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Assessing the Anchorage and Critical Wind Speed of Urban Trees using Root-Plate Inclination in High Winds

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Abstract. This study demonstrates a new method to assess the anchorage of urban trees by quantitative analysis of the relationship between root-plate inclination and regional wind data. The load required for root failure correlates with loads required to achieve a specified inclination in the non-destructive range. Since load correlates with wind speed, researchers studied the reaction of urban trees in high-wind events. Specifically, researchers studied whether wind data from regional weather stations can be used to find the correlation between wind speed and root-plate inclination. More than 200 trees in 57 storms in three years were tested using tilt sensors, installed at their base. The analyses show that wind-speed data can be taken from weather stations several kilometers away from the tree. The quality of the wind speed-tilt correlation does vary, depending on local conditions and topography. The tree's reaction to wind can be extrapolated by 10 km/h beyond the measured maximum wind speed in many cases. The reliability of the extrapolation can be assessed statistically. The shape of the curve fitted to the wind and tilt data allows differentiating safe from unsafe trees in wind events of 50 to 60 km/h. The curve of trees with signs of failure in high winds was significantly different from that of the remaining trees. Based on techniques from static pulling tests, this approach can be used to estimate the wind speed at anchorage failure. While previous approaches using tilt sensors merely indicate whether a tree needs further monitoring, the result of this method is a likelihood of failure.

Key Words. Anchorage; Germany, Root-Plate Inclination; Tree Risk Assessment; Wind; Wind Load.

In many parts of the world, there is a legal obligation to assess the likelihood of failure of urban and roadside trees (Smiley et al. 2012; Rust 2016). Frequently, failure is initiated by damage to root systems, compromising the anchorage of trees. Consequently, there is a need for cost-effective ways to assess the anchorage strength of large numbers of trees.

Wind is the major load on trees and a principal cause of their failure (Metzger 1893; Jacobs 1936; Mergen 1954). The wind load in the crown causes a turning moment at the base of the tree that inclines the stem base. This stem-base inclination is a function of the turning moment and the stiffness of the root–soil system (Coutts 1983; Lundström et al. 2007).

The initial stiffness of the root–soil system correlates with the anchorage strength of a tree (Neild and Wood 1999; Jonsson et al. 2006; Detter and Rust 2013). Results from static pulling tests on several European and North American tree species show a close correlation of the bending moment required to tilt a tree to 0.25 degrees and the bending moment at failure (Detter and Rust 2013).

Thus, measurements of the rotational angle of the root plate in winds can be used to assess the anchorage strength of trees (James et al. 2013). So far, however, the tilt data are evaluated without using wind data quantitatively and depend on wind measurements as close to the tree as possible. Yet, in many urban sites, where a tree is to be assessed, it will be difficult or even impossible to correctly install a 10 m pole for wind measurements.

To date, quantitative analyses of the relationship between tree motion and gust wind speed have been limited to forests (Mayer 1987; Peltola 1996; Kerzenmacher and Gardiner 1998; Flesch and Wilson 1999; Moore and Maguire 2005; Rudnicki et al. 2008; Schindler et al. 2013; Bullock et al. 2015). Often, instruments were installed rather high on the stem, confounding root-plate rotation and stem bending by tacitly assuming trees were firmly anchored in the ground.

The average wind speed may be far below the gust wind speed. Thus, the randomly occurring gusts pose the main load to the trees. Their size and direction vary, and measuring the wind that a specific tree is exposed to is expensive and technically complex. In this paper, researchers study how peak root-plate inclination per time-slot correlates with the peak wind gust speed in the same time slot, using official regional data and thus avoiding the need for setting up specific instruments close to the trees.

Researchers explore the benefit of empirical relationships between wind speed and inclination to assess data quality. Moreover, storms are rare and occur unpredictably. Therefore, the study authors test whether the reaction of a tree to wind in the more often occurring low wind events can be extrapolated to help to predict the behavior of the tree in stronger storms. Lastly, new criteria to assess the safety of trees using inclination and wind data are proposed.

MATERIAL AND METHODS

Trees and Sites

Two hundred four trees were measured in 57 wind events. A varying number of trees (1 to 20) were tested per storm. The highest wind speeds in the wind events ranged from 40 to 102 km/h (Beaufort scale force 6 to 10). Two hundred trees were in, or near, the city of Rostock, Germany (Figure 1). In Rostock, height above sea level varies between 10 m and 30 m. One tree was standing in Hamburg, Germany, and two trees were located in the Netherlands.

Genera tested included: *Abies*, *Acer*, *Betula*, *Larix*, *Picea*, *Pinus*, *Populus*, *Pseudotsuga*, *Quercus*, and *Tilia*. The height of the trees ranged from 10 m to 36 m, circumferences at 130 cm above ground level ranged from 104 to 505 cm. Several broad-leaved trees were tested in leaf and without leaves.

Detailed results are shown for a row of 10 *Tilia platyphyllos* along a road in a mixed industrial/residential area (mean height: 16.2 m, mean circumference: 1.93 m; Figure 1; Figure 2; Figure 3; Figure 4; Figure 5; Figure 6; Figure 7), an *Abies concolor* growing among single family homes (height: 19.5 m, circumference: 1.74 m; Figure 2; Figure 4), and a poplar in the countryside, just outside of Rostock (height: 30 m, circumference: 5.05 m; Figure 4).

Instrumentation

The inclination of the root plate was measured dynamically using accelerometers (Tree Motion Sensors, argus electronic GmbH, Germany). The sampling rate of these sensors is 20 Hz, and the resolution is 0.01 degree. Sensors were installed at the base of the trunk. Assuming that stem bending of the lowest 5 cm of the trunk is negligible, and neglecting deformation in the root plate, their readings are used as root-plate inclination.

