University of Sopron (Soproni Egyetem)

Simonyi Karoly Faculty of Engineering, Wood Science and Applied Arts

The József Cziraki Doctoral School of Wood Science and technologies

The reliability and applications of dynamic tree stability inspection

Author: Shadabeh Fathi

Supervisors: Prof.Dr. László Bejó and Prof. Dr. Ferenc Divós

Sopron

`

2020

The reliability and applications of dynamic tree stability inspection

Dissertation for doctoral (PhD) degree

University of Sopron József Cziráki Doctoral School

of Wood Sciences and Technologies

………………………….………... programme

Written by:

Shadabeh Fathi

Made in the framework of….. programme

of the József Cziráki Doctoral School, University of Sopron

Supervisor: Dr. ….. I recommend for acceptance (yes / no)

(signature)

The candidate reached 100 % at the complex exam,

Sopron, ...

Chairman of the Examination Board

As assessor I recommend the dissertation for acceptance (yes/no)

First assessor (Dr. ....) yes/no

(signature)

Second assessor (Dr. ....) yes/no

(signature)

(Possible third assessor (Dr. ....) yes/no

(signature)

The candidate reached ....% in the public debate of the dissertation

Sopron ,….. ....

Chairman of the Assessor Committee

Qualification of the doctoral (PhD) degree …..

`

....

Chairman of the University Doctoral

and Habilitation Council (UDHC)

`

DECLARATION

I, she undersigned Shadabeh Fathi by signing this declaration declare that my PhD thesis entitled The reliability and applications of dynamic tree stability inspection was my own work; during the dissertation I complied with the regulations of Act LXXVI of 1999 on Copyright and the rules of the doctoral dissertation prescribed by the University of Sopron József Cziráki Doctoral School, especially regarding references and citations.

Furthermore, I declare that during the preparation of the dissertation I did not mislead my supervisors or the programme leader with regard to the independent research work.

By signing this declaration, I acknowledge that if it can be proved that the dissertation is not self-made or the author of a copyright infringement is related to the dissertation, the University of Sopron is entitled to refuse the acceptance of the dissertation.

Refusing to accept a dissertation does not affect any other legal (civil law, misdemeanour law, criminal law) consequences of copyright infringement.

Sopron, 2020/09/17

…………………………………..

Shadabeh Fathi

`

Table of Contents

`

`

List of figures

`

`

`

List of tables

`

`

Chapter I. Introduction and problem statement

The stability of trees is an important issue both in the forest and in an urban environment. In the forest, tree stability is especially critical in the proximity of roads and hiking trails, where falling trees may pose a serious risk of accidents. From an economics point-of-view, individual tree stability is less consequential. In this case, research usually focuses on the statistical evaluation of the windfall damage caused by different levels of high wind (e.g. Moore and Maguire 2005; Peltola 2006)

In an urban environment, trees provide many benefits, including shading, windbreak, decoration, relaxation, improved air quality and reduced temperatures. Unfortunately, urban trees sometimes also pose various risks. Falling branches, trunk breakage or uprooting do not only lead to nuisance and cleanup expenses. They may result in considerable damage to public and private property, and also in personal injury, or, in extreme cases, death. The accurate assessment of tree stability and safety is therefore crucial in preventing these highly undesirable outcomes.

1.1 The assessment of tree stability and safety

The simplest way to determine health of urban trees is by visual inspection. Certain problems may be identified based on visible signs. Structural stability and safety cannot be directly established by this method, However, visual characteristics can serve as the basis for determining the health and structural integrity of trees, which has a knock-on effect on stability. Visual tree inspection also requires special expertise, much anatomical knowledge and practical experience, and leaves a lot of room for human error.

Most information of visual inspection can be obtained from the tree crown. Tree growth characteristics and the impact of weather conditions leave a visible mark on the trunk of trees. Root system damages may also be recognized by visual inspection. Sometimes these damages do not have an immediate effect on the

`

health and stability of the trees, but in time noticeable discrepancies appear. According to the standard (WSL 1997) in completely healthy trees, 100% of the leaves have normal color and size. If any part of the foliage is damaged, it is a sign that the quality and health of the tree is compromised. The standard classifies trees into 4 health categories (slightly damaged, significantly damaged, severely damaged and dead), based on the percentage of damage to the foliage. Early detection of signs like crown damages or trunk idiosyncrasies may prevent more serious damages or unfortunate accidents related to trees.

