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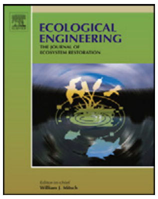

An index based on silvicultural knowledge for tree stability assessment and improved ecological function in urban ecosystems

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ABSTRACT

Trees in the city not only have an ornamental function but also a role in improving the ecological function in urban ecosystems that has been substantially disturbed by human activities such as environmental pollution. Today the ecological role of urban greenery is clearer than ever and is included in the new scientific field of ecological engineering, which is the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both. Trees in an urban environment show many difficulties in surviving in it because the ecological conditions that exist in the cities are worse than these of the nature. One of these seems to be the heavy wind loads. But even though rough surfaces slow down the wind speed, tall buildings can cause wind tunnel effects that stress a tree as much or even more than if it was positioned in an exposed, unprotected site. An urban tree must be able to endure all the damages and loads from the wind throughout its life. The ability of a tree to withstand wind loads of gale forces depends on its shape and its dimensions. The objective of this paper is the evaluation of tree stability based on the aboveground silvicultural characteristics in order to create an empirical index which can correlate tree stability with these features. Silvicultural characteristics that play the greatest role on tree stability are crown ratio (CR), crown asymmetry index (CAI), and tree height (H). Consequently, tree stability index (TSI) is formed by them. According to TSI values, tree stability was classified in three categories (classes): high, moderate and crucial stability. The limits of the transition from one class to another, as the classes themselves are depended on the number of variables that represent silvicultural characteristics.

1. Introduction

The urban ecosystem consists of both the “grey” and the “green” infrastructure. The “grey” element is the result of human impact and includes every possible infrastructure as buildings, roads, etc. The “green” element includes urban greening and peri-urban forests. Green zones are a basic element of ecological engineering affecting city planning. Vegetation in the city not only has an ornamental function but also a role in regulating the environmental function: it retains atmospheric water, contributes to evapo-transpiration, represents a filter against pollution and an excellent regulator of the air, heat and damp with the urban surroundings. Today the ecological role of urban greenery is clearer than ever. Urban greening contributes to increase the quality of life for many communities and their residents (Hauer and Johnson, 1992; Gomez et al., 1998; Dafis, 2001).

In some countries, town planning teams consist mainly of architects, thus leaving the team with little ecological knowledge of urban greenery and how to use it properly (both as regards the quantity and the right plant species). This matter falls within the sphere of ecological engineering and we feel it is of fundamental importance for environmental guarantees and urban ecology. As it is referred to by Rosemond and Anderson (2003) one goal of ecological engineering should be to shift human impacts on ecosystems to a more natural response that takes into account local, native conditions. In addition, techniques used in the study of non-human species, particularly in quantifying their effects on ecosystem processes and other populations could be employed in ecological engineering studies. Also, the goal of ecological engineering is to better integrate society with its supporting environment (Bergen et al., 2001). Creating integrated urban and other built environments is a potential application for ecological engineering. Increasing calls for ‘greening’ urban environments, allowing for more of a connection between place and nature in

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built environment, will require design that includes ecology and engineering. Traditional landscape architecture, and urban horticulture approaches can be augmented by ecological engineering. And deals with the new scientific field of ecological engineering which is the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both (Mitsch, 1998).

For the last 50 years there has been a growing realization that the solutions to most of environmental problems reside in making cities more efficient in their consumption of energy and materials and disposing of waste products, and in altering patterns of urban development to reduce the amount of impervious "grey" infrastructure and to increase the amount of "green" infrastructure, particularly trees (Carreiro, 2006). This realization has been expressed in the concepts of the eco-cities movement, adopted by many environmentalists and urban designers throughout the world (Register, 2002; Carreiro, 2006). According these it is adopted the perception that the accomplishment of healthy ecosystems is possible only if urban vegetation is included in the procedure of urban design (Moll et al., 1995; Kuchelmeister, 1998; Tsitsoni et al., 2007). The goal of the vegetation ecological approach is to create real green environments as the basis of human existence (Miyawaki, 1998).

Within current engineering practice the tendency is to use ecology as an indicator or assessment tool in such broad scale practices as watershed management, ecosystem management, integrated natural resource management and urban planning and development (Gattie et al., 2003).

For most people each tree is a given, static, permanent feature of urban environment. However, trees, whether long-lived or not, will inevitably collapse and decompose, and no trace will remain from their existence. Trees, that are not adapted to the conditions of an urban ecosystem, can die from causes such as a disease or insect attack, drought, uprooting, and catastrophic stem failure in high winds, or from combinations of factors working together (Hauer and Johnson, 1992). Furthermore, effuse and without planning pruning could drive in that direction.

