An Assessment of Falling Trees Due Strong Winds in LISBON: Affected Species and Microclimatic Simulation

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Abstract: Fallen trees due to strong winds are well recorded in Lisbon. However, species identification is needed to increase urban trees management. This paper aimed at the identification of the most vulnerable trees to strong winds in Lisbon, through a hybrid approach method by proximity. The occurrence database was compiled together with basic structural city maps. Four criteria were designed to presuppose the trees species by approximation: i) Trees must be within 15 m from the street center; ii) At least 3 individuals within 30 m from the occurrence must belong to the same species; iii) The surrounding species must be representative in the street (>50%); iv) Visual analysis of street/avenue medians. Microscale analysis through supervised classification and micrometeorological simulations of strong winds were performed. Morus nigra L., Tipuana tipu (Benth.) Kuntze, Liriodendron tulipifera L., Prunus cerasifera Ehrh. and Koelreuteria paniculata Laxm. were identified as the species that fall the most. In 57.7% of cases (425 fallen trees), the wind speed 12-hours before the occurrence was greater than 7 m s$^{-1}$. Alvalade neighborhood showed 22.7% tree canopy cover while the microclimatic simulation revealed two main vulnerability zones: Brazil and Church avenues, where winds were stronger possibly due acceleration effect.

Keywords: vulnerable trees; street trees; fallen trees; wind simulation; vulnerability zones

1. Introduction

Greening projects in cities are increasingly being encouraged due to all benefits trees bring to urban environment. They contribute to longer pavement life, filtering pollutants, intercepting rainfall, ameliorating urban air temperatures and maintaining local biodiversity and environmental services [1; 2; 3; 4].

Since the Dutch elm disease (DED) in Ulmus Americana L. occurred in the middle of 20th century, east of USA (NY, Chicago, Washington DC), where an accidental introduction of DED devastated millions of trees, urban forest health has been the key factor in urban areas. To maintain urban diversity, Santamour Júnior (1990) [5] recommends no more than 10% of the same species, 20% of genus and 30% of botanical family. According to Lisbon City Hall (2010) [6], the city has more than 600,000 planted trees within the urban area and 200 different species. However, 55% of all trees are only 5 botanical genera [7].

Soares et al. (2011) [8] evaluated the economic benefits of 41,247 street trees brought to Lisbon and found an annually economy of $ 8.4 M (about 7. M € at present rate) to Lisbon City Hall for ecosystems services (energy savings, cleaner air, increased property values, reduced stormwater runoff and CO2 absorption), while $ 1.9 M (1.6 M €) is spent on maintaining, providing a cost-benefit ratio of 4.48:1. Andresen (1982) [9] evaluated the potential suitability of trees species on Lisbon streets
and concluded that *Celtis australis* L. had the best performance, followed by *Tipuana tipu* (Benth.) Kuntze and *Grevillea robusta* A. Cunn. ex R. Br, while *Populus* spp. L. didn’t obtain satisfactory results. Fast-growing species should be avoided in areas of strong winds, such as *Robinia* spp. L. and *Populus* spp. L. [10].

However, along with their benefits, negative impacts can occur during strong winds/windstorms events, when many trees and branches fall in the streets. Therefore, street trees plantation must be carefully planned to maintain their integrity and to prevent their fall onto people, vehicles, etc. In Lisbon, the autumn and the winter are the season where trees fall the most (Figure 1): about 60.0% of total occurrences and the main directions of the storms were from SW, S and W. During the summer, most of the falling branches occurs due to the *Nortada* wind regime, a strong and persistent north wind that occurs frequently in the Iberian Peninsula western coast. The value of 7 m s\(^{-1}\) in a period of 6 hour before the occurrence registered in a database made to study this phenomena was the threshold found to be responsible for the fallen trees [11]. Ribeiro and Lopes (2011) [12] discovered that streets disposed in a north/south direction registered the highest levels of falls due to strong winds provoked by a “canyoning or venturi effect”. Mattheck and Breloer (1997) [13], specialists on biomechanics, realized the adaptive growth, where the trees modify the internal structure of trunks to avoid the rupture and prevent their fall. According to Albers et al. (2003), there are seven categories responsible for fall: decay, fissures, root problems, weak branches union, cankers, bad architecture and deadwood [14].

