [see Duryea et al. (2007) for a review], far fewer have examined the effect of decay. Gibbs and Greig (1990) found that 32% of failures were associated with decay, but the effect of decay varied among species. In contrast, Kane (2008) observed far fewer failures associated with decay, which was due to the preponderance of uprooted trees. Decay presumably influences the likelihood of branch failure during ice accretion (Hauer et al. 2006), but Equations 2 and 3 indicate that decay must be substantial or eccentric to reduce the load-bearing capacity of a trunk or branch. This is why Kane and Finn (2014) found little evidence that defects increased the likelihood of failure of trees loaded by snow.

Degradation of wood due to decay reduces the load-bearing capacity of a tree, and guidelines to assess the effect of the amount of decay exist. Many studies have focused on the performance of decay-detecting devices, which are often used to assess the extent of decay in a trunk, branch, or root. When assessing the likelihood of failure, however, qualified arborists assess more than just the location and amount of decay. Whether a threshold amount of decay or a reduction in a factor of safety exists for particular species or loading conditions remains an important research question.

STATIC LOAD TEST OF URBAN TREES

Static load tests on trees use a rope or cable attached to the tree to apply a controlled static load to test the strength of the trunk and to estimate the stability of the tree in the ground (Sinn and Wessolly 1989;

Wessolly 1991; Brudi and van Wassenaer 2001; van Wassenaer and Richardson 2009). Static load tests can be used to assess maximum loads at failure in the trunk or root plate by testing to destruction (Peltola 2006; Lundstrom et al. 2007), or can be used to induce non-destructive bending stress (σ) in the trunk in the linear elastic range. During these tests, axial trunk strains (ε) are measured on the marginal fibers of the trunk, and Hooke's Law

[4] $$E = \sigma / \varepsilon$$

is used to extrapolate the critical bending moment of the defective trunk from a guideline value for critical fiber compression (Wessolly 1991; Brudi and van Wassenaer 2001). Clair et al. (2003) stated that wood follows approximately a simple one-dimension Hooke's Law in the longitudinal direction. Critical compression often is determined from previous laboratory tests on wood specimens or assumed from the literature (Jessome 1977; Lavers 1983; Brudi and van Wassenaer 2001; Spatz and Pfisterer 2013), which can confound the analysis. As material properties vary with wood density (Niklas and Spatz 2010), their correlation is believed to remain constant (Brudi and van Wassenaer 2001; Wessolly and Erb 1998). This method may be useful, but the tests made in the elastic range of the wood (i.e., linear and recoverable strains) only allow for predictions of the proportional limit of the stress–strain curve. This point of primary failure serves as a criterion for the safety of urban trees (Detter et al. 2015) despite the fact that presumed plastic strains may occur and increase the bearing capacity of living trees. The ultimate strength of tree trunks may be estimated from the proportional limit, but with limited reliability (Pfisterer and Spatz 2012; Detter et al. 2014).

The static load test (Wessolly 1991) provides a quantitative approach for non-destructively assessing the uprooting resistance of intact or compromised root systems of standing trees. During the test, the root-plate rigidity is measured because it has also been identified as a good indicator for anchorage strength (Ray and Nicoll 1998; Ghani et al. 2009). A close correlation between bending moments required to induce small changes in soil-root–plate inclinations and the maximum resistive moment of the root system generated during the uprooting process has been established for several species (Vanomsen 2006; Smiley 2008; Lundström et al. 2009) and was used to extrapolate failure loads (Lundström et al. 2009; Sani et al. 2012; Smiley et al. 2014). The generalized tipping curve postulated by Wessolly (1994; 1996) has been criticized (Vanomsen 2006), but a similarity in tipping behavior across species with a maximum resistive moment of the anchorage at low angles between two degrees and six degrees has been reported from many studies (Coutts 1986; England et al. 2000; Vanomsen 2006; Lundström et al. 2007). The angle of root–plate rotation at maximum resistance is greater for young trees (Crook and Ennos 1996; Stokes 1999), and likely varies with tree age class (Stokes 1999; Yang et al. 2014). Root architecture (Mickovski and Ennos 2003; Dupuy et al. 2007), and soil structure (Ray and Nicoll 1998; Rahardjo et al. 2013, which are important components to the resistance to uprooting.