An urban tree must be able to endure all the damages and loads, from gravity, snow or from the wind throughout its life. For nearly all trees, the greatest load is from the wind that comes as gusts of rapid, periodic, dynamic events. In terrestrial environments forces caused by wind are the most ubiquitous and important cause of dynamic loading (Grace, 1977) on the trees. Wind is the most persistent of the harmful natural forces to which any individual tree or forest stand is subjected (Jacobs, 1936; James et al., 2006).

Considerable research into the interaction between wind and tree movement has been contacted in order to better understand the mechanics of wind damage and wind-induce physiological responses (Gardiner, 1995; Kerzenmacher and Gardiner, 1998; Moore and Maguire, 2004).

The result of storm winds are forces twisting and bending tree parts causing either the part to fail or the supporting soil to fail. Trees sense structural stress and attempt to minimize failures through reactive growth. Trees modify their structure over time as they are challenged by wind. Trees are biologically designed to sustain average wind loads (Coder, 2007). Although the relationship between wind loading and tree has been studied, a detailed understanding of the effect of wind loading and tree weight on the internal wood structure and reactions has not been developed yet (Horacek, 2003).

Trees in an urban environment seem to be protected from heavy wind loads. But although rough surfaces slow down the wind speed, tall buildings can cause wind tunnel effects that stress a tree as much or even more than if it were positioned in an exposed, unprotected site on a field (Hirtz, 1981; Grey and Daneke, 1986; Stathopoulos and Storms, 1986; Brudi and van Wassenaer, 2002; Dafis, 2001).

The ability of a tree to withstand wind loads of gale forces is calculated by including the shape of the load – bearing structure (trunk and crown), the properties of green wood and the forces that occur in a gale – force wind gust (Brudi and van Wassenaer, 2002). When trees are healthy, without any trace of decay and knowing that the main cause of failure is a wind speed > 30 m/s (Kane, 2008), the aboveground silvicultural characteristics play the greatest role on tree stability.

Taking into account that tree failure by wind poses risks for the urban environment, the humans' safety and their property, the determination of tree stability and the evaluation of tree risk are imperative.

The objective of this paper is the assessment of tree stability by their aboveground silvicultural characteristics in order to create an empirical model which can correlate tree stability with these features.

2. Materials and methods

2.1. Research area

The city of Thessaloniki extends in an area with elevation between 0 and 350 m. The climate is Mediterranean, with an obvious continental impact through the seasons. Wind conditions diverse through the year. In winter, the northern wind named Vardaris that comes from the valley of Axios River prevails. In spring, the presence of southern-west sea breezes is more frequent. In summer, prevailing winds are northern and also south western, decreasing in September, and from November northern and western winds are dominating (Tsitsoni and Zagas, 2001).

2.2. Data collection and analysis

The research took place on the street trees of three representative roads in the centre of the city of Thessaloniki, which are orientated to wind direction Vardaris. The number of the trees that were measured are presented in Table 1.

According to literature (Stathers et al., 1994; Wessolly, 1995, 1996; Peltola et al., 2000; Brudi and van Wassenaer, 2002; Horacek, 2003; Kolařik, 2003; Sterken, 2005; James et al., 2006; Coder, 2007), tree stability is directly related to the aboveground silvicultural characteristics of each individual. Thus, in order to try an empirical estimation of tree stability and the construction of a mathematical model as well, the measurements that have been recorded for each individual are: Tree species, breast height diameter (D), tree height (H), height at crown base and the radius of the crown R_1, R_2, R_3, R_4, which were used to calculate two crown diameters $\mathrm{CD}_1 = R_1 + R_2$ and $\mathrm{CD}_2 = R_3 + R_4$.

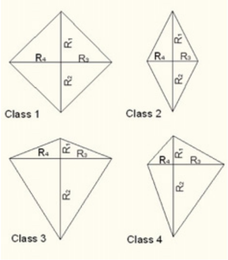
Based on the above measurements, the horizontal and vertical dimensions of the crown were calculated and estimated as they are referred by Assmann (1970): crown length (CL), crown ratio (CR), live crown ratio (LCR), crown width (diameter) ratio or crown index (CWR or CDR), crown fullness ratio (CFR), degree of spread (DS), and crown projection ratio (CPR).

Table 1
Total number of street trees and number of trees in the sample per avenue and per species.