![Figure 1. Yearly occurrences of fallen trees and branches from 1990-2014. Source: Lopes et al. (2016) [15].](image)

Although trees’ fall occurrences are well recorded in Lisbon, species identification isn’t made correctly and sometimes is totally absent. Then, the objective of this paper was to identify the most vulnerable trees to strong winds in Lisbon, through a method based in “proximity” of individuals.

The results of this paper are organized in two parts: in the first (3.1), the mesoscale pattern (the hole city) assessment of the most fallen species, by means of the proximity approach, was made; The second one (in sections 3.2 and 3.3) the neighborhood of Alvalade (in the northern part of the city), was chose to investigate the main causes (strong wind and phytosanitary conditions) of the falls in the city.

### 2. Materials and Methods

#### 2.1. Study city

Lisbon is located at 38°43’ N and 9°09’ W. The city has 100.05 km\(^2\) with a population about 547,733 inhabitants [16]. The weather is Subtropical-Mediterranean climate (Köppen-Geiger climate classification: Csa), with mild winters and warm to hot summers. According to the Portuguese Sea and Atmosphere Institute [17] the average annual precipitation is 726 mm, average temperatures ranges from 11.6°C in January to 23.5°C in August and winds prevails from north and northeast with average intensities of about 13.5 km h\(^{-1}\).
2.2. Work flowchart

In this research, a Geographical Information System - GIS (ESRI ArcMap) was used to, respectively, evaluate the location of the unknown species by proximity with other known and to determine - with a Kernel Density technique, the areas of the city where the falls had occurred the most in the last 24 years. This contributes will be used in future risk analysis of windstorms in Lisbon. MultiSpec© (Purdue University) for multispectral processing and analyzing image data was used to produce high resolution landcover classification to evaluate the vegetation distribution in the Alvalade neighborhood; and ENVI-met software - a micrometeorological model [18] was used to estimate wind conditions around the buildings during windstorms. At the end of the work, several recommendations were made to maintain urban forest in good health. A flowchart of all processes is shown in Figure 2.

![Flowchart regarding all processes made on this work.](Image)

2.3. Unknown tree species determination by proximity with other known species

The Lisbon Fire Department and the Zephyrus - Climate Change and Environmental Systems research group of CEG/IGOT ULisboa has a database with 3767 cases of falling trees recorded over the period of 1990 to 2014 (with exception of 2009, where data is absent). This database has some limitations that should be mentioned: (i) the record corresponds to the time of the call and not exactly the moment of the fall; (ii) the records don’t refer to falls in parks and squares that didn’t affect any public good; (iii) information about species, size and general condition is not systematically collected by the fire brigade; (iv) many cases may have been recorded hurriedly, which can influence the data reliability. From previous research [11], it was observed that 57.7% fell due wind exceeding 7 m s⁻¹ in a period up to 12 hours before the fire brigade receives the call. These trees were plotted in the GIS and compiled with structural vectored maps of blocks, roads and streets. A list of inventoried trees (47,713 individuals of which 26,595 had scientific names known) was compiled.

For the total assessment of the most vulnerable trees to strong winds all registered falls must be known. Since most of the species names were absent on the original database, we presupposed them through an “approach method by proximity” (Figure 3), designed to infer the specie name by it surrounding conditions. This novel method consists on crossing the fall occurrences database with vectored data where, by proximity of stand individuals and a visual analysis of the planting site, trees’ scientific names can be assumed. This method is possible due to tree line arrangement in the streets. There are four criteria (Figure 3) that must be filled to be considered a positive presumption.
Figure 3. Criteria for specie presumption for Lisbon’s fallen trees database: (i) Trees must be within 15 m from the street center. According to Lisbon’s Master Plan (PDML, 2012), the widest avenue, plus its sidewalks, has 30 m. Then, to be sure all trees on sidewalks will be quantified, a 30 m buffer should be placed. In the figure beside, we can see: 1) the street center ( ), recorded trees ( ) and fallen trees ( ⋆ ); 2) 30 m wide buffer; 3) considered fallen trees ( ▲ ) - contained on the buffer.

