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The effect of wind gusts on root plate inclination in urban trees

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Authors' notes'

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Abstract

Objective: To analyze the effect of wind gusts on the root plate inclination in urban trees and to identify the dendrometric variables that most interfere with the trees' response regarding the root plate inclination in order to contribute to the management of urban planning aimed at sustainable cities.

Methodology: The inclination data was collected by Tree Motion Sensors (TMS), which record the actual inclination of the tree root plate. The maximum and average slope and the number of slope occurrences were related to the maximum wind gust and the dendrometric characteristics of the trees.

Originality/Relevance: The Urban Forest is fundamental for improving the environmental and housing quality of cities. However, trees encounter stressful conditions in the urban environment which can compromise their structure and stability, increasing the risk of falling. Research that analyzes the effects of loads exerted by natural elements on urban trees can provide relevant information for predicting fall risks.

Results: Wind was the factor responsible for approximately 51% of the occurrences of root plate tilting and most of the trees showed a tendency to sway in a southwest/northeast direction. *Lagerstroemia speciosa* (L.) Pers. was the species with the greatest inclination angle. DBH and crown diameter were the variables which showed a significantly strong correlation with root plate inclination.

Contributions to management: These results can help to develop preventive measures against tree falls, contributing to the effective management of urban forestry in order to establish more sustainable and resilient cities, so as to support sustainability actions applied to urban planning.

Keywords: tree stability, urban forestry, risk mitigation, falling trees.

O EFEITO DE RAJADAS DE VENTO NA INCLINAÇÃO DA PLACA DE RAÍZES EM ÁRVORES URBANAS

Resumo

Objetivo: Analisar o efeito de rajadas de vento na inclinação da placa de raízes em árvores urbanas e identificar as variáveis dendrométricas que mais interferem na resposta das árvores quanto à inclinação da placa de raízes, de modo a contribuir com a gestão do planejamento urbano direcionado a cidades sustentáveis.

Metodologia: Os dados de inclinação foram coletados pelo *Tree Motion Sensors* (TMS), que registra a inclinação real da placa de raízes de árvores. A inclinação máxima, média e o número de ocorrências de inclinação foram relacionados com a rajada de vento máxima e com as características dendrométricas dos indivíduos arbóreos.

Originalidade/Relevância: A Floresta Urbana é fundamental para a melhoria da qualidade ambiental e habitacional das cidades. Contudo, no ambiente urbano, as árvores encontram condições estressantes que podem comprometer sua estrutura e estabilidade, aumentando o risco de queda. Pesquisas que analisam os efeitos das cargas exercidas por elementos naturais nas árvores urbanas podem fornecer informações relevantes para a previsão dos riscos à queda.

Resultados: O vento foi o fator responsável por aproximadamente 51% das ocorrências de inclinação da placa de raízes e a maioria das árvores apresentou tendência de oscilação no sentido sudoeste/nordeste. *Lagerstroemia speciosa* (L.) Pers. foi a espécie com maior ângulo de inclinação. O DAP e o diâmetro de copa foram as variáveis que apresentaram uma correlação significativamente forte com a inclinação da placa de raízes.

Contribuições para a gestão: Estes resultados podem auxiliar a elaboração de medidas preventivas à queda de árvores, contribuindo com a gestão efetiva da silvicultura urbana em vista do estabelecimento de cidades mais sustentáveis e resilientes, de modo a amparar ações de sustentabilidade aplicadas ao planejamento urbano.

Palavras-chaves: estabilidade de árvores, floresta urbana, mitigação de risco, queda de árvores.

EFFECTO DE LAS RÁFAGAS DE VIENTO EN LA INCLINACIÓN DE LA PLACA RADICULAR DE LOS ÁRBOLES URBANOS

Resumen

Objetivo: Analizar el efecto de las rachas de viento sobre el vuelco de la placa radicular en árboles urbanos e identificar las variables dendrométricas que más interfieren en la respuesta de los árboles respecto al vuelco de la placa radicular.

Metodología: Los datos de inclinación se recogieron mediante sensores de *Tree Motion Sensors* (TMS), que registran la inclinación real de la placa radicular. El máximo, la media y el número de inclinaciones se relacionaron con la ráfaga de viento máxima y las características dendométricas de los individuos arbóreos.

Originalidad/Relevancia: El bosque urbano es fundamental para mejorar la calidad medioambiental y de la vivienda de las ciudades. Sin embargo, en el entorno urbano, los árboles se enfrentan a condiciones de estrés que pueden comprometer su estructura y estabilidad, aumentando el riesgo de caída. Las investigaciones que analizan los efectos de las cargas ejercidas por los elementos naturales sobre los árboles urbanos pueden aportar información relevante para la predicción de los riesgos de caída.

Resultados: El viento es el factor responsable de aproximadamente el 51% de los casos de inclinación de la placa radicular y la mayoría de los árboles mostraron una tendencia a oscilar en dirección suroeste/noreste. *Lagerstroemia speciosa* (L.) Pers. fue la especie con el mayor ángulo de inclinación. El DAP y el diámetro de la copa fueron las variables que mostraron una correlación significativamente fuerte con la pendiente de la placa radicular.