Wind speed 10 meters above ground level was supplied by the website Wind Finder (Wind Finder 2017), reporting data from a weather station located three kilometers east of the city center of Rostock, operated by meteomedia Gmbh (MeteoMedia 2017). The trees are located 3 to 11 km southwest of this weather station (Figure 1). For the analyses, the peak (gust-) wind speed was

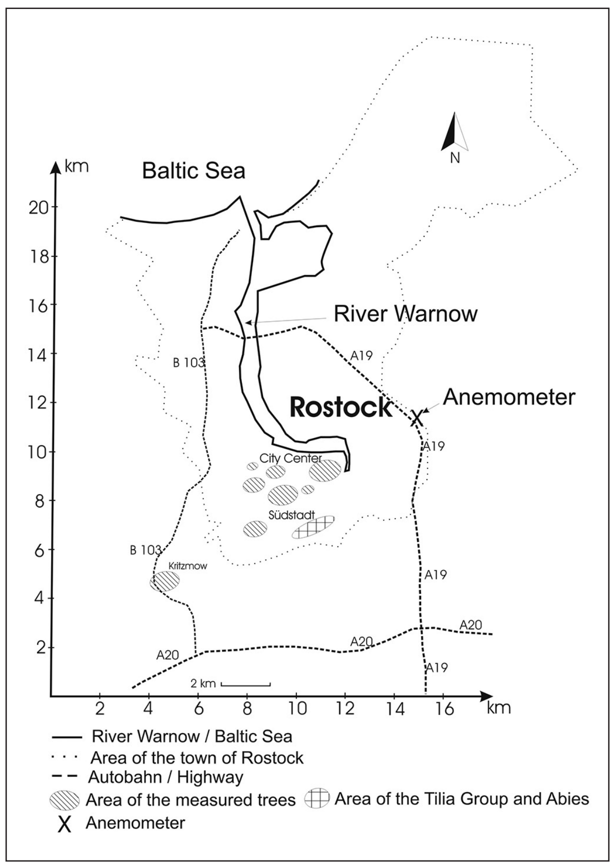

Figure 1. Map of sites in the City of Rostock, Germany.

used. The wind data recorded at this official weather station is subsequently called regional wind.

The wind data of the trees in the Netherlands (by J.W. de Groot, J.H. Wildschut. Boomadviesbureau De Groot) was recorded with a 3-cup anemometer (MAX40+, Ekopower, Netherlands, 1 Hz sampling frequency, 10 meters above ground level).

Tilt Measurement

Similar to the test setup of James et al. (2013), one sensor was attached very close to the base of the tree, at most 5 to 10 cm above ground level. This sensor is called the "base sensor." In many cases, a second sensor was attached at two meters height. This sensor is termed the "control," and was mainly used to distinguish between tilt and ambient noise.

Statistical Analysis

Researchers used wind data of a weather station 3 to 11 km away from the trees. Different gusts will hit the trees and the weather station. Moreover, the distance between weather stations and trees, together with fluctuating wind speed, introduces a time lag between the time series of wind speed and tree inclination. However, there is a high probability that similar gusts will hit both the anemometer and tree within time slots of 60 to 120 minutes. Therefore, wind speed and tree inclination were aggregated, using their maxima over a given period. Using time slots of 60 minutes creates 24 peak-wind and peak-tilt values per day. When the time slot length is increased to 120 minutes, the correlation between wind and tilt increases, but the number of data points per day decreases to 12. In this study, the authors used 60 minutes.

Many models have been developed to analyze the oscillation of individual trees in fluctuating wind (e.g., Mayer 1987; Kerzenmacher and Gardiner 1998). But none provides a mechanistic equation that could be applied to the statistical analysis of the relationship between wind speed and root-plate inclination of the type of trees commonly found in urban areas. Therefore, a simple empirical equation was sought for the regression analyses. While Hale et al. (2010) found a linear relationship between the maximal hourly turning moment and the square of the average hourly wind speed at the canopy top, in this study, an exponential function was preferred because of its greater flexibility and better fit:

$$I = ae^{bu} \qquad [1]$$

where u is the peak gust wind speed per time slot, I is the peak root-plate inclination per time slot, and a and b are parameters.

This function was used to correlate wind and tilt data in all analyses using robust nonlinear weighed regression with the square of wind speed as weights. For further analyses, researchers used a subset of trees that had been monitored in more than three wind events, with one wind event having at least 60 km/h maximum wind speed. Using the exponential function, basal tilt was estimated at a wind speed of 60 km/h, and the wind speed to tilt the trees to 0.25 degrees. Data were analyzed with robust linear and nonlinear mixed-effect models in R (R Core Team 2016).

RESULTS

Quality of Data

Wind speeds below 30 km/h resulted in a very low signal to noise ratio and were omitted from further analyses. Plotting inclination against wind speed allowed researchers to assess the quality of the data and to identify possible outliers (Figure 2). In most cases, the correlation between maximal wind speed and root-plate inclination within a period was satisfactory with an R^2 around 0.75 (Figure 3). This correlation increased with wind speed.

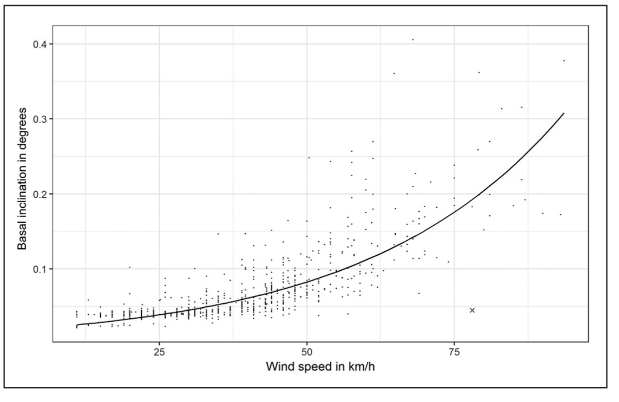

Figure 2. Correlation between maximal wind speed and root-plate inclination for one tree (*Abies concolor*) in five wind events with different maximal wind speeds. The *x* indicates a possible outlier caused by a mismatch of wind data and tilt data. Without statistical evaluation, data points like this might influence the assessment of the tree.