Advancement in nondestructive testing (NDT) led to the development of a number of more reliable techniques and instruments in the past 75 years. Various methods and techniques have been advanced during these years, and various manufacturers offer equipment for tree condition and safety assessment.

Applicable non-destructive techniques include the following:

- Sound velocity evaluation
- Acoustic tomography
- Impedance tomography
- Resistance drilling
- Static pulling test
- Acoustic root mapping
- Electromagnetic radiation-based techniques
- Ground penetrating radar (for root detection)

`

Non-destructive testing has several advantages compared to visual assessment. Instrument-based measurements are replicable, more reliable, and – depending on the technique applied – often faster and simpler than a thorough visual inspection. On the other hand, some of the techniques – like the pulling test for example – are tedious and time consuming. Also, the interpretation of the results often requires specialized knowledge and expertise, and instrumented measurement results are best interpreted coupled with the conclusions of visual inspection

The traditional and accepted way to directly establish tree stability is the pulling test. It is a very well researched and established method, based on theoretical considerations of tree mechanics, as well as extensive practical experimentation (Brudi and Wassenaer 2002). This method is considered as a standard in most of Europe (especially in Germany) for tree stability evaluation, and is also applicable for trunk safety assessment. However there are several disadvantages associated with this technique, including:

- testing is tedious; it requires heavy equipment (cable, winch, ladder, etc.) to be lugged to the test site;

- it is also time-consuming; testing one tree (including setup, testing and dismounting) takes approx. 30 minutes;

- testing requires wind velocities below 20 km/h, because heavy winds may interfere with the test through modifying the loads and movement/deformation.

- an anchor point is needed for fixing the cable. Such point may not be readily available, at least not in a convenient direction or distance;

- finally, and most importantly, testing is done in a static manner, while the lateral wind loading that may uproot or break trees is dynamic in nature. The behavior of trees may be very different under dynamic loading, especially since the trunk, branches, twigs and leaves constitute a complex vibrating system, and static loading is probably a poor representation of such situations.

`

Nevertheless, static pulling is a safe, well-established method with a solid theoretical basis. A better, less tedious and dynamic method would be favorable, but only if its reliability can be clearly demonstrated.

1.2. Dynamic tree stability assessment

A novel approach emerged recently for assessing tree stability and trunk safety. Instead of static loading, this technique uses actual wind loads. This is a more realistic loading scenario, but unfortunately the interaction of the wind loads and the movement of the various part of the tree is a highly complex process, governed by many variables, and impossible to accurately describe or model at our current level of scientific advancement. Therefore there is no direct correlation between momentary wind loads and tree movement or deformation. Scientists have been able to overcome this problem by employing a statistical approach, which will be described in more detail in chapter 3.3.

In addition to the above-described challenges, there are other issues that need to be considered when employing dynamic testing. One of these is wind direction. Depending on the geographical area, winds most frequently blow from the same point of the compass. Such winds are called prevailing winds, and their direction depends on the geographical location. Prevailing winds are often strong, and therefore trees tend to develop their crown, trunk and root systems so as to be most resistant in this direction. On the other hand, "the wind blows wherever it wants" (John 3:18, NLT), and is under no obligation to follow the prevalent direction. The stability of trees can be markedly different in crosswinds than in prevailing winds, and the operator has no control over this factor.

As with any kind of approach, dynamic tree stability assessment has various advantages and disadvantages. Advantages include the following:

`

- Testing is simple, does not require heavy equipment, much preparation, or dangerous maneuvers like climbing the tree.
- Although testing is time consuming, several trees can be measured at the same time, which ultimately makes it more productive than the pulling test.
- Trees are tested in realistic, dynamic loading scenarios.
- The determination of the safety factor (a measure of tree stability) is much simpler; it does not require tree geometry and drag factor that may be complicated to measure accurately and introduce a measure of uncertainty in pulling test results.
- Low wind velocity is not a requirement for the measurements.

Disadvantages include:

- Measurement requires a wind velocity of at least 25 km/h,
- There is less control on measurement parameters, including loading intensity and measurement (wind) direction,
- This technique is not as well established as the pulling test; information supporting the reliability and usage experience is still being collected. Therefore arborists are often skeptical.

Since the dynamic method allows testing several trees at once with ease, it may be a useful tool to examine several trees in various conditions to extend our knowledge base about the behavior of trees in different circumstances, and examine the effect of factors such as wind direction, precipitation, temperature, pruning, etc. This was the primary goal of the doctoral research project outlined in this dissertation, along with collecting further data about the applicability and reliability of the new technique.