Aportaciones para la gestión: Estos resultados pueden ayudar al desarrollo de medidas preventivas para la caída de árboles, contribuyendo a la gestión eficaz de la silvicultura urbana con vistas a establecer ciudades más sostenibles y resilientes.

Palabras-clave: estabilidad de los árboles, silvicultura urbana, mitigación de riesgos, caída de árboles

Introduction

The urban forest is an essential component for maintaining the environmental quality and sustainability of urban ecosystems (Yang et al., 2021). It promotes various benefits, such as stabilizing and improving the temperature, minimizing the effects of pollution, providing food and shelter for fauna, as well as contributing to the leisure and well-being of the population (Leitão, 2016; De Melo, De Lira Filho & Júnior, 2019). However, all trees have the potential to present some degree of risk to people, buildings and public facilities, especially those that are older, weakened by pest attacks and inadequately managed (Li et al., 2022).

The stressful environment imposed on the development of trees further contributes to this aggravation in cities. Trees are often subjected to severe environmental stress and mechanical damage, especially to the root system, due to soil compaction, poor planting conditions and pollution (Ghani, Stokes & Fourcaud, 2009). They are restricted to critical spaces imposed by landscaping projects, which consequently reduce the services they can offer (Mullaney, Lucke & Trueman, 2015). This is why they require careful management in urban areas, as a fall of part or all of their structure can result in accidents and serious damage (James, Haritos & Ades, 2006). However, it is indisputable that the likelihood of a safety incident tends to be minimal compared to the ecological, social and economic benefits of trees (Li et al., 2022).

The strength of root anchorage is essential for the stability of trees, which requires adequate space. Anchoring is carried out by the thickest and most lignified roots of the plant, starting from the nodes closest to ground level (Dupont et al., 2018) several factors influence this strength, including root architecture, depth, physical and analytical properties of the soil, shape and weight of the root plate and the location of the rotational axis (Rahardjo et al., 2014). Understanding how this process occurs can help prevent the tree from uprooting when subjected to certain adversities (Dupont et al., 2018). However, there is a lack of information on

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the structural volume of the root plate that is required and the characteristics in relation to the wind resistance of trees (Krišāns et al., 2020).

For trees to withstand the stresses of the environment, they need to develop mechanically reliable safety factors in their root system, trunk and crown (Brazolin, 2009). This requires modifications to the mechanical properties of trees, creating internal tensions and optimizing their shape and structure through adaptive growth in order to maintain a constant state of mechanical tension, avoiding breakage (Mattheck & Vorberg, 1991; Sone, Noguchi & Terashima, 2006).

The greatest load among the natural forces to which a tree is subjected is caused by the wind, which can come in the form of rapid, periodic and dynamic gusts (James, Haritos & Ades, 2006). Trees sway dynamically in response to horizontally incident winds as a result of the combination of torsional and bending torques at their base, which can cause the tree to fall in situations where the torque exceeds the resistance of the tree's rooting system (Ataíde et al., 2015; Yang et al., 2021). Thus, tree failure under wind action occurs when the tree tilts beyond the limit set by the rotation angle (James, Hallam & Spencer, 2013a).

Individual tree susceptibility to wind damage depends on tree species, soil properties, tree health and root plate volume (Krišāns et al., 2020). This makes thorough understanding of wind-tree interactions of paramount importance in order to minimize economic losses and damage to human life (Yang et al., 2021).

This study makes it possible to fill a gap in sustainable urban planning actions, which constantly emphasize the need to add trees in cities, but make little progress in developing tools capable of promoting this safely and efficiently. Studies on the effects of loads exerted by natural elements on trees, such as wind and rain, can provide a better basis for generating simplified calculation models for predicting the risks associated with a given event (Ferreira, 2017).

Appropriate preventive and protective measures can be taken to effectively avoid the occurrence of a fall if the risk is detected in advance (Li et al., 2022). Therefore, it is assumed that wind is one of the main factors interfering with the stability of urban trees and that specific dendrometric characteristics can provide greater resistance to trees.

In this context, the aim of this study was to analyze the effect of wind gusts on root plate inclination in urban trees and to identify the dendrometric variables that most interfere with the trees' response to root plate inclination.

Material and Methods

Selection of specimens in the study area

This study was conducted on the campus of the Federal University of Viçosa, in Viçosa, Minas Gerais. The region's climate is Cwa according to the Koppen climate classification, a humid subtropical climate with dry winters, mesothermal, with average, maximum and minimum annual temperatures of 19, 26.1 and 14 ºC, respectively. The average annual rainfall is 1,314.2 mm, with a water deficit between May and September and a surplus between December and March (Soares Júnior, 2000). The prevailing wind direction for the city of Viçosa is northeast, followed by north (INMET, 2019).

The topography is hilly with narrow, humid valleys, and the region's soils are predominantly latosols at the top and on the slopes of the elevations, and red-yellow argisols on the plateaus. The municipality is part of the Atlantic Forest biome in the phytogeographic region called Semi-deciduous Seasonal Forest, in which there is physiological rest and partial foliage fall during the winter periods (IBGE, 2019).