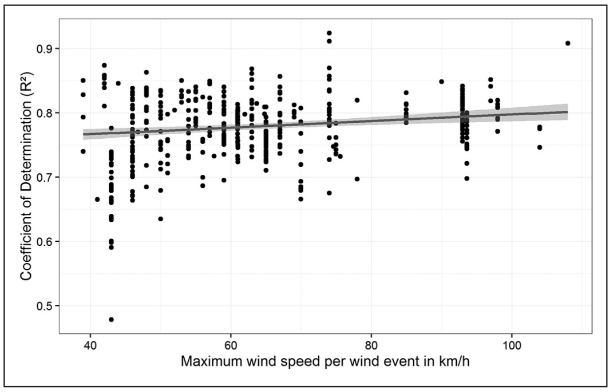

Figure 3. Correlation between maximal wind speed and root-plate inclination in wind events with different maximal wind speeds. Each point represents the coefficient of determination of the correlation between wind speed and basal inclination of one tree in one wind event. The line displays a linear regression with a small but significant positive slope and its confidence interval.

Reproducibility of Results

Results of measurements of the same tree in different wind events, often from different directions, and with or without leaves, were in general comparable.

Figure 4 shows results of an *Abies concolor* measured in five wind events and a *Populus* spec. measured in six wind events differing in direction and magnitude. The *Abies* grows in a suburban neighborhood and is sheltered to the south by a *Betula pendula*, while the poplar grows in the countryside just outside of Rostock and showed clear signs of failure (cracks in the soil around the tree, opening and closing in the wind). Inclination and the slope of the wind-tilt curve were low in all wind events for the fir, but high for the poplar.

Figure 5 and Figure 6 display results of a row of *Tilia* in two wind events, differing in their main direction (Figure 5), and with and without leaves in two wind events of the same direction (Figure 6). The differences between the two data sets are small and not significant. Often, root-plate inclination of trees in leaf and without leaves were comparable, although leafless trees moved considerably faster (data not shown).

In all wind events, and with or without leaves, the reaction of the trees was well below the criteria of unsafe trees, which will be discussed later. However, the response of trees close to buildings was more variable. The street and the trees are north–south aligned. The trees were tested in storms from the west and south. Due to the tunneling and shielding effects of the houses located west of the trees, there were variations of the tilt reaction in the westerly storm. Trees in gaps between houses tilt more than trees sheltered by houses (Figure 7).

Failure

Some trees showed cracks in the soil around the trunk, which in some cases could be observed opening and closing in storms. These trees with signs of root-system failure inclined significantly greater than the rest of the trees (Figure 8). At 60 km/h, the difference was 0.06 degrees (se = 0.009 degrees).

Extrapolation

To test whether results of low wind events can be extrapolated to higher wind speeds, researchers used a subset of 29 trees with data of more than three wind events, one of which had a maximum wind speed of at least 60 km/h. Inclination was then estimated at 60 km/h and 70 km/h from the wind-tilt relationship of every event, so some of these were extrapolated, while others were within the range of measured data. To analyze how the maximum wind speed in a single event influenced these estimates, a linear mixed-effects model was fit to these data (Figure 9). When a 50 km/h wind event was used to estimate root-plate inclination at 60 km/h, root-plate inclination was on average underestimated by 8%, when data are extrapolated to 70 km/h, root-plate inclination was underestimated by 15%.

DISCUSSION

Somewhat surprisingly, in many cases, there was a close correlation between root-plate inclination and regional wind speeds, often recorded some kilometers away from the trees. This distance necessitates the aggregation of the data over periods of up to two hours. The longer these periods are, the better the correlation will be, but the fewer data points remain. When wind data can be recorded at a weather station close to the tree, shorter time slots of 10 to 30 minutes can be chosen.

Outliers in the wind-tilt curves are not errors in either wind or tilt measurements: it rather means that the wind condition at the tree was different from the wind at the weather station, or the wrong time lag was chosen.