ii. At least 3 individuals within 30 meters from the fallen tree ( ⋆ ) must belong to the same specie. According to the planting scheme, trees are spaced in 10 m from each other. We delimited a 30 m distance to ensure the tree belongs to the same specie. So ⋆ is probably *Tipuana tipu* ( ● ).

iii. To be considered a specific specie, the immediate surrounding stand tree must have more than 50% of representativeness from all trees on the analyzed street section. In the example beside there are 19 trees: ( ● ) represents 57.8% of all trees, while ( ◆ ) represents 41.2%. So, ▲ can possibly be ◆ (*Pyrus callierrana*).

iv. A visual analysis of street and avenue medians must be done. Not always the specie planted on sidewalks are the same planted on avenue medians. On the example beside, there are five different species planted on this avenue section. With previous criteria filled, ▲ can possibly be ◆.

After all criteria filled, the original database was updated. Figure 4 shows Lisbon’s planting scheme. Only one specie is planted on each street as a pattern to simplify management actions. However, misplantation can occur - different colors among others indicate different species. The figure also shows the presupposing of a fallen tree (in red) to be *Fraxinus angustifolia* Vahl, though the filling of established criteria above.
Figure 4. Example of trees planting scheme in Lisbon. By completing the above criteria, the fallen tree (in red) specie can be presupposed to be *Fraxinus angustifolia* Vahl (brown).

2.4. Tree canopy cover and sanity of trees: a microscale analysis in Alvalade neighborhood.

The evaluation of tree canopy cover was made by means of a supervised classification of the Alvalade neighborhood (northern part of the city), using a high-resolution image (WorldView-2 satellite). The area has 21.5 ha (495 m x 435 m) and is delimited between Church, Rome and Brazil avenues and Campo Grande (Figure 5). The applied algorithm was ECHO (Extraction and Classification of Homogeneous Objects), to carry out the desired identification and discrimination of street trees [19].

<table>
<thead>
<tr>
<th>Class</th>
<th>Percent</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree canopy</td>
<td>22.7</td>
<td>4.9</td>
</tr>
<tr>
<td>Grass</td>
<td>7.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Asphalt</td>
<td>8.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Shadow</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Ceramic roof</td>
<td>19.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Concrete</td>
<td>39.9</td>
<td>8.6</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100.0</strong></td>
<td><strong>21.5</strong></td>
</tr>
</tbody>
</table>

Figure 5. a) Alvalade studied area. The 74 sampled trees are marked in yellow. The image was taken from Google Earth®. b) Land use and cover thematic map made by supervised classification. The kappa statistic (process accuracy) was 98.5%. The representativeness of the classes and their areas are in the table.

A sample of trees (marked on Figure 5 in yellow) were used and a sanitary inspection was made to assess their health and ecological conditions. This procedure (which results will be discussed further on in the next sections) will allow us to create a set of guidelines for future management plans on the area.
2.5. Wind simulation in microscale using ENVI-met

The ENVI-MET micrometeorological software is a set of models that are able to study the interactions between vegetation, soil and the urban boundary layer atmosphere [18]. Jung et al. (2009) stated that this model is also very suitable to simulate strong winds around the buildings and street trees [20]. A part of Alvalade neighborhood satellite image was photo interpreted and the main features were modeled (Figure 6).