The load to cause failure may be lower when a cavity (hollow) extends more than one-third of the axial length of the trunk (Spatz and Niklas 2013). Spatz et al. (1997) suggested that both tangential and longitudinal *E* may be important when modeling hollow plant trunks. Their work considered the giant reed (*Arundo donax*) (Spatz et al. 1997), but the findings transfer to trees with hollow trunks with regard to transverse stresses (Spatz and Speck 1994) and local buckling.

Static load tests have been coupled with full-scale, optical 3D digital image correlation (DIC) measurements of deformations and strains on the surface of branches, trunks, and roots. DIC promises to further study the biomechanics of bending, torsion, and fracture in woody plants. The first results of studies related to urban trees have been published recently [Sebera et al. 2014; Löchteken and Rust 2015; Hesse et al. 2016; Sebera et al. 2016; Dahle (*in review*)].

Much of the work on static load tests has concentrated on the relationship between stress and strain within the proportional limit. While this may be useful when studying primary failure of a tree trunk, researchers should also consider the impact of plastic strains in terms of the load-carrying capacity of urban trees. The adoption of DIC measurements may allow a more in-depth understanding of strains during static load trials.

ROOT FAILURES

As trees grow in size, their root system develops greater strength (Crook and Ennos 1998; Mickovski and Ennos 2003). The ability to support trees depends on root spread (Mergen 1954; Nicoll and Ray 1996; Tobin et al. 2007), root architecture (Coutts et al. 1999; Dupuy et al. 2005; Ji et al. 2007; Khuder et al. 2007; Gilman and Masters 2010; Krause et al. 2014), soil type (Mattheck et al. 1997; Moore 2000; Dupuy et al. 2005; Ji et al. 2007; Ow et al. 2010), and root-plate development (Dupuy et al. 2005; Fourcaud et al. 2008; Lundström et al. 2009; Dupuy et al. 2007; Ghani et al. 2009). While soil conditions (type, texture, and moisture content) are important factors (Day et al. 2010) in root/tree stability, this review is concentrating on the root system's influence on tree stability.

Several models for the mechanics of uprooting are proposed from experimental studies (e.g., Coutts 1986; Wessolly 1996; Ennos 2000). Model simulations have investigated the mechanics of anchorage and uprooting (Dupuy et al. 2007; Rahardjo et al. 2013; Yang et al. 2014). During the uprooting process, the pivot point shifts from the trunk axis to a hinge point on the leeward side of the trunk directly outside the trunk–root joint (Coutts 1986; Ennos 2000) where the greatest strains were measured for buttressed trees (Crook et al. 1997) and young trees with tap roots (Stokes 1999). Compression failure can be found after uprooting in this region as well (Mergen 1954; Coutts 1986).

The most important region appears to be the soil–root plate (Dupuy et al. 2005; Ji et al. 2007; Tobin et al. 2007; Ghani et al. 2009). The soil–root plate includes the first-order roots in the zone of rapid taper, and the soil in which these roots grow, and resists the turning moment and holds a tree in the ground. Ghani et al. (2009) found that turning moment in *Eugenia grandis* was affected by trenching at 0.5–1.0 m, and root depth was the major factor for undamaged trees or if roots were trenched at 1.5 m distance. The depth of the soil–root plate appears to be an important factor in stability (Mickovski and Ennos 2003; Nicoll et al. 2006a; Fourcaud et al. 2008; Ghani et al. 2009), especially in sandy (Dupuy et al. 2005; Ji et al. 2007) or clayey soils (Dupuy et al. 2005).