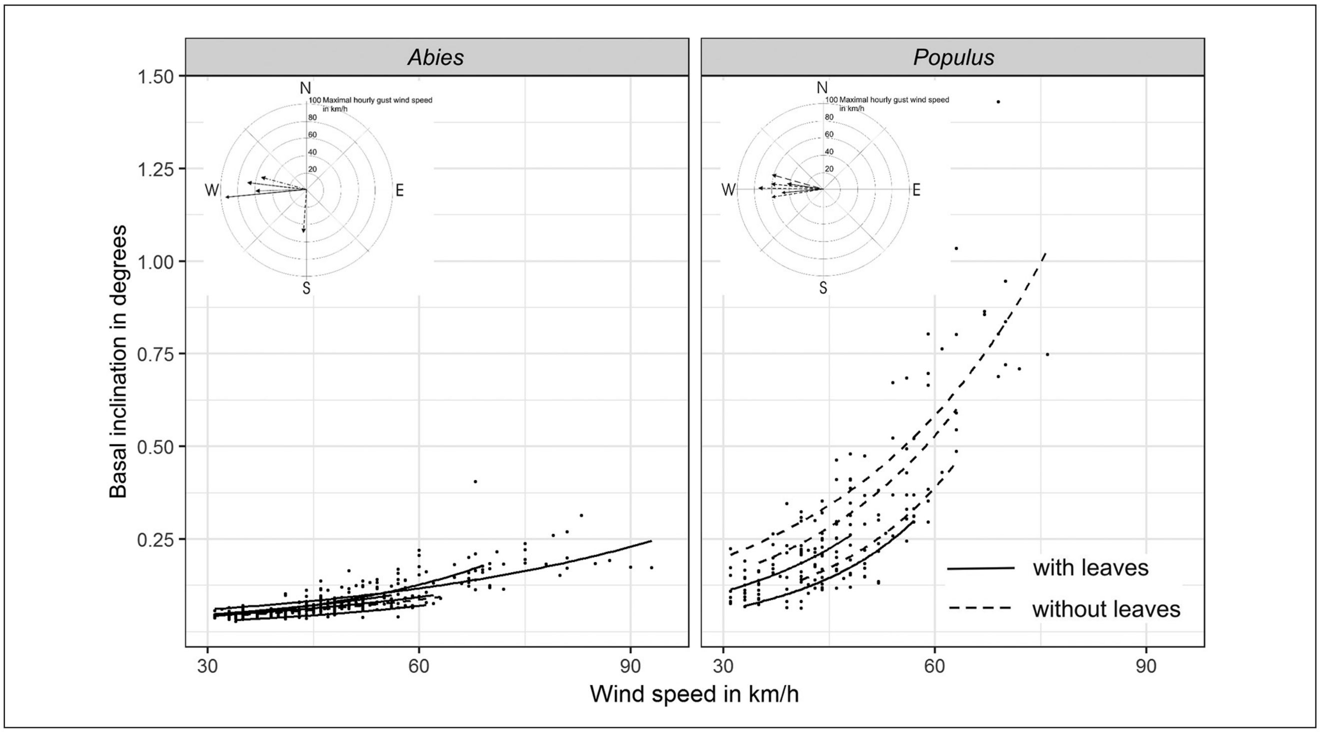

Figure 4. Root-plate inclination of an *Abies concolor* in five wind events and a *Populus* sp. in six wind events, differing in direction and magnitude. The *Abies* grows in a suburban neighborhood, while the poplar grows in the countryside, just outside of Rostock, and showed clear signs of failure (cracks in the soil around the tree, opening and closing in the wind). Inclination and the slope of the wind-tilt curve were low in all wind events for the fir but high for the poplar.

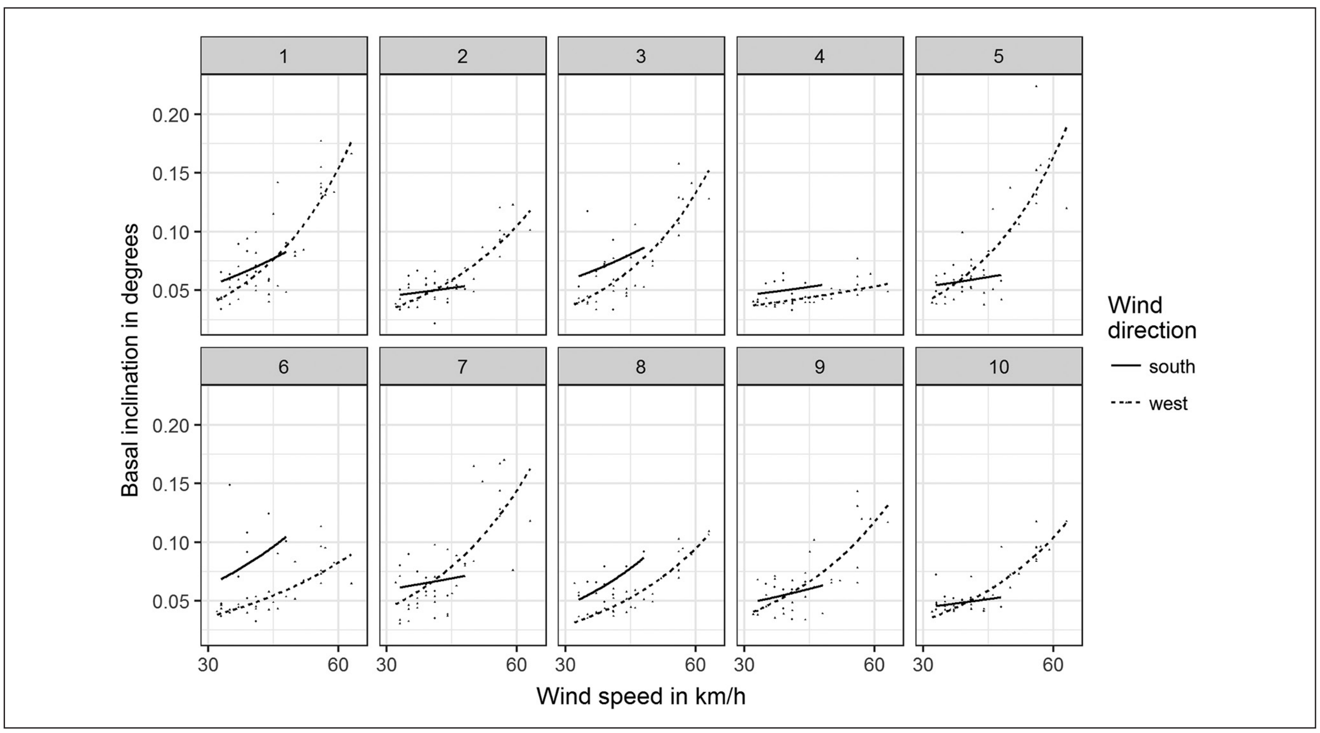

Figure 5. Root-plate inclination of a row of 10 *Tilia* in two wind events, differing in main direction. Each panel displays data of one tree in two wind events.