![ENVI-MET digitized model of buildings, vegetation and soil, with their corresponding highs.](image)

The input values for the initial conditions are presented in Table 1. As for this research, the only variables required were wind speed and directions around the buildings (CFD model) the simulation started at 12:00h UTC. In this case, the condition of starting the model in the hour before the heating surfaces starts was not necessary and therefore, not considered. As it was seen before [11], the autumn and the winter are the seasons were street trees fall the most in Lisbon. Therefore, strong southwestern (230º) winds (10 m s⁻¹) day was chosen from the IGOT database and used as scenario for the simulation. The specific humidity at 2500 m was obtained from the University of Wyoming atmospheric soundings database [22]; the other meteorological data was observed in the Lisbon Airport meteorological station, distributed by the NOAA/NCDC (National Oceanic and Atmospheric Administration/National Climatic Data Center) portal [23].

<table>
<thead>
<tr>
<th>Variable</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start simulation at day (dd.mm.yyyy)</td>
<td>18.02.2006</td>
</tr>
<tr>
<td>Start simulation at time (hh:mm:ss)</td>
<td>12:00:00</td>
</tr>
<tr>
<td>Total simulation time in hours</td>
<td>1:00</td>
</tr>
<tr>
<td>Save model state each (min)</td>
<td>60</td>
</tr>
<tr>
<td>Wind speed in 10 m ab. ground (m s⁻¹)</td>
<td>10</td>
</tr>
<tr>
<td>Wind direction (°)</td>
<td>230</td>
</tr>
<tr>
<td>Roughness length (z_0) (m) at the meteorological station</td>
<td>0.1</td>
</tr>
<tr>
<td>Initial temperature of the atmosphere (K)</td>
<td>293.5</td>
</tr>
<tr>
<td>Specific humidity at 2500 m (g/kg)</td>
<td>1.7</td>
</tr>
<tr>
<td>Relative humidity at 2 m (%)</td>
<td>86</td>
</tr>
</tbody>
</table>

Trees inside the model are, in average, 10 m tall. For this reason, the output was exported at 9 m above the ground, where the contact between leaf’s canopy and wind is larger.
3. Results

3.1. Mesoscale analysis: Fallen patterns and species identification in Lisbon

The “approach method by proximity” (explained in section 2.3), allowed the identification of the scientific names of 736 trees (19.5% of all occurrences) (Figure 7).

Figure 7. Map with 3767 falling trees over the period from 1990 to 2014 in Lisbon. Red dots correspond to all tree falls recorded in the period, while green dots, presupposed species of the fallen trees. The frequency of presupposed fallen trees can be seen in the Figure 8, where we compared the current inventoried known species with presupposed falls. We considered trees with, at least, 50 individuals registered on the inventory to guarantee specie representativeness. The top 8 (more than 49‰) is composed by Morus nigra L., Tipuana tipu (Benth.) Kuntze, Liriodendron tulipifera L., Prunus cerasifera Ehrh, and Koelreuteria paniculata Laxm., Sophopora japonica and Populus spp. However, when total falls are analyzed Celtis australis, Tipuana tipu (Benth.) and Jacaranda Mimosifolia are the three most representative because they represent the most common species in the city. Crossing this two groups, Tipuana tipu appears as the most representative in relative and absolute falls and should be considered more vulnerable than the others by landscape architects.

Based on a GIS kernel density technique, the distribution of fallen trees was conducted (Figure 9). As it was pointed out by Lopes et al (2016) [15], the pattern has remained basically the same in the analyzed period (1990-2014): “the main traffic axis and more “urban forested” streets between Baixa and Campo Grande, the Alcântara valley, the plateau of Campo de Ourique, Estrada de Benfica, and Olivais and Encarnação neighborhoods are the most affected”, but new areas in the northern part of the city are emerging as the most hazardous related to tree and branches falls: namely along Alameda das Linhas de Torres (one of the main exits to the north municipalities) and the Telheiras neighborhood (red and yellow areas in Figure 8). According to the authors, this increase of fallings in the last years can be related with the quality of the inventory (that has been recently improved with georeferencing techniques and digital support), or can be due to the aging of specimens and lack of maintenance [15].
Figure 8. a) Fallen trees frequency (‰) in Lisbon (1990-2014). The listed species showed more than 50
individuals on the inventory to guarantee its representativeness. b) Total falls.
3.2. Microscale analysis: Phytosanitary assessment in the Alvalade neighborhood