Using FEM analysis, Ji et al. (2007) reported that lateral roots provided 30% of total anchorage strength in clay soils. The distribution of forces among lateral roots was found to be unequal, with a ratio between 1:2 and 1:3 between leeward and windward *Pinus radiata* roots (Watson 2000), but the author cautioned that measurements on the leeward side were undertaken outside the effective roots zone. Smiley (2008) reported that anchorage strength of *Platanus* × *acerifolia* changed more than 15% if the root plate was trenched at a distance less than twice the trunk diameter, and roughly 35% if lateral roots were severed at the trunk base. During subsequent tests, the side where roots were cut only had an influence when soil was water saturated, but not under dry conditions (E.T. Smiley pers. comm.), again demonstrating the importance of soil condition in tree stability.

Urban trees do not have strong central vertical roots (Nielsen 2010). Tap roots, when present, may add some structural support (Mickovski and Ennos 2003; Fourcaud et al. 2008) especially in juvenile trees until lateral roots develop (Burdett et al. 1986; South el al. 2001; Khuder et al. 2007). While the geometry of the root system changes over time, the basic geometry of the root plate is laid down early and remains unchanged (Coutts and Lewis 1983; Khuder et al. 2007) in trees growing naturally. Watson and Tombleson (2002) suggested that an early indicator of tree stability is the increase in biomass of lateral roots near the trunk in seedlings. Coutts and Lewis (1983) report that in *Picea sitchensis*, structural roots are laid down early. It is likely that root pruning, whether in the nursery or post-transplanting, may alter long-term stability (Gilman and Masters 2010).

Picea glauca roots appear to respond to loading regimes quicker than trunks (Urban et al. 1994). When trees are inclined to a greater degree (above 1–2.5 degrees) at the trunk base, they do not return to their upright position (Sinn 1990) and the stiffness of the root–soil plate is decreased (Lundström et al. 2009). The same result can be achieved by cyclic loading beyond one degree inclination (Rogers et al. 1995; Vanomsen 2006). In a reaction to high loading, root shape can be altered by loading (Stokes et al. 1998; Stokes 1999), and adaptive growth of roots decreases the likelihood of overturning after a loading event (Stokes 1999; Berthier and Stokes 2006; Khuder et al. 2007). When growing on the uphill side of a slope, more first-order *Picea sitchensis* lateral roots were found (Nicoll et al. 2006b), and roots can have thicker-walled fibers and small diameter vessels that increase mechanical support (De Micco and Aronne 2010). It is possible that a rapid screening tool could be developed to use root system plasticity as selection criteria for more mechanically stable trees.

During static load tests of *Picea abies*, *Abies alba*, and *Pinus sylvestris*, Lundström et al. (2007) found that 75% of the variation of the turning moment in the soil–root plate was explained by tree mass, trunk mass, trunk diameter, or tree height, either alone or in combination. The critical turning moment in a number of conifers throughout Great Britain increased by 10%–15% when roots were able to penetrate the soil deeper than 80 cm (Nicoll et al. 2006a). A negative linear relationship was found between the force to cause a tilt and the distance of root severance as multiples of trunk diameter (Smiley 2008) as well as the percentage of *Acer rubrum* roots severed (Smiley et al. 2014), suggesting that models can be built to predict tree instability due to trenching.

While roots play an important role in terms of anchoring the tree into the ground, the importance of soil cannot be neglected. Soil can only stretch by less than 2% while roots can stretch 10%–20% (Tobin et al. 2007), especially when less than 2 mm in diameter (Mattia et al. 2005). Fine roots act to hold the soil together, which helps define the dimension of the soil–root plate (Tobin et al. 2007). The fine roots play a role in physical support as they help hold the soil in place (Genet et al. 2005), which may be important when the soil is saturated and under high wind conditions (Figure 6). Tobin et al. (2007) suggested that models of overturning of shallow root systems should include four mechanical components: 1) weight of soil–root plate, 2) tensile strength of windward roots, 3) tensile strength of soil, and 4) resistance to bending of roots at the hinge point (Coutts 1986; Blackwell et al. 1990). The water content, as well as the location of water in the root–soil plate play important roles in the resistance to uprooting in storms (Kamimura et al. 2011).