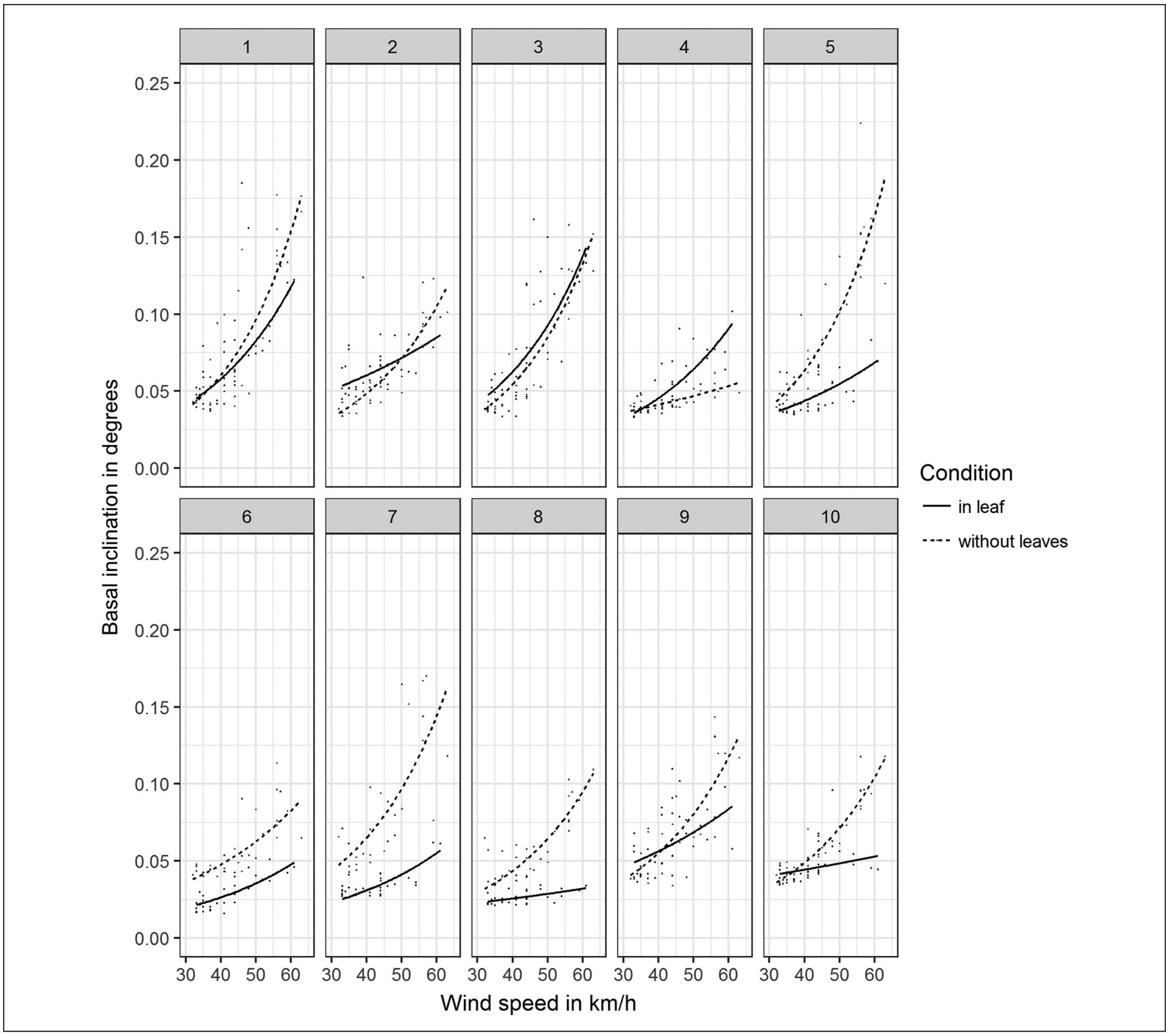

Figure 6. Root-plate inclination of a row of 10 *Tilia* in summer and winter as a function of wind speed. Each panel displays data of one tree in two wind events.

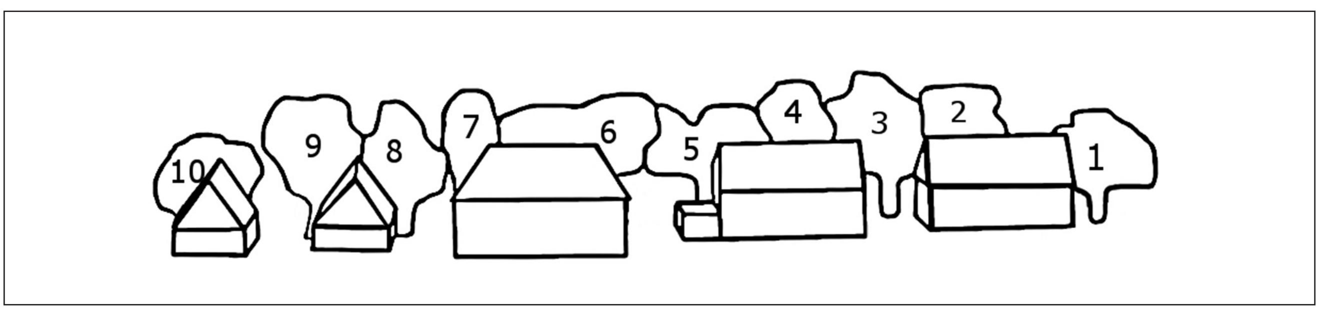

Figure 7. Sketch of the row of the 10 *Tilia* in Figure 5 and Figure 6.

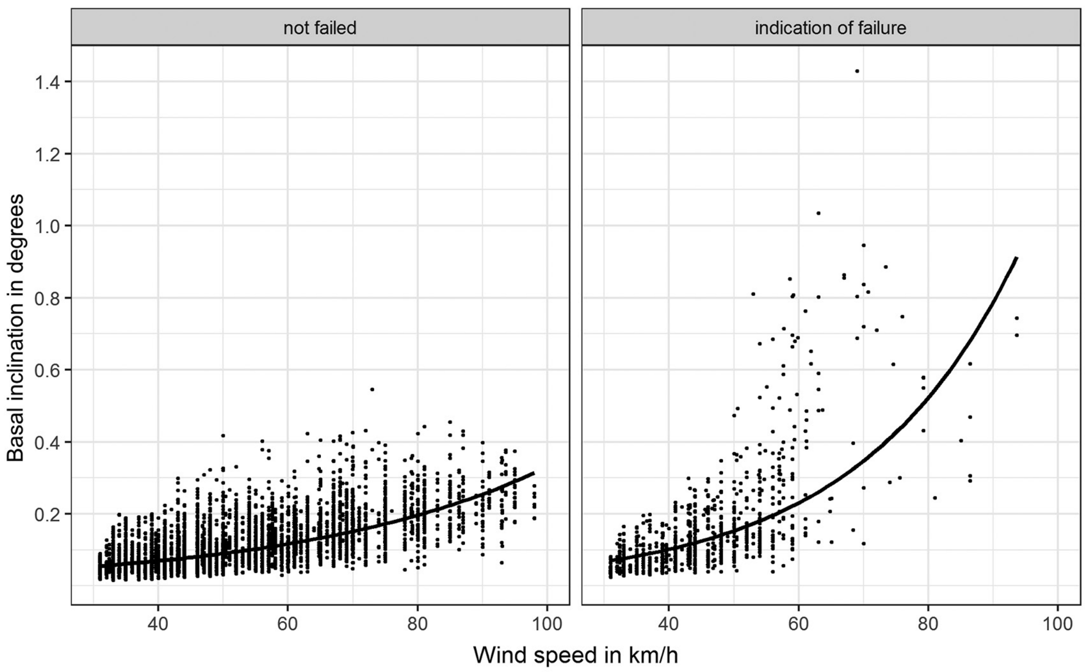

Figure 8. Root-plate inclination of all trees in all wind events, grouped by indications of failure. Two of the trees with indications of failure, including the poplar in Figure 4, failed in a storm in October 2017.