Name of the avenue	Species	Number of trees
Nikis' Avenue	*Platanus orientalis*	81
Egnatias' Avenue	*Celtis australis*	76
	Albizia julibrissin	37
Karamanlis' Avenue	*Populus × euramericana cv. 'I-45/51'*	28

Table 2
Variable classes and values.

Class value	Height classes	CR classes	CFR classes	H/D classes	DS classes	CAI classes
1	<5 m	<0.33	$\leq$0.50	<30	$\leq$0.50	$R_1 = R_2 = R_3 = R_4$ ($CD_1 = CD_2$)
2	5 m–10 m	0.34–0.5	0.51–0.75	30–60	0.51–0.75	$R_1 = R_2$ and $R_3 = R_4$
3	10 m–15 m	0.51-0.66	0.76–1.00	60–90	0.76–1.00	$R_1 > R_2$ or $R_1 < R_2$ and $R_3 = R_4$
4	15 m–20 m	>0.67	>1.00	>90	>1.00	$R_1 \neq R_2 \neq R_3 \neq R_4$



R_1 = crown radius 1, R_2 = crown radius 2, R_3 = crown radius 3, R_4 = crown radius 4

Class 1: $R_1 = R_2 = R_3 = R_4$

Class 2: $R_1 = R_2$ and $R_3 = R_4$

Class 3: $R_1 \neq R_2$ and $R_3 = R_4$

Class 4: $R_1 \neq R_2 \neq R_3 \neq R_4$

Fig. 1. CAI classes according to the position of tree trunk in the crown projection area.

Additionally, two other indices were calculated, the slenderness index (H/D) and a crown asymmetry index (CAI) (Kontogianni, 2009).

According to literature (Petty and Worrell, 1981; Petty and Swain, 1985; Valinger et al., 1993; Wessolly, 1995, 1996; Brudi and van Wassenaer, 2002; Horacek, 2003; Kolařik, 2003; Cullen, 2002; Sterken, 2005; James et al., 2006; Coder, 2007), tree stability decreases when the following silvicultural characteristics increase: tree height, slenderness index, crown ratio, crown fullness ratio, degree of spread, crown length, total tree size, crown roundness and crown asymmetry. The above-mentioned variables were selected in order to express a tree stability index (TSI) in relation with the above-ground silvicultural tree characteristics. Variables which affect the TSI variability were selected by the method of simple correlation and simple linear regression.

The effect of a combination of variables is more silviculturally important than an individual effect. The combination effect was estimated by the method of stepwise multiple regression analysis. SPSS v.15 was used for the statistical analyses.

3. Results

The selected variables for TSI determination are: tree height (H), slenderness index (H/D), crown ratio (CR), crown fullness ratio (CFR), degree of spread (DS), crown asymmetry index (CAI). Because of the heterogeneous expression of the variables they are categorized to an equal number of classes. Four classes were selected and the corresponding values are 1, 2, 3, and 4 in a descending tree stability (1 = maximum tree stability, 4 = minimum tree stability). The values of each variable corresponding to the four classes are shown in Table 2 and Fig. 1.

Table 3
Simple regression results of silvicultural characteristics on TSI.

Independent variable	r	R^2	SEE%[a]
H	0.63	0.39	8.3
CR	0.69	0.47	7.8
H/D	0.12	0.02	9.5
CFR	0.24	0.06	9.3
DS	0.37	0.14	8.8
CAI	0.51	0.26	8.4

[a] SEE% = standard error of estimation as percentage (%) of the average of the dependent variable.

The sum of the classes' values of the six variables for each tree is called *tree stability index* (TSI). The TSI values range from 6 to 24. Thus, each tree has a TSI value. The lower TSI value the highest tree stability and the highest TSI value the more crucial tree stability.

Each independent variable affects the TSI variability as shown in Table 3.

Multiple regression analysis showed that tree stability index (TSI) is more affected by the combination of crown ratio (CR), crown asymmetry index (CAI), and tree height (H).

So, the multiple regression equation: $Y = a + bX_1 + cX_2 + dX_3$

$$\text{Takes the form of:}\quad \mathrm{TSI} = a + b\,\mathrm{CR} + c\,\mathrm{CAI} + dH$$

where TSI = tree stability index, X_1 = CR = crown ratio, X_2 = CAI = crown asymmetry index, $X_3 = H$ = tree height, (a, b, c, d) = coefficients of equation. The results are showed in Table 4.

Consequently, TSI is formed by the three variables (H, CR, CAI) and its values range from 3 to 12. Based on that range three tree stability categories (classes) have been distinguished: *high* tree stability, *moderate* tree stability, and *crucial* tree stability (Table 5).