Figure 6. Tree failure resulting from saturated soil conditions during tropical storm Ernesto, in 2006.

The soil–root plate is an important area of future study because root failures are common in amenity trees. Data from the International Tree Failure Database (ITFD) indicate that root failures make up 35.6% of total tree failures (ITFD 2014). Models to predict the resistive moment of the soil–root plate of forest- or plantation-grown trees can offer insights into the behavior of amenity trees. Root architecture varies according to age, species, and growing conditions, so models may not apply over the range of variability in these parameters. In particular, belowground growing conditions in urban areas are distinctly different from those in which most previous work has occurred. The texture and volume of soil available to amenity trees in urban areas often precludes ready application of prediction models derived from forest- or plantation-grown trees. Whether belowground space in urban areas can be designed to enhance the resistive moment provided by the soil–root plate is a compelling question. The frequency with which tree roots are damaged in urban areas adds another level of complexity in predicting the resistive moment that the soil–root plate provides—this is another important area for future study. Since nursery production methods can influence the geometry of early root plate formation, there is a need to continue efforts in developing an understanding of what might be considered a normal root architecture to then appraise root system quality.

CONCLUSION

In the last twenty years, arboricultural researchers have attempted to better understand how trees withstand loading, largely in the context of assessing the likelihood of tree failure. Tree form and the material properties of wood determine the load-bearing capacity of a tree. Material properties, like *E* and *MOR*, vary ontogenetically and by species and growing conditions. Although many references include wood properties, most of the work comes from specimens taken from forest- or plantation-grown trees, and defect-free specimens of lumber. Applying these values to living branches, trunks, and roots of open-grown trees in urban areas should be done with care. More work on living trees is needed to obtain accurate material properties for individual trees and allow for variations in species and location. Variability in *E* and *MOR* influences the load-bearing capacity of trees, but the effect of tree form often supersedes that of *E* and *MOR*, because changes in diameter have a curvilinear influence on *I* of a branch, trunk, or root. For branches and trunks, diameter and length often follow predictable proportionalities, but very little of the empirical work has been conducted on amenity trees in urban areas. More data describing the allometry of the branches, trunks, and roots of amenity trees in urban areas are critical to better understanding their load-bearing capacity. Additional research is needed to better understand where maximum loading occurs on a trunk or branch in order to predict where failure is most likely to occur.

A commonly assessed structural defect in trees, decay reduces the load-bearing capacity of branches, trunks, and roots, and determining threshold extents of decay is a useful line of investigation. Advanced techniques to assess the effect of decay such as static pulling tests provide a baseline of assessment, but need additional refinement and validation. Static load tests are also used to assess belowground stability since the soil–root plate is integral to anchoring trees and providing a resistive moment against loading. Exploring the root architecture of amenity trees growing in urban areas to determine whether existing models can predict the resistive moment provided by the soil–root plate of amenity trees is another important area for future study.

Sophisticated measuring devices and analytical techniques (e.g., DIC and FEM) hold great promise to improve the study and practice of assessing the load-bearing capacity of trees. The complicated structure of most amenity trees growing in urban areas still presents many challenges—in both research and practice—to overcome.

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Résumé. Au cours des 30 dernières années, les chercheurs ont commencé à utiliser des principes biomécaniques pour comprendre la stabilité des arbres urbains. Cette revue de littérature s'est concentrée sur les ouvrages relatifs aux arbres des milieux urbains tempérés, mais a également inclut des documents provenant d'autres disciplines et climats selon leur pertinence. La capacité de charge (ou portante) d'un arbre dépend de sa taille, de sa forme et des propriétés matérielles de son bois. À mesure que le tronc et les branches augmentent en diamètre, leur capacité de charge s'accroît. Les propriétés matérielles (par exemple, les coefficients d'élasticité et de rupture) qualifient la rigidité et la résistance intrinsèque du bois, qui influent respectivement sur la déflexion sous charge et la capacité de charge. Dans le bois, les propriétés matérielles varient en fonction de divers facteurs, dont la direction de la charge, la teneur en humidité et l'âge de l'arbre. La carie du bois réduit la capacité de charge d'un arbre. Bien que les praticiens aient élaboré des lignes directrices pour évaluer son impact, ces règles existantes devraient être analysées, améliorées ou rejetées sur la base de tests scientifiques rigoureux. Des tests de charge statique ont été développés pour répondre à cette question, ainsi que pour analyser la probabilité de déracinement (chablis) qui représente jusqu'à 35% des défaillances d'arbres. Bien que l'on ait beaucoup appris, plusieurs questions demeurent quant à la capacité de charge statique des arbres croissant en milieu urbain.