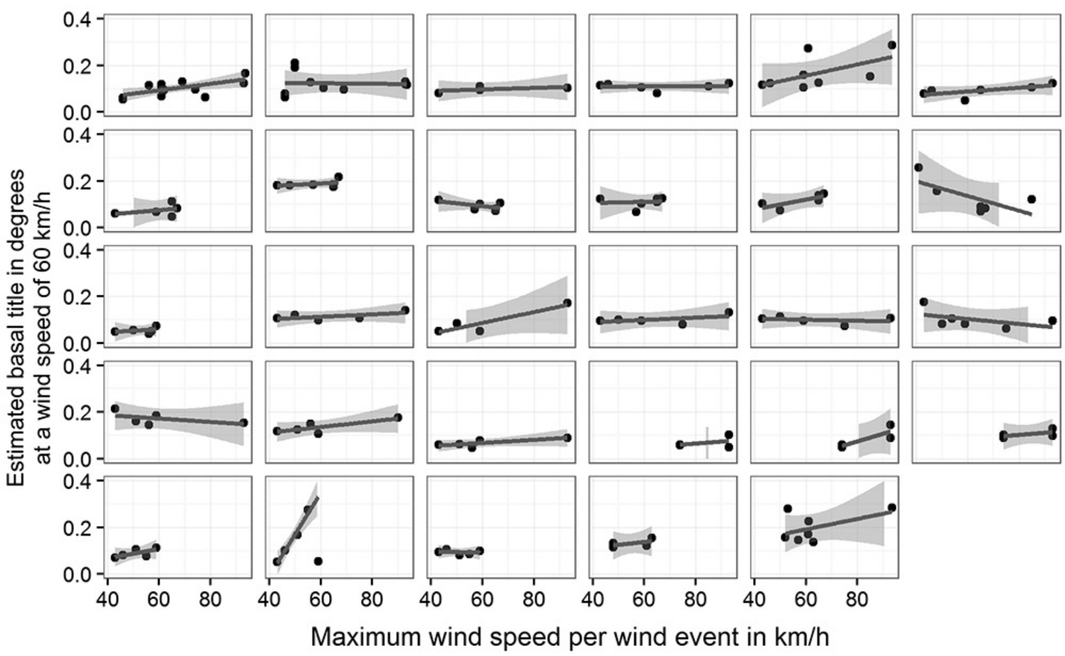

Figure 9. Estimates of root-plate inclination at 60 km/h derived from wind events of different maximal wind speeds. Each panel displays results of one tree (n = 29 trees). Every point is an estimate from one wind event. Points to the left of 60 km/h are extrapolations, points to the right of 60 km/h are not. A horizontal line indicates consistent estimates across wind events, a positive slope indicates that the tree's anchorage is overestimated in low wind events. Regression with 95% confidence interval.

The approach to using a simple empirical regression is justified by the fact that although mechanistic models of the relationship between wind speed and tree inclination might be available (Kerzenmacher and Gardiner 1998; Sellier and Fourcaud 2005; Sellier et al. 2006; Gardiner et al. 2008; Sellier et al. 2008; Sellier and Fourcaud 2009; Pivato et al. 2013), most input parameters of individual trees, like coefficient of drag, wood properties, or crown structure, are not. Previous work has mostly been based on static pulling tests, and used empirical gust factors to account for dynamic effects of wind. This new method can be used to assess these dynamic effects on individual trees without the need for complex and expensive meteorological measurements.

Previously, measurements like those reported here have been interpreted in terms of fixed thresholds, like 0.6 degrees above 60 km/h and 1 degree above 70 km/h (James et al. 2013). The presence of copious outliers demonstrates that using a statistical correlation instead of single data points will avoid the misinterpretation of single, extreme measurements. A statistical analysis will allow researchers to assess the reliability of the results. This is especially important when the correlation is extrapolated beyond the range of measured data. The current analysis demonstrates that the relationship between root-plate inclination and regional wind speed can indeed be extrapolated by at least 10 km/h of wind speed. This considerably increases the occasions and areas when and where this method can be applied.

It is important to emphasize that the wind-tilt curves presented here show the relation of root-plate tilt to regional wind. The wind immediately at the tree might differ from the regional wind because of the tunneling or sheltering effects of other trees or of nearby infrastructure. However, regional wind has been referred to in legal cases when a tree caused damage because it provides the only available data. Thus, knowing the reaction of the tree in relation to that regional wind is helpful to describe and evaluate the root-plate safety.

Some of the trees in the study showed extreme root-plate inclination that has rarely been found so far. After these events, these trees had concentric cracks in the soil close to their base, which is usually interpreted as a sign of failure (Mattheck and Breloer 1993; Dunster et al. 2013). In one of these trees (the poplar in Figure 4), a large root broke during one of our measurements. Researchers used this subset to identify criteria for potentially hazardous trees. Their inclination at medium (>50 km/h) to high wind speeds was consistently higher than in trees without signs of failure. That means monitoring root-plate inclination in storms of 50 to 60 km/h gust wind speed does allow predicting tree safety.