The tree specimens were selected based on the following priority criteria: proximity between the specimens, adequate physical condition (no apparent damage to the roots and trunks), absence of trunk crookedness, good phytosanitary condition (no apparent pests or diseases), similarity in diameter at breast height, similarity in the environmental characteristics of the surroundings, similar bed conditions and similarity in total height values. As a result, the

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sample consisted of nine species commonly used in the afforestation of Brazilian cities, with three individuals per species, totaling 27 trees.

As espécies analisadas foram: *Cenostigma pluviosum* (DC.) Gagnon & G.P.Lewis (Sibipiruna), *Ceiba speciosa* (A.St.-Hil.) Ravenna (Paineira), *Delonix regia* (Bojer ex Hook.) Raf. (Flamboyant), *Handroanthus impetiginosus* (Mart. ex DC.) Mattos (Ipê-roxo), *Handroanthus serratifolius* (Vahl) S.Grose (Ipê-amarelo), *Lagerstroemia speciosa* (L.) Pers. (Escumilha), *Libidibia ferrea* (Mart. ex Tul.) L.P.Queiroz (Pau-ferro), *Moquilea tomentosa* Benth. (Oitizeiro) e *Spathodea campanulata* P. Beauv. (Espatódea).

Data collection

The data collection period was defined based on a previous historical analysis of local conditions, including the months of the year and the times of day when the wind is strongest in the region. Data was therefore collected between February and March 2019, between 1pm and 5pm. The Weather Company's weather forecast was consulted daily to avoid collecting data on a day with low wind availability.

Data on the root plate inclination was collected using Tree Motion Sensors (TMS) (Figure 1). These sensors record the dynamic movement of the tree and are from the manufacturer Argus Electronic GMBH, a German technology which enables recording the inclination in the root zone of the tree in the X, Y and Z directions (North/South, East/West and vertical), with an accuracy of 0.01º, taking 20 readings per second (20 Hz). TMS works autonomously, is programmable and stores data over time. At the end of each monitoring period, the sensor was removed from the tree and the data transferred to a computer using the Treesensor software program.

The small, portable and non-invasive sensors (Figure 1A) were attached to the trees using two screws (Wood Screw, flat head, 2.5 x 20 mm). A pair of TMS sensors was used on each selected tree, where one sensor was fixed at the trunk base between 5 and 10 centimeters above ground level, called the "base sensor" (Figure 1C), and the second called the "control"

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(Figure 1C) was installed on the tree trunk at a height of two meters above the ground, according to the recommendations of Gocke, Rust and Rust (2018).

Figure 1

Tree Motion Sensors (TMS). A) TMS sensor; B) Level bubble in the sensor; C) Base and control sensors installed on the tree

Source: Produced by the authors.

The need to use two sensors on the same individual serves to certify that an event (wind) has occurred in the tree and also to eliminate noise by comparing the data from the control and base sensors. The control sensor records the inclination due to the base rotation, the additional inclination due to the trunk bending and an acceleration due to the trunk displacement as the tree swings from side to side. The base sensor only measures the tilt at ground level. The data recorded by the base sensor is therefore the root plate inclination values, which allows us to understand how the tree is anchored.

With the help of a compass, the devices were always positioned in a northerly direction and aligned horizontally using a spirit level (Figure 1B). After installing the equipment and starting the recording process, each collection lasted three hours, providing a total of 216,000 data points per tree. The three-hour period was considered sufficient in a similar study to analyze the stability of the species *Populus* × *canadensis* Moench, *Quercus robur* L. and *Alnus glutinosa* (L.) Gaertn. in Germany (Esche, Detter & Rust, 2018).

The wind information was obtained from hourly data from the official INMET automatic station in Viçosa. This station is positioned within the boundaries of UFV, close to the specimens evaluated, and less than 2 km from the furthest sample. Thus, the wind gust values between 1pm and 5pm on the collection days were stored.

Dendrometric characterization

After selection, the trees were properly characterized. To do so, the following information was collected: tree height (m), estimated using a retractable pole; diameter at breast height - DBH (m), measured with a tape measure at 1.30 m from the ground; crown diameter (m), measured with a tape measure, based on the crown projection to the ground, in which two perpendicular diameter measurements were obtained; and height at the beginning of the crown (m), referring to the distance between the ground and the lower part of the crown, using a retractable pole.

With the crown diameter values obtained in the field, it was possible to calculate the crown area for each individual using the traditional formula for the circumference area.

By subtracting the height values at the beginning of the crown from the total height values, the crown height of each individual was calculated. With this value and the average crown diameter value, the crown volume for each individual could be calculated using the traditional cylinder volume formula:

$$V_c = \pi * \left(\frac{d}{2}\right)^2 * H_t$$

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In which:

Vc - crown volume (m³)

d - crown diameter (m)

Ht - crown height (m)

It is worth noting that when calculating crown area and volume, the characteristic crown shapes of each species were not taken into account.

We used a formula derived from volumetric equations applicable to the sustainable management of native forests in the state of Minas Gerais (CETEC,1995) to calculate trunk volume:

$$V_f = 0.00007423 * (CAP * 100)/\pi)^{1,707348} * H_t^{1,16873}$$

In which:

Vf - stem volume (m³)

CAP - circumference at breast height (1.30 m) (m)

Ht - total height (m)

These dendrometric variables had to be obtained in order to check for correlation with the root plate inclination values.