The class boundaries, the transition from one class to another and the classes themselves interpret how many of the three tree variables take extreme values and particularly maximum ones (values 3 and 4). Therefore, when two of three variables take maximum values the tree is in crucial stability. On the contrary, when two of three variables take minimum values, the tree is in high stability. In all other cases, the tree is characterized as of moderate stability. According to these, all street trees were ranked in stability classes depending on their TSI values (Table 6).

All plane trees and half of the poplars are of crucial stability. Nevertheless, the majority of street trees are of moderate stability, since they are species of large height, with tall and spread crowns, without crown symmetry (Table 7).

Table 4
Multiple regression results.

Coefficients of equation	St. error of coefficients	t-Test	R^2	SEE%[a]	F-test
$a = 6.362$	0.314	20.250*	0.78	5.1	251.794**
$b = 0.984$	0.071 (2.1%)[a]	13.828*			
$c = 1.014$	0.068 (1.9%)[a]	14.894*			
$d = 0.388$	0.066 (3.0%)[a]	5.911*			

[a] Percent (%) of the average of independent variable.

* Value is significant at .05.

** Value is significant at .01.

Table 5
Tree stability classes as formed by TSI values.

TSI values	Tree stability classes
3–5	High
6–9	Moderate
10–12	Crucial

4. Discussion

Tree height (*H*) interprets 39% of the TSI variability and it means that *H* is an important factor in tree stability. According to Popa (2000) tree height over 20 m is a great risk for tree stability.

While species' effects are dependent on temporal and spatial change, they nonetheless are useful in ecological engineering. Thus, further study should be encouraged to identify species characteristics and their range of responses that yield results that are beneficial to humans and ecosystems (Rosemond and Anderson, 2003).

One of the potential applications of ecological engineering is the integration of society and ecosystems in built environments (for example, in landscape architecture, urban planning, and urban horticulture applications) (Bergen et al., 2001).

By the constant moderate wind velocity and direction, trees are swerved from the vertical axis. Failure occurs when the horizontal forces on a tree transmitted down the trunk to create a stress that exceeds the resistance to breaking or turning of the root–soil system (Horacek, 2003). Wind forces on tree canopies create an overturning moment about the base that is expressed in units of Newton meters. As height increment goes on, trees can become increasingly prone to failure. For example, a force of 100 N applied at a height of 10 m creates a moment of 1000 N m, but the same force at the 30 m height generates three times as much torque (Horacek, 2003). Plane trees in the study area are of crucial stability because of their large height. On the contrary, smaller trees of the species *Celtis australis* perform sufficient stability.

A larger canopy will catch more wind, and the aerodynamic drag will increase drag forces on the tree (James et al., 2006). Thus, it is important for crown length to be formed proportionally with tree height. That is confirmed by the present study results, where crown ratio (CR) interprets 47% of TSI.

The majority of trees of the species *Platanus orientalis* and *Populus × euramericana cv. 'I-45/51'* have asymmetric crowns whereas the crown of *C. australis* and *Albizia julibrissin* is more spherical and this fact is confirmed by the research results of Batala and Tsitsoni (2007). And that is why the percentage of trees of crucial stability for the first two species is 87.7% and 46.4% correspondingly, whereas for *C. australis* and *A. julibrissin* is 22.4% and 0.0% correspondingly.

An interaction between the components of the crown can prevent the generation of natural harmonic sway frequencies and minimize extreme dynamic loads that would potentially cause mechanical failure (James et al., 2006).

Trees tend to grow adaptively and thus to self-optimise their loading patterns enough to withstand all but the most exceptionally strong winds (Lonsdale, 2003). In a review of previous studies on tree sway, Moore and Maguire (2004) described the effect of branch removal on sway frequency. Removal of branches on the top of the crown appeared to have the greatest effect, with up to 80% of the crown mass having to be removed before an increase in the natural frequency is noticeable. Moore and Maguire (2004) showed that changes in natural frequency with crown removal did not appear to be caused by changes in damping ratio, but rather by changes in mass distribution of the trees. According to Wessolly (1996) some of the visual possibilities of recognizing stability problems are the height and slenderness of trees and also their shape, as tall slender and forked trees are more dangerous than squat specimens because of the danger of shaking. Because of human actions (i.e. pruning, vandalism, etc.) many trees in the study area have a crooked or forked stem which promotes the crown asymmetry and as a consequence, decreases tree stability. Research results shows that 47% of the street trees are of crucial stability mainly caused by incorrect treatment and irrational pruning.