Applications

Measurements and analyses as presented here might be used to assess the anchorage of more trees than is economically feasible with static pulling tests. The assessment will be more reliable than previous approaches of not using the empirical relationship between root-plate inclination and wind speed. The often close statistical correlation allows extrapolating by perhaps 10 km/h, so that more wind events can be used: trees that tilt 0.25 degrees or more at 50 km/h will have an inclination of 0.6 degrees or more at high wind speeds followed by signs of root failure. This is considerably lower than previously proposed thresholds (James et al. 2013), and it is based on data from solitary urban trees as opposed to conifers in plantations (Coutts 1983). A further criterion might be the gradient of the wind-tilt curve: if root-plate inclination increases rapidly at a wind speed of 60 km/h, it is likely to exceed critical values at wind speeds below the design wind speed (e.g., Beaufort 10). All trees within the current study with signs of failure had a combination of poor anchorage and a steep gradient in the relationship between inclination and wind speed.

The major practical limitations of the method will be that it relies on wind events, which may not occur in a given time frame, and on weather stations, which provide representative data for the site. The closer to the tree the wind is recorded, the better the fit of the data will be. In addition, trees might be sheltered by neighboring structures. In these cases it might be better to record at least two wind events from different directions. The method might not be suited for trees in complex terrain where differences between the sites of the tree and the weather station are too large. Rather than for the immediate assessment of a tree, the method will be most suited to medium- and long-term monitoring. At least in one of the trees with decay caused by *Kretschmaria deusta*, anchorage declined over successive wind events.

Standard pulling tests for anchorage rely on the fact that there is a linear correlation between load at a root-plate inclination of 0.25 degrees and load at failure (Detter and Rust 2013). Therefore, wind speed at failure (i.e., critical wind speed) can be estimated from data as presented here, as can a wind-load analysis of the tree. Researchers estimated the wind speed at a root-plate inclination of 0.25 degrees for 25 trees with at least three wind events (Figure 10). When the wind speed had been lower than necessary to incline the tree to 0.25 degrees, the wind-tilt relationship was extrapolated, otherwise measured data were used. Plotting these wind speeds against maximum wind speed per wind event allows researchers to assess the influence of this wind speed on the assessment of the tree. Figure 10 shows relatively low variation for a wide range of maximum wind speed per wind event. Thus, given a design wind speed for the tree and inclination data in high winds, its safety can be assessed and a likelihood of failure estimated.

Acknowledgment. We want to thank the green department of the city of Rostock and Kritzmow for supplying tree information and access to the trees. The company deGroot boomadvisor from the Netherlands contributed valuable data to the tree-wind data base and their accurate wind data helped allot. Two anonymous reviewers helped to improve the manuscript significantly. Franziska Ruhl is an employee of argus electronic GmbH. Lothar Göcke left argus electronic GmbH in May 2017.

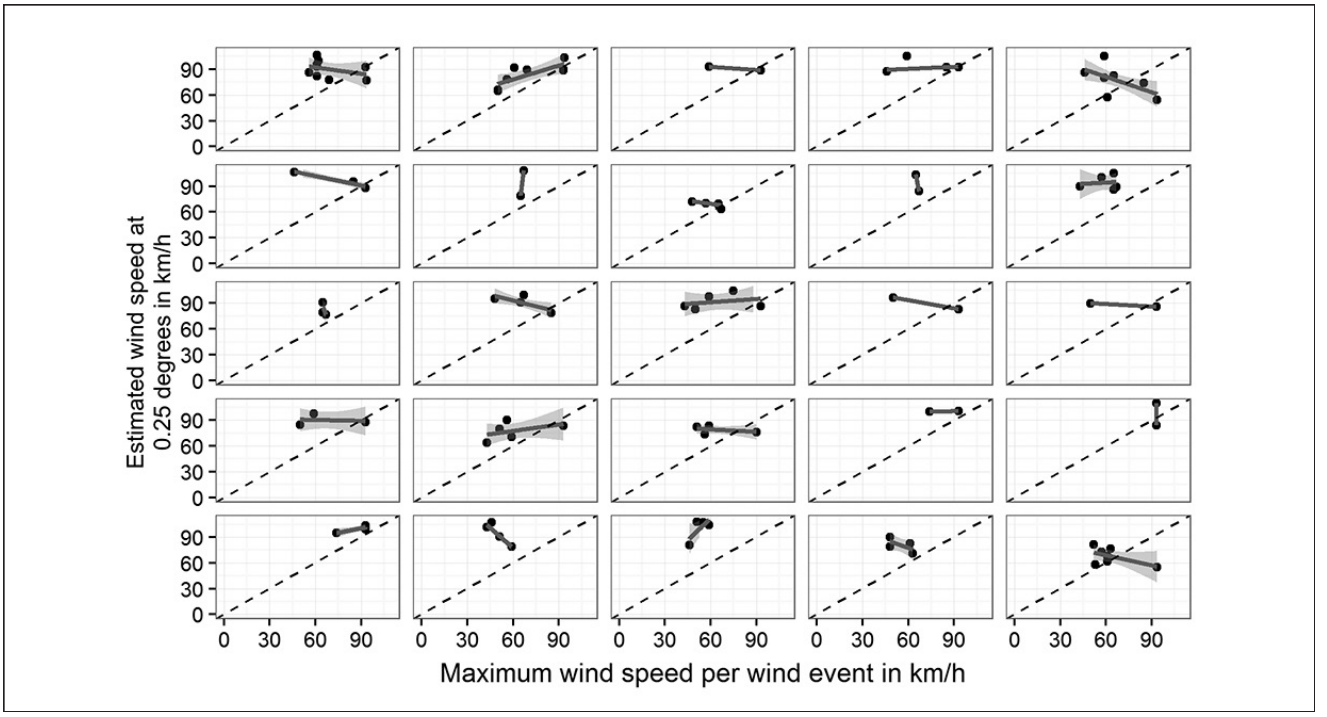

Figure 10. Extrapolated and measured wind speed to cause a root-plate inclination of 0.25 degrees. Each panel displays data of one tree (n = 25 trees). Data points to the left of the dashed 1:1 line are extrapolated from wind events where maximum wind speed was lower than necessary to incline the trees to 0.25 degrees. Points to the right of the dashed line were measured in wind events with higher maximum wind speed. A more or less horizontal line indicates, that estimates of anchorage strength are similar across several wind events. If extrapolation were perfect, all points for one tree should be on a horizontal line. A positive slope indicates that at low wind speeds anchorage is underestimated, a negative slope indicates that the tree was assessed too optimistically at lower wind speeds.