Data processing

The Treesensor software program was used to generate a detailed report on the records in a text file. The variable used to express the root plate slope provided by the sensor, referred to in the file as the resulting slope (xy), was checked after every collection day. This is because the data from the control sensor is used to distinguish the slope from the “background” noise. In

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this way, the base sensor slope is only validated if the control sensor slope has a higher value (Gocke, Rust & Rust, 2018). When this condition was not met, the collection was repeated.

The maximum inclination recorded for a tree over the monitoring period was related to the maximum wind gust using a scatter diagram created in the Microsoft Office Excel program. This scatter plot was created with the variable maximum root plate slope on the y-axis and maximum wind gust obtained during the monitoring period on the x-axis. It was then possible to evaluate this relationship from the equation generated by the scatter diagram.

The maximum slope has been used as the main criterion for assessing tree root anchorage in various studies, such as those carried out by James, Hallan & Spencer (2013b) and Gocke, Rust & Rust (2018). However, according to the latter authors, although this maximum inclination value is useful for pointing out the transient peaks that occur during winds and for providing an indication of the tree's stability, it may be an oversimplification of the tree's total response. Therefore, in addition to the maximum slope value, it was necessary to look at the average generated by the entire data set, as well as the number of slope occurrences. This information was extracted from the radar graph generated by the Treesensor program.

The radar graph consists of plotting the XY information, referring to the north/south (Y) and east/west (X) root plate inclination, indicating the directional response of the tree to the wind action. Thus, the movement direction can be observed. The radar graph was presented individually for each species and only for the base sensor, which refers to the root plate inclination values. Each graph also shows the number of tilt events, expressed as a percentage of time.

Analysis of the graphs, in addition to indicating the movement direction and the percentage of time with oscillation, was also used to monitor differences in behavior between the species. In view of the variability between individuals of the same species, a statistical correlation analysis was carried out between the dendrometric characteristics of the trees and the root plate inclination. Pearson's correlation coefficients (r) were calculated using the Genes

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program. The parameter cited by Mukaka (2012) was used to interpret the values found, in which: $|r| \geq 0.9$, indicates a very strong correlation; $0.7 \leq |r| < 0.9$, strong correlation; $0.5 \leq |r| < 0.7$, moderate correlation; $0.3 \leq |r| < 0.5$, weak correlation; and $0 \leq |r| < 0.3$, negligible correlation.

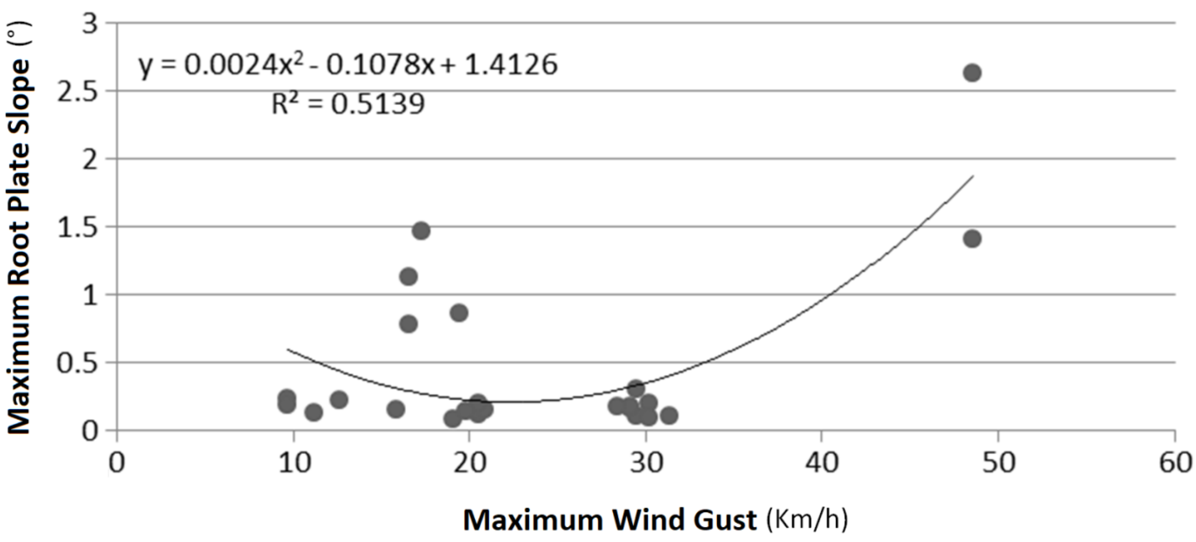
Results

Root plate inclination

The relationship between the maximum root plate slope of the individuals analyzed and the maximum wind gust value, obtained by creating a dispersion diagram, resulted in a second-degree polynomial equation, whose trend line generated a determination coefficient of 0.5139 (Figure 2).

Figure 2

Scatter diagram between maximum slope and maximum wind gust



Source: Produced by the authors.

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It can therefore be inferred that 51.39% of the variation is explained by the regression model, i.e. approximately 51% of the factors influencing the slope were due to the wind gust alone. It is also worth noting that the correlation was direct, i.e. the higher the wind gust, the greater the root plate inclination.