An increase of likelihood of failure of larger and taller trees has been observed in previous studies (Foster, 1988; Gibbs and Greig, 1990; Duryea et al., 2007), a fact that generally proceeds from the present study. However, tree size by itself cannot explain clearly the possibility of tree fall because it is not possible to prognose the damage type despite the crucial tree stability is defined. Previous reports of failures of conifers, which generally occurred on more slender tree, showed high rate of failure, likely due to the comparatively small range of slenderness values (Petty and Worrell, 1981; Petty and Swain, 1985).

The mechanics of failure are influenced by the interaction of tree size and shape, wind speeds and topography (Stathers et al., 1994). Most root failures because of catastrophic wind, did not involve

Table 6
Street trees distribution in the three stability classes.

Tree stability classes	*Albizia julibrissin*	*Celtis australis*	*Platanus orientalis*	*Populus × euramericana cv. 'I-45/51'*
High	5.40%	5.30%	0.00%	0.00%
Moderate	94.60%	72.40	12.30%	53.60%
Crucial	0.00%	22.30%	87.70%	46.40%

Table 7
Street trees distribution in the height, crown ratio, and crown asymmetry index classes.

	Species	Class value 1	Class value 2	Class value 3	Class value 4
H classes	*Albizia julibrissin*	91.80%	8.20%	0.00%	0.00%
	Celtis australis	18.40%	81.60%	0.00%	0.00%
	Platanus orientalis	2.50%	24.70%	39.50%	33.30%
	Populus × euramericana cv. 'I-45/51'	10.70%	82.10%	7.20%	0.00%
CR classes	*Albizia julibrissin*	18.90%	32.40%	43.20%	5.50%
	Celtis australis	2.60%	9.20%	34.30%	53.90%
	Platanus orientalis	0.00%	1.20%	8.60%	90.20%
	Populus × euramericana cv. 'I-45/51'	0.00%	21.40%	25.00%	53.60%
CAI classes	*Albizia julibrissin*	0.00%	0.00%	27.00%	73.00%
	Celtis australis	10.10%	3.90%	50.00%	36.00%
	Platanus orientalis	0.00%	3.70%	19.80%	76.50%
	Populus × euramericana cv. 'I-45/51'	0.00%	0.00%	14.00%	86.00%

defects, visible or not, prior to failure (Kane, 2008). In Brewster, Massachusetts, almost all root failures (96%) involved living trees, and 82% had no defects. Additionally, in the same research, no girdling roots or obstruction to root growth were observed on any root failures (Kane, 2008). So this study focalized on silvicultural characteristics that influence static loads on a tree because of its dimensions.

Saturated soils reduce shear strength of a soil, which was already comparatively low because of the coarse texture, predisposing trees to windthrow (Foster, 1988). Tree failure is a complicate phenomenon that includes a series of many factors that they cannot be described with mathematical models. Hence the impact of the ecological site, as for example saturated soils or, as several researches show (i.e. Moore, 2000; Moore and Maguire, 2001; Peltola et al., 2000), soils with small depth that restrict root development and formation make uprooting more probable.

Urban foresters do not have the luxury of waiting decades for additional tree failure data to be collected and analyzed. A prudent approach to reducing the likelihood of tree failure is to assess risk by conservatively prioritizing management actions such pruning and removal based on systematic assessments (Hauer and Johnson, 1992; Smiley and Kane, 2006; Sterken, 2005). However it is recognized that some tree failures in catastrophic wind storms are unpredictable with the current level of understanding of tree failure (Kane, 2008).

Based on the findings of this research on tree stability assessment, it seems that:

The construction of an empirical index to predict easily and cheap the tree stability of street trees in urban environment is possible.

Every aboveground tree silvicultural characteristic has an influence on tree stability index. From these the factors with the most significant impact are the crown ratio (CR), tree height (H) and the crown asymmetry index (CAI). The interaction of these characteristics explicates the 78% of the total variability of tree stability index.

According to TSI values, tree stability was classified in three classes: *high*, *moderate* and *crucial* stability. The limits of the transition from the one class to another, as the classes themselves are depended on the number of variables that represent silvicultural characteristics, take the extreme values (3 and 4). Hence, if two of the above factors take the extreme values, the tree is in a status of crucial stability. Contrariwise, if only one factor's value tends to an extreme value and at the same time the values of the two other factors are in the minimum value, the tree is in a status of high stability. The intercalary combinations put a tree in a status of moderate stability.

In the study area the 45.7% of the street trees are in crucial stability. The main reason for that is the improvident, without planning pruning, that causes trunk's split-up that leads to crown asymmetry and consequently decrement of tree stability.

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