`

1.3. Research objectives

The main goals of the doctoral research described in this dissertation were, as follows:

- The verification of the applicability and reliability of the dynamic testing technique for tree stability assessment by comparing its results to static testing and uprooting test results.

- Assessing how dynamic tree stability is affected by various factors, including:
  - soil moisture content,
  - wind direction, and
  - seasonal foliage changes.

- Assessing the effect of anthropogenic influences on the stability of trees, through examining the effect of root damages and pruning.

`

Chapter II. Literature review

2.1. Nondestructive testing

Non-destructive testing is a descriptive term used for the examination of materials and components in such a way that does not destroy them or change their usefulness. NDT or NDE (Nondestructive Evaluation) can be used to find, localize and measure surface and subsurface flaws and defects, to examine the internal construction of materials and structures, or to estimate various material characteristics in a non-invasive (or minimally invasive) way.

The first NDT-method coming into industrial application was the X-Ray Technique in 1895 by Conrad. Non-destructive testing as a modern industry emerged after the Second World War. Nowadays the NDT technician has become the front-line diagnostic professional providing material measurement and monitoring to all industries. NDT methods have become the materials evaluation choice in the field on all private sector areas. (IAEA 2001)

Ultrasonic testing was the latest to come to the industry approximately in 1912. The industrial use of ultrasonic testing started simultaneously in three countries: the USA, GB and Germany. In 1931, Saddik obtained a patent for using ultrasonic waves, using two transducers to detect flaws in solids.

Preliminary research on nondestructive testing for wood and wood products was first done in Germany. Many different types of equipment and techniques were developed for the wood industries during the decades, and are now in widespread use. Recently, in addition to wood and wood products, researchers started focusing on testing trees as well.

Since trees are considered natural capital, there is an increased emphasis around the world to address forest and ecosystem health issues. The marketplace is becoming increasingly global in nature. The biggest motivation to pursue non-destructive testing in the wood and wood product industries was the need to use them in the

`

best way possible. These challenges necessitate accurate, cost-effective non-destructive tests (Brashaw et al 2014).

Postharvest non-destructive evaluation methods such as machine stress rating (MSR), and ultrasonic veneer grading have been the standard procedures for evaluating wood stiffness and strength. Wood quality research had shown that most properties of wood can be predicted by a range of nondestructive methods, and also through simple acoustic measurements in live trees (Wang et al. 2007)

Non-destructive tests can detect internal decay and defects in urban and forest trees. The science of tree stability analysis uses non-destructive evaluation and biological and engineering principles.

In some of the research to evaluate the stability of trees, the roots were examined. Many factors affect the root system (soil conditions, weather, age of tree, biological factors). Root length, root angle, number of roots, and root diameter varies greatly between species. In trees, as in engineered structures, if the normal service loads create stresses that are just below the strength of the material, they have practically no strength reserve, and the smallest accident may lead to breakage (Matteck et al 1993).

Wood in trees is flexible, and behaves as neither an ideal solid nor an ideal fluid (Vogel 1996). Trees should be able to safely withstand high winds. The safety factor is calculated relative to the high wind level typical to a geographical area (Cullen 2002).

`

2.2 The assessment of tree health and safety using nondestructive methods

Trees provide enormous benefits, such as balancing the ecosystem, prevention of desertification and global warming, as well as human well-being in urban ecosystems (Pitarma et al 2018). As mentioned in section 1.1 there are many types of equipment for evaluating the trees. These will be introduced in this section.

2.2.1. Resistograph

The Resistograph is a reliable device for assessing the condition of trees as well as that of wooden structures. The device is based on a drilling resistance measuring method by Rinn (1990) in Heidelberg, Germany.

This device (**Figure 1**) is designed so that arborists are able to detect wood decay, stages of rot, hollow areas, cracks and ring structure (Allison and Wang 2015). As the micro drill enters the tree, the resistance of the wood causes increased power uptake in the drill. The instrument translates these variations into a diagram, which is printed by a Bluetooth printer (**Figure 2**) or may be downloaded to a computer. Variations in drilling resistance are evident in the diagram; a region of lower resistance usually implies some form of internal damage (like rot or cavities).