Given that root plate inclination occurs directly in response to wind gusts, a detailed analysis was performed for each individual in order to identify trends between species. Counting the tilt occurrences made it possible to see how many times each tree reacted to wind episodes in a given time interval and thus provide information on the percentage of monitored time in which the tree oscillated. In addition, point-by-point recording of the inclination provided by the radar graph makes it possible to analyze the predominant geographical direction of the occurrences (Figure 3).

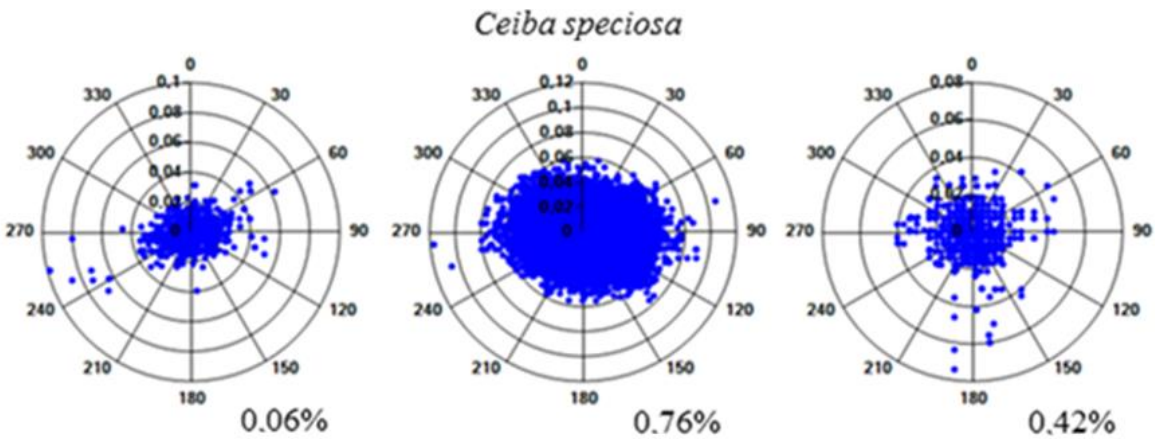
The radar graph follows the direction of the cardinal points, where 0 represents north and each concentric circle shows the inclination angle values, the scale of which is shown on the vertical line. In this way, each point refers to an inclination angle value and the geographical direction of that occurrence. The percentage reported below the graphs refers to the percentage of oscillation time.

It can generally be seen that most of the trees tended to sway in a southwest/northeast direction. The specimens of *Handroanthus serratifolius* showed average root plate inclination 51.46% of the time, those of *Lagerstroemia speciosa* 42.53%, *Cenostigma pluviosum* 30.39%, *Handroanthus impetiginosus* 8.74%, *Libidibia ferrea* 8.72%, *Moquilea tomentosa* 8.38%, *Delonix regia* 5.96%, *Spathodea campanulata* 5.56% and those of *Ceiba speciosa* 0.41%.

When analyzing the inclination angle value, *Lagerstroemia speciosa* was the most outstanding species, where the projected graphs reached the maximum scale of 0.6, 0.8 and 0.5, the highest of all the specimens. *Handroanthus serratifolius* followed with scales of 0.08, 0.6 and 0.5. Thus, although *Lagerstroemia speciosa* had a steeper slope, *Handroanthus* *serratifolius* had the highest occurrence of events, followed by *Lagerstroemia speciosa* and *Cenostigma pluviosum*.

Figure 3

Results of the tilt points for each individual and percentage of time monitored when the tree swayed