Zusammenfassung. Über die letzten 30 Jahre haben Forscher angefangen, zum besseren Verständnis von der Stabilität von Bäumen, biomechanische Prinzipien hinzuzuziehen. Dieser Rückblick konzentriert sich auf die Literatur über Bäume in gemäßigt temperierten urbanen Landschaften, aber es schließt auch relevante Arbeiten aus anderen Disziplinen und Klimaten ein, die hierzu passen. Die lasttragende Fähigkeit von Bäumen ist von der Größe, Form und den Materialeigenschaften des Holzes abhängig. Wenn der Stamm und die Äste im Durchmesser zunehmen, steigen auf ihre lasttragenden Fähigkeiten. Die Materialeigenschaften (z.B. Moduli der Elastizität und Bruchfähigkeit) beschreiben im Wesentlichen die Holzsteife und Stärke, welche die Biegung unter Last und die lasttragenden Fähigkeiten von Holz beeinflussen. Im Holz können die Materialeigenschaften in Relation zu einer Reihe von Faktoren variieren, einschließlich der Richtung der Last, Feuchtigkeitsgehalt und Baumalter. Holzfäule reduziert die lasttragende Fähigkeit von Bäumen. Obwohl die Praktiker Richtlinien entwickelt haben, um diesen Effekt zu untersuchen, sollten die existierenden Richtlinien auf der Basis einer rigorosen wissenschaftlichen Prüfung untersucht, verbessert oder verworfen werden. Um dieser Fragestellung zu begegnen, wurden Tests zur statischen Last entwickelt, wie auch Untersuchungen zur Wahrscheinlichkeit von Entwurzelungen, die bei bis zu 35 % allen Baumversagens eine Rolle spielt. Während viel gelernt wurde, bleiben dennoch viele Fragen zur statischen lasttragenden Fähigkeit von Bäumen in urbanen Landschaften bestehen.

Resumen. En los últimos 30 años, los investigadores han comenzado a emplear principios biomecánicos para comprender la estabilidad de los árboles urbanos. Esta revisión se centra en la literatura referente a los árboles en los paisajes urbanos templados, pero también incluye trabajo relevante de otras disciplinas y climas según sea apropiado. La capacidad de carga de un árbol depende de su tamaño y forma y de las propiedades del material de su madera. A medida que el tronco y las ramas aumentan de diámetro, su capacidad de carga aumenta. Las propiedades del material (por ejemplo, módulos de elasticidad y rotura) describen rigidez y resistencia intrínseca de la madera, que influyen en la deflexión bajo carga y la capacidad de carga, respectivamente. En la madera, las propiedades del material varían en relación con una variedad de factores, incluyendo la dirección de la carga, el contenido de humedad y la edad del árbol. El decaimiento de la madera reduce la capacidad de carga de un árbol. Aunque los profesionales han desarrollado lineamientos para evaluar su efecto, las directrices existentes deben ser investigadas, refinadas o rechazadas sobre la base de pruebas científicas rigurosas. Se han desarrollado pruebas de carga estática para abordar esta cuestión, así como investigar la probabilidad de desenraice, que representa hasta un 35% de los fracasos de los árboles. Aunque se ha aprendido mucho, subsisten muchas cuestiones sobre la capacidad de carga estática de los árboles que crecen en los paisajes urbanos.