The phytosanitary assessment was made in the Alvalade neighborhood, one of the most vulnerable in the city (Figure 9) and the samples were obtained from visual inspection, (the procedure was explained in section 2.4 and Figure 5). Drastic pruning’s (43.2 %), included bark (36.5%) and hollows (29.7%) are the main sanity problems found in Alvalade neighborhood trees (Table 2). Although this sample is not representative of the whole city, this situation is a photographic enlightenment on how trees are being mismanaged. The choice of the most adapted species, the improvement of planting sites, the care with correct pruning’s and not to damage/remove roots are the most effective practices in urban forest management. Also, the ideal height of the first ramification (above 1.8 m), for not blocking pedestrians flow on sidewalks is a fundamental measure [15].

Table 2. Sampled trees’ sanity on a part of Alvalade neighborhood. Drastic pruning is responsible for most of the problems found on studied trees. The same tree can have more than one sanity attribute.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drastic pruning</td>
<td>43.2</td>
</tr>
<tr>
<td>Included bark</td>
<td>36.5</td>
</tr>
<tr>
<td>Hollow</td>
<td>29.7</td>
</tr>
<tr>
<td>Weak branch union</td>
<td>28.4</td>
</tr>
<tr>
<td>Deadwood</td>
<td>28.4</td>
</tr>
<tr>
<td>Fissure</td>
<td>27.0</td>
</tr>
<tr>
<td>Interferences (sign/lamppost)</td>
<td>16.2</td>
</tr>
<tr>
<td>Unbalance</td>
<td>13.5</td>
</tr>
<tr>
<td>Shallow root</td>
<td>8.1</td>
</tr>
<tr>
<td>Small bed</td>
<td>1.3</td>
</tr>
</tbody>
</table>

3.3. Microscale analysis: wind acceleration zones

Additionally to structural failures, bad sanitary and health conditions, wind accelerations due to ventury effect in the more exposed streets to southern windstorms (generally north/south oriented) can exacerbate and fasten the falls. Although the relations between the areas of acceleration and the falls are not completely explained, as can be seen in Figure 10 (where the wind simulation for winter windstorm is shown), most of the falls occurred in patches around Brazil and Church avenues...
(northern and southern areas respectively) where simulated strong winds (>9 m s⁻¹) can be observed. Some other areas wind small winds registered falls that can be due to turbulence (not investigated in this paper) and other wind storm directions, that should be investigated in future research.

Figure 10. Wind simulation for winter in Alvalade neighborhood, with wind direction blowing predominantly from SW (230°). Winds vary from less to strong intensities. Higher intensities can be seen around Brazil (northern patches) and Church (southern patches) avenues.

4. Discussion

4.1. Fallen specie identification

There was a higher concentration of fall cases around Lisbon’s downtown area (Figures 7 and 9), especially in the main traffic axis and more “urban forested” streets. Through the approach method by proximity, we can highlight the species most occurrences: *Morus nigra* L., *Tipuana tipu* (Benth.) Kuntze, *Liriodendron tulipifera* L., *Prunus cerasifera* Ehrh, and *Koelreuteria paniculata* Laxm. (Figure 7) respectively, corroborating the results obtained by Rego and Castel-Branco (1998) [24]. In their work, the authors developed a ranking of species adaptability in Lisbon, ranging from 1 (poor adaptation) to 4 (good adaptation). They have found similar results: *Tipuana tipu* (Benth.) Kuntze and *Prunus cerasifera* Ehrh. have a poor adaptation to Lisbon urban conditions (receiving 1 on the rank), while *Koelreuteria paniculata* Laxm. (rank=2) and *Morus nigra* L. (rank=3) were relatively better adapted to same conditions.