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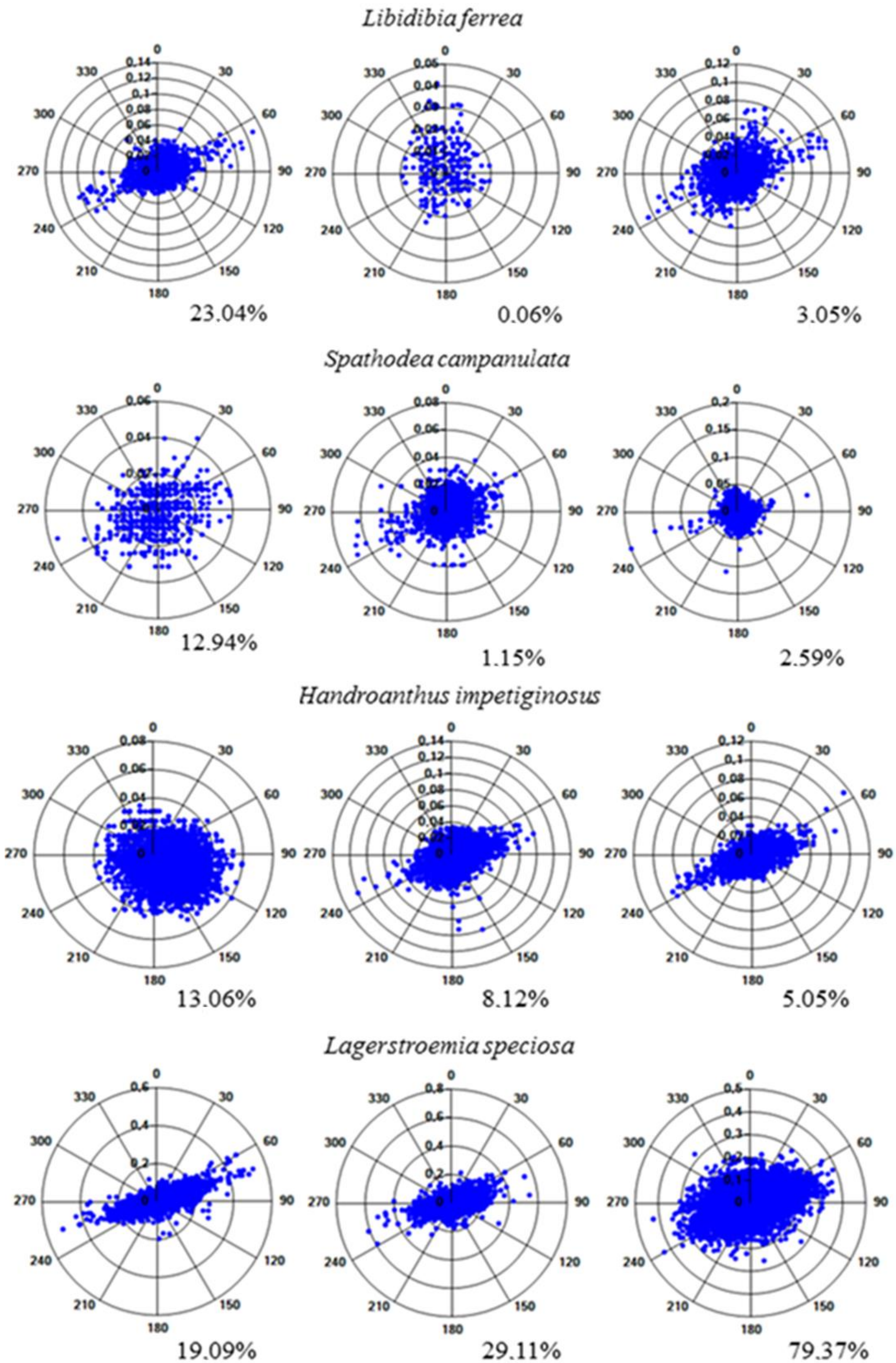
Libidibia ferrea
23.04%
0.06%
3.05%
Spathodea campanulata
12.94%
1.15%
2.59%
Handroanthus impetiginosus
13.06%
8.12%
5.05%
Lagerstroemia speciosa
19.09%
29.11%
79.37%

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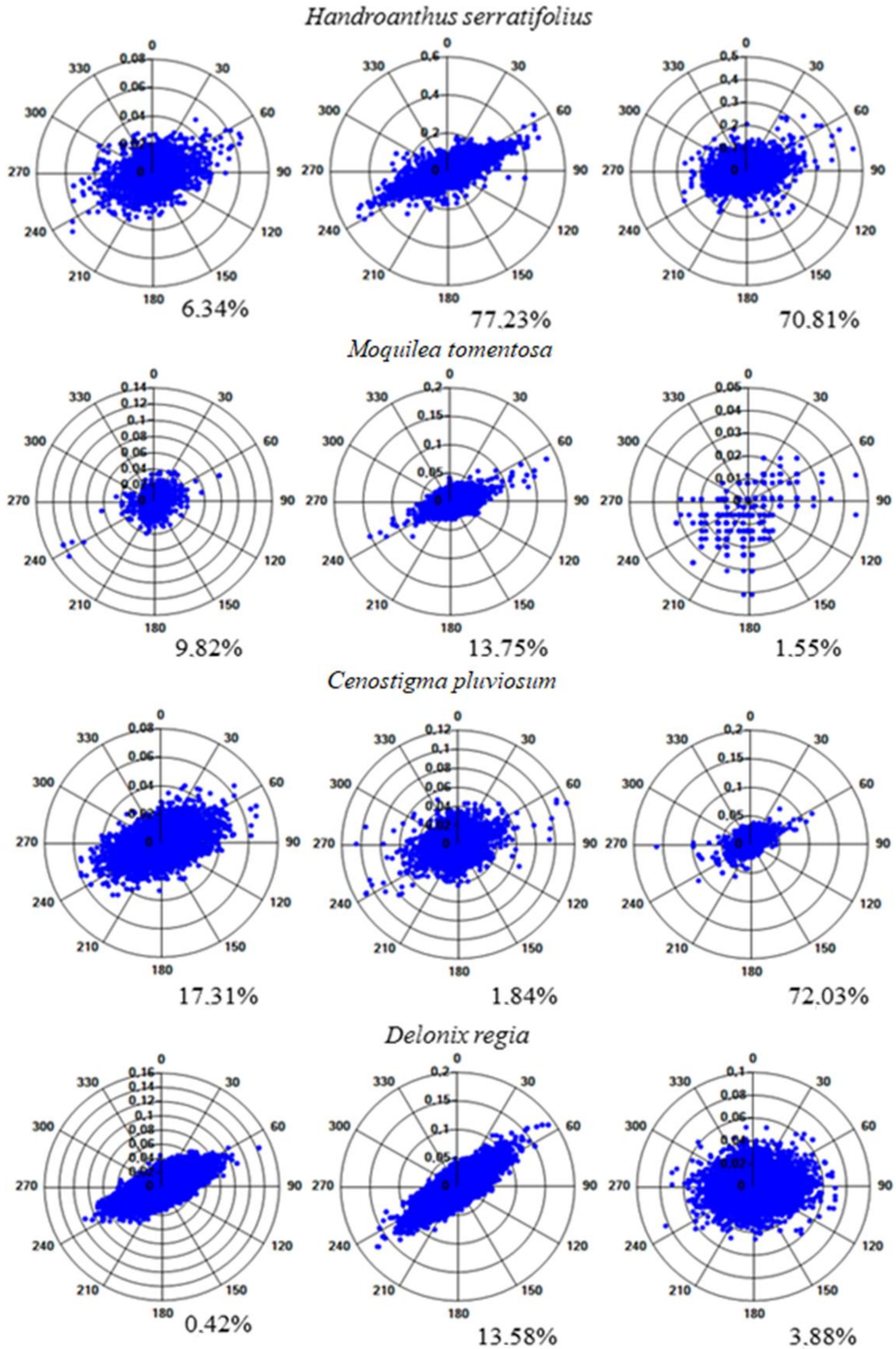