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Résumé. Cette recherche présente une nouvelle méthode pour évaluer l'ancrage des arbres urbains par l'analyse quantitative de la relation entre l'inclinaison de l'assise racinaire et les données régionales sur le vent.

La charge requise pour un déracinement est en corrélation avec les charges nécessaires pour atteindre une inclinaison précise pour une tige sans pour autant entraîner sa destruction. Sachant que la charge est en corrélation avec la vitesse du vent, les chercheurs ont étudié la réaction d'arbres urbains lors de vents violents. Plus précisément, les chercheurs ont évalué si les données enregistrées sur le vent, provenant de stations météorologiques régionales, pouvaient être utilisées pour établir une corrélation entre la vitesse du vent et l'inclinaison de l'assise racinaire. Plus de 200 arbres au cours de 57 orages ont été évalués pendant trois années à l'aide de capteurs d'inclinaison installés à leur base.

Les analyses montrent que les données de vitesse du vent peuvent être recueillies de stations météorologiques distantes de plusieurs kilomètres de l'arbre. La qualité de la corrélation entre la vitesse du vent et l'inclinaison varie en fonction des conditions locales et de la topographie.

Dans de nombreux cas, la réaction de l'arbre au vent peut être extrapolée jusqu'à 10 km/h au-delà de la vitesse maximale mesurée du vent. La fiabilité de l'extrapolation peut être estimée statistiquement.

La forme de la courbe ajustée aux données de vent et de l'inclinaison permet de distinguer les arbres sécuritaires des arbres problématiques en présence de vents de 50 à 60 km/h. La courbe des arbres présentant des signes de déficience lors de vents violents était sensiblement différente de celle des autres arbres.

Sur la base des techniques d'essais avec traction statique, cette approche peut être utilisée pour estimer la vitesse du vent au moment du soulèvement racinaire. Tandis que les approches précédentes, utilisant des capteurs d'inclinaison, indiquaient simplement la nécessité d'un suivi davantage approfondi, le résultat de cette nouvelle méthode est une probabilité de défaillance.

Zusammenfassung. Diese Studie demonstriert eine neue Methode zum Untersuchen von der Verankerung urbaner Bäume durch eine quantitative Analyse der Relation zwischen Wurzeltellerneigung und regionalen Winddaten.

Die erforderliche Windlast für das Wurzelversagen korreliert mit der erforderlichen Last, um eine spezifische Neigung im nichtdestruktiven Bereich zu erzielen. Seit Last mit Windgeschwindigkeit korreliert wird, studieren Forscher die Reaktionen von Straßenbäumen bei Starkwindereignissen. Die Forscher studierten besonders, ob die Daten von regionalen Wetterstationen verwendet werden können, um die Korrelation von Windgeschwindigkeit und Wurzeltellerneigungen zu bestimmen. Mehr als 200 Bäume in 57 Stürmen in drei Jahren wurden mittels eines an der Stammbasis installierten Sensors untersucht.

Die Analyse zeigte, dass die Windgeschwindigkeitsdaten auch von Wetterstationen genommen werden können, die einige Kilometer vom Baum entfernt sind. Die Qualität der Windgeschwindigkeit-Versagen-Korrelation kann in Abhängigkeit von lokalen Bedingungen und Topografie variieren.

Die Reaktion des Baumes auf den Wind kann in vielen Fällen bei 10 km/h über das gemessene Maximum hinaus extrapoliert werden. Die Zuverlässigkeit der Extrapolation kann statistisch untersucht werden.

Die Form der Kurve aus Wind- und Versagensdaten erlaubt eine Differenzierung von sicheren und unsicheren Bäumen in Windereignissen von 50-60 km/h. Die Kurve von Bäumen mit Anzeichen von Versagen bei starken Winden war deutlich anders als die der verbliebenen Bäume.

Basierend auf Techniken aus statischen Zugversuchen, kann dieser Ansatz dazu verwendet werden, die Windgeschwindigkeit beim Versagen der Verankerung zu bestimmen. Während vorherige Ansätze die Versagenssensoren hauptsächlich als Indikator verwendeten, ob der Baum weitere Überwachung erfordert, kann das Resultat dieser Methode etwas zur Wahrscheinlichkeit des Versagens aussagen.

Resumen. Este estudio demuestra un nuevo método para evaluar el anclaje de árboles urbanos mediante el análisis cuantitativo de la relación entre la inclinación de la placa de la raíz y los datos regionales de viento. La carga requerida para la falla de la raíz se correlaciona con las cargas requeridas para lograr una inclinación especificada en el rango no destructivo. Dado que la carga se correlaciona con la velocidad del viento, los investigadores estudiaron la reacción de los árboles urbanos en eventos de vientos fuertes. Específicamente, los investigadores estudiaron si los datos del viento de las estaciones meteorológicas regionales se pueden utilizar para encontrar la correlación entre la velocidad del viento y la inclinación de la placa de la raíz. Se probaron más de 200 árboles en 57 tormentas en tres años utilizando sensores de inclinación instalados en su base.

Los análisis muestran que los datos de velocidad del viento se pueden tomar de estaciones meteorológicas a varios kilómetros del árbol. La calidad de la correlación de velocidad-inclinación del viento varía, dependiendo de las condiciones locales y la topografía.

La reacción del árbol al viento puede extrapolarse a 10 km / h más allá de la velocidad máxima del viento medida en muchos casos. La confiabilidad de la extrapolación puede evaluarse estadísticamente.

La forma de la curva ajustada a los datos de viento e inclinación permite diferenciar árboles seguros e inseguros en eventos de viento de 50 a 60 km / h. La curva de los árboles con signos de falla en los fuertes vientos fue significativamente diferente de la de los árboles restantes.

Con base en las técnicas de pruebas estáticas de tracción, este enfoque se puede utilizar para estimar la velocidad del viento en caso de falla de anclaje. Mientras que los enfoques anteriores que usan sensores de inclinación simplemente indican si un árbol necesita más monitoreo, el resultado de este método es la probabilidad de falla.