4.2. Tree canopy cover and their sanitary conditions

Regardless recording a high number of occurrences of fallen trees on the studied period, Alvalade neighborhood is one of Lisbon’s greenest neighborhoods. The kappa statistic from the supervised classification (Figure 5b) showed excellent process accuracy: 98.5% of concordance, according to Landis and Koch (1977) [25] proposed scale (where values between 0.81 and 1.00 have almost perfect agreement).

The Alvalade neighborhood studied has 22.7% of its area covered by trees’ canopies (Table in figure 5b). This value almost reaches the expected to residential neighborhoods, according to American Forests (2008) [26] that recommends 25% for urban residential areas.

When trees’ sanitary conditions were analyzed, some attention must be paid to how trees are being handled: drastic pruning (43.2%), included bark (36.5%) and hollows (29.7%) are the main sanitary problems found on Alvalade neighborhood trees [15]. This situation lights an alert on how trees are being mismanaged. All the problems can be avoided through the correct choice of species.
that are more adapted to urban conditions, and the improvement of planting sites, removing barriers and obstacles to roots and branches, guaranteeing a healthier plant development. The height of first ramification, above 1.8 m, was considered satisfactory not blocking pedestrians flow on sidewalks. An example of planning it’s seen in the Santo Antonio neighborhood (in Alvalade), where the city government conducted a detailed study of the urban trees, through visual assessment and GIS, to indicate a fall index and the maintenance for each case [28].

4.3. Wind simulation in microscale

It was possible to identify vulnerability zones around Brazil (northern patch) and Church (southern patch) avenues, due to the predominance of SW at this time of the year. The trees probably fell by a phenomenon called street canyoning or ventury effect. Street canyons are formed by local conditions such as high buildings and structures that accelerates wind speeds. A street canyon can be defined by the ratio of adjacent building heights (H) divided by street width (W), also known as H/W or aspect ratio, where a regular canyon has a ratio value up to 1. Authors like Arnfield (2003) [29] and Vardoulakis et al. (2003) [30] studied the influence of street canyons on dispersion of pollutants and it influenced on wind circulation patterns. This phenomenon should be studied on Lisbon’s streets to prevent fall occurrences and give base to better arborization plans, as some examples were previously indicated.

5. Conclusions

Street trees and green parks are essential to provide urban ecosystems services: to mitigate the urban heat island effect, to control the atmospheric pollution, to provide urban diversity, recreation, etc. But along with their benefits, negative impacts can occur during strong winds/windstorms events, when many trees and branches fall in the streets.

The trees falls occurs in all the city but the main traffic axis and more “urban forested” are the most affected. It was possible to presuppose the most frequent fallen species in Lisbon, through approach method by proximity in GIS being, respectively: *Morus nigra* L., *Tipuana tipu* (Benth.) Kuntze, *Liriodendron tulipifera* L., *Prunus cerasifera* Ehrh. and *Koelreuteria paniculata* Laxm. These species showed the worst resistance for urban arborization purpose. In absolute terms, *Tipuana tipu* appears as the most representative because its dissemination in the city and should be considered more vulnerable than the others.

Although a part of Alvalade neighborhood showed to be an arborized site, with 22.7% of tree canopy cover, the trees needs better management, since the main identified problem was drastic pruning (43.2%). This incites the formation of epicormic shoots with weak connection to main trunk, damaging, therefore, biomechanics issues.

Some recommendations must be done like: (i) sanity intervention on urban trees in the city of Lisbon; (ii) the Fire Department should have botanical identifiers on its team for future researches and for standardization of fall records methodology; (iii) choose other areas in Lisbon to perform wind simulations in order to study strong winds and the sanity of trees; and (iv) investigate the relationship between falling trees and H/W ratio.

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Author Contributions: Flávio Mendes analyzed the data, performed the computer simulations and wrote the paper; Felipe Petean revised the English writing and illustrated the approach method using GIS; Ezequiel Correia processed data in GIS; António Lopes supervised the research, analyzed the data and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.
References