Source: Produced by the authors.

Influence of dendrometric variables

The graphs show the great variability between individuals of the same species. Therefore, we also tried to analyze whether there was any correlation between the dendrometric characteristics of the trees and the root plate slope (Table 1).

Table 1

Results of Pearson's correlation between dendrometric variables and the slope variables analyzed

Dendrometric variables	Average inclination	Maximum inclination	Occurrence of tilt
DAP (m)	-0.7696*	-0.4989	-0.5652
Crown diameter (m)	-0.8942**	-0.7058*	-0.5871
Total height (m)	-0.5545	-0.6875*	-0.4521
Canopy height (m)	-0.567	-0.5335	-0.487
Crown start height (m)	0.0045	-0.2700	0.0438
Crown volume (m^3)	-0.726*	-0.5850	-0.5837
Trunk volume (m^3)	-0.6025	-0.4192	-0.5415
Crown area (m^2)	-0.8441**	-0.6090	-0.5533

Note: ** Significant at 1% probability of error ($p<0.01$), * significant at 5% ($p<0.05$); negative signs indicate an inverse relationship between the variables. Source: Own elaboration

The dendrometric variables that had a significant correlation with the average inclination angle were diameter at breast height (DBH), crown diameter, crown volume and crown area. The values indicated that these variables were the only ones with a strong correlation. Among them, the average crown diameter showed the highest correlation, indicating that 89% of the average slope can be explained by this characteristic.

The total height, crown height and trunk volume variables showed a moderate correlation with the average inclination angle. It should also be noted that the existing correlation was negative for these variables, i.e. the higher the dendrometric values, the lower the occurrences of inclination due to the fact that they are inversely proportional variables.

The maximum root plate inclination angle showed a strong correlation with the crown diameter variable (0.70) and a moderate correlation with the total height variable at the 5% significance level. Both negative correlations indicate that the larger the crown diameter and tree height, the lower the maximum inclination value.

There was no significant correlation between the dendrometric elements and the occurrence of root plate inclination, but the highest values were also obtained for the DBH, average crown diameter, crown volume, trunk volume and crown area variables.

In this evaluation it was possible to statistically confirm the relationship between the dendrometric variables, DBH, total height, crown diameter, crown volume and crown area with the root plate inclination. However, only DBH and crown diameter showed a strong correlation with inclination, allowing us to state that more stable trees have higher crown diameter and DBH values.

Discussion

Root plate inclination

The results indicated that the wind was responsible for approximately 51% of the occurrences of tree tilt and this relationship is direct, i.e. the tilt angle is greater as the wind gust increases.

The direct correlation between the maximum inclination of the trees and the maximum wind gusts is due to the dynamic effects of the wind, and so it was to be expected that they would vary depending on the location of the measurements, corroborating the results obtained by James, Hallam and Spencer (2013b). One of the explanations for the points being scattered is probably due to the distance from where the tree analysis was carried out and the wind data recorded at the weather station (Esche, Detter & Rust, 2018). As in the work by Gocke, Rust &

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Rust (2018), the wind condition at the tree was probably different from the wind recorded at the station.

Another important factor is the tree's exposure to the wind. The influence of neighboring trees, buildings and houses can create barriers that influence the stability of a particular tree. Trees in open fields experience more frequent wind impacts during their development and therefore adapt by allocating structural resources to increase stability (Peterson & Claassen, 2013). In contrast, protected trees, when exposed to wind (for example, due to the removal of a neighboring tree), are more unstable because they have not developed structural resources to increase their stability. Although the variation in wind conditions is relevant, it is important to note that no study was found on root plate analysis where the wind conditions were monitored at any given time, all of which used information from the nearest official stations, such as James, Hallam & Spencer (2013b), Gocke, Rust & Rust (2018) and Esche, Detter & Rust (2018).

The urban environment exposes these trees to various external factors that can influence their stability, such as injuries, inadequate planting conditions, wind corridors and barriers formed by the layout of buildings. These characteristics significantly interfere with the tilting behavior of the species, but the analysis carried out showed that wind gusts were a significant factor in determining the maximum root plate inclination value.

The tendency to oscillate in a southwest/northeast direction may be related to the response to northeast winds, which are predominant in the region (INMET, 2019). According to Reis (2005), the predominant annual average wind direction in Minas Gerais is NE, L and SE, and for Sant'Anna Neto (2005), the Southeast region receives winds from the east and northeast throughout the year. According to both authors, the main factor responsible for the predominance of winds in these directions is the South Atlantic anticyclone.

The higher the gust, the more the tree leans and the swaying movement is mainly in the wind's direction, with some lateral and looping movements (James, Haritos & Ades,

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2006). According to the authors, the tree never returns to zero or rest during the swaying movement, it returns in response to the wind. In this study, it was observed that most of the individuals analyzed swayed in the direction of the prevailing wind. Some individuals had a uniform sway without a dominant inclination, which may indicate the true stability of the individual or an unreal stability influenced by nearby barriers such as houses, buildings or other trees that prevent direct action by the wind.

Research carried out to assess root plate oscillation usually only looks at inclination values and not the time monitored during which the trees oscillated. Thus, no records were found on the analysis of this number of oscillation occurrences, all of which solely dealt with the maximum inclination recorded, as can be seen in the studies by James, Hallam & Spencer (2013b) and Gocke, Rust & Rust (2018).

In addition to the maximum inclination, the most common variable to be considered in this type of research, the average of the inclination angles recorded over the monitoring period and the number of inclination occurrences proved important to aid understanding, as they show different results and can therefore contribute to a more detailed analysis.

Bearing in mind that individuals that sway more are possibly less stable, the species that obtained the best results in terms of stability were *Ceiba speciosa*, followed by *Spathodea campanulata* and *Delonix regia*, which may be related to the characteristics of their canopy. These species precisely correspond to the individuals with the largest canopy volume sampled, which is in line with what was discussed earlier, as this is a characteristic which strongly correlates with stability. According to James, Haritos and Ades (2006), the mechanical stability of a tree is its ability to withstand and adapt to the external forces that occur throughout its life.

In strong winds and storms, the less energy transferred from the wind to the tree, the greater the chance of survival. Tree canopies reduce the energy transfer that is propagated to the stem and minimize the occurrence of drag through the dynamic mass damping of the canopy. These results agree with what James, Haritos and Ades (2006) found in their work, in

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which they found that the trees with the lowest number of root plate oscillations were predominantly those with the largest canopy dimensions.

When analyzing the number of tilt events as a percentage of time, *Handroanthus serratifolius* showed the highest number of events. Thus, although it did not have the highest tilt value, it was the species that oscillated the most during the monitoring period, which may also lead to less stability. This result shows that the tilt value and the number of tilt events should not be assessed in isolation to characterize the stability of a tree, as they together provide more satisfactory results.

Influence of dendrometric variables

Regarding the correlations between dendrometric variables and the root plate inclination, other studies have already pointed in the same direction. Peltolaetal (2000) found a significant correlation between the maximum resistive moment at the trunk base, i.e. resistance to uprooting, and the DBH and crown area dendrometric variables. Trees of the same height with larger DBHs were more resistant to uprooting than trees with smaller DBHs.

With regard to average crown diameter, previous studies have reported that as the crown decreases, there is a tendency for the damping effect to decrease, making the trees more susceptible to wind forces (Milne, 1991; James, Haritos & Ades, 2006). In other words, wind loads are minimized by the complex movement of the canopy, reducing the force transmitted to the trunk, from the trunk to the roots and then to the ground.

Trees with larger crowns are more influenced by the wind and this causes growth tensions in the trunk, developing greater mechanical resistance and consequently increasing its resistance to wind gusts (Stathers, Rollerson & Mitchell, 1994). Nielsen (2005) found that larger diameters and larger crown areas imply greater stability when related to height. Thus, the lower the height/diameter ratio and the higher the crown length/total height ratio, the more stable the trees.

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Understanding which dendrometric variables most interfere with the anchoring of trees for different species is fundamental. This is because some authors have already stated that the critical moment for the tree to fall is generally related to its size and does not differ significantly between species of similar size (Peterson & Claassen, 2013; Cannon, Barrett & Peterson; 2015; Ribeiro, 2015). This is why studies looking at different species are essential to improve urban forestry management.

Conclusion

This study contributes to sustainability actions applied to urban planning, since it addresses one of the main problems related to the maintenance of trees in the city: their physical stability. The stability of urban trees is directly related to their ability to withstand wind gusts, since they are exposed to a greater number of harmful and poorly understood external factors in this environment. We found that the maximum root plate inclination was directly related to the intensity of the wind gusts, although the intensity varied even between individuals of the same species.

The root plate inclination angle is smaller in trees with high DBH and crown diameters. Measuring the root plate inclination presented by individuals can help manage the risk of these specimens falling. The diversity of species used in Brazilian afforestation calls for more effective progress in urban forestry development, since the lack of information on basic aspects hinders the consolidation of well-developed planning.

Knowing the behavior of different species is essential to support effective urban forestry management in order to establish more sustainable and resilient cities.

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