Figure 1 – The Resistograph equipment

`
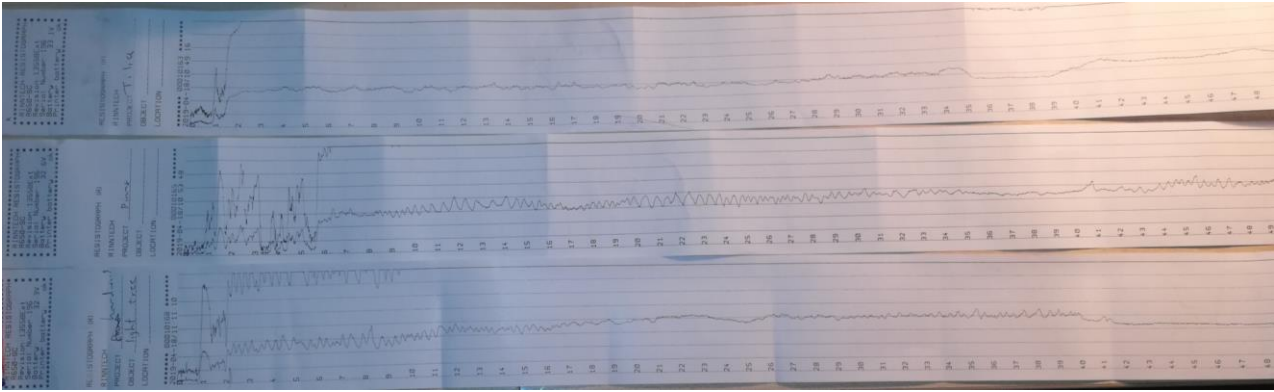
Figure 2 – Printouts of some Resistograph tests

More sensitive versions of the equipment have higher spatial resolution and can even detect variations due to different early wood and latewood density, and thus the annual ring structure can be examined.

One limitation of the device is that it should be precisely oriented so that the path of drilling goes through the decay zone, cavity or other internal anomaly in the trunk. It has been suggested that the resistograph technique is best suited to confirm and determine the extent of decay in trees after suspect trees are identified by other methods such as visual inspection, stress-wave timing or acoustic tomography (Allison and Wang 2015).

2.2.2. Impedance Tomography

This equipment is able to detect the size and location of regions with active fungi attack in the trunk non-destructively It works based on electric resistivity measurements using several sensors around the trunk (**Figure 3**).

`

Figure 3 – Impedance Tomography (Vizvári, et al.2015)

The basic measurement principle is that electrical resistivity increases/decreases if there is a change in the concentration of ions in a certain region within the trunk. Impedance tomography is based on creating an excitation field inside the trunk and measuring potential differences between several sensors around the circumference. This allows the creation of a "resistivity map", or tomogram, which may facilitate the detection of fungal attacks even in the very early stages when the mechanical performance of the tree is not yet affected, or when the disease does not affect the mechanical properties at all.

Electrical impedance tomography was first applied to wood by Just and Jacobs in 1998. After that there have been several applications of this technique, e.g. to detect decay (Dubbel et al. 1999, Bieker and Rust 2010a), red heartwood in beech (Weihs et al. 1999, Hanskötter 2004) and in wild service tree (Weihs 2001), and brown heartwood in ash (Weihs et al. 2005). It can also be used to determine the exact sapwood area in various species (Bieker and Rust 2010b, Lin et al. 2012), and to detect red hart in beach (Goncz et al. 2017).

2.2.3. Acoustic propagation time measurement

`

A simple acoustic wave propagation velocity measurement technique is based on measuring the sound propagation time (or Time of Flight, ToF) between two sensors, typically placed on opposite sides of the tree trunk (**Figure 4**). Measured propagation times are shorter in healthy material, but longer if there is decay in the measurement path, because the signal is usually forced to 'detour' around the decayed area. Wave velocity (calculated from the measured time and the distance of the sensors) is compared to a reference value (either measured on a healthy tree, or taken from literature, e.g. Divos and Szalai 2002) to determine the probable presence of decay.

Figure 4 – Schematic photo showing the operation principle of the Microsecond Timer (Divos et al 2011)

`

The stress wave timing method was first applied to determine degradation in trees by Mattheck and Bethge (1993), and has been in use as a simple yet effective technique since. While this technique can detect the presence of extensive decay with good probability, it cannot determine the extent or exact location of the damaged area.

2.2.4 Acoustic tomography

The acoustic tomograph is designed to detect hidden holes and decay in trees by non-destructive acoustic testing. The measurement is an extrnsion of the simple stress-wave timing technique, based on attaching several sensors around the trunk (**Figure 5a**), and measuring sound propagation time between each pair of sensors. Data is then analyzed using reverse backpropagation to create a high-resolution sound-velocity map of the trunk cross section, where lower velocity regions may indicate decay, cavities or some other internal anomaly (**Figure 5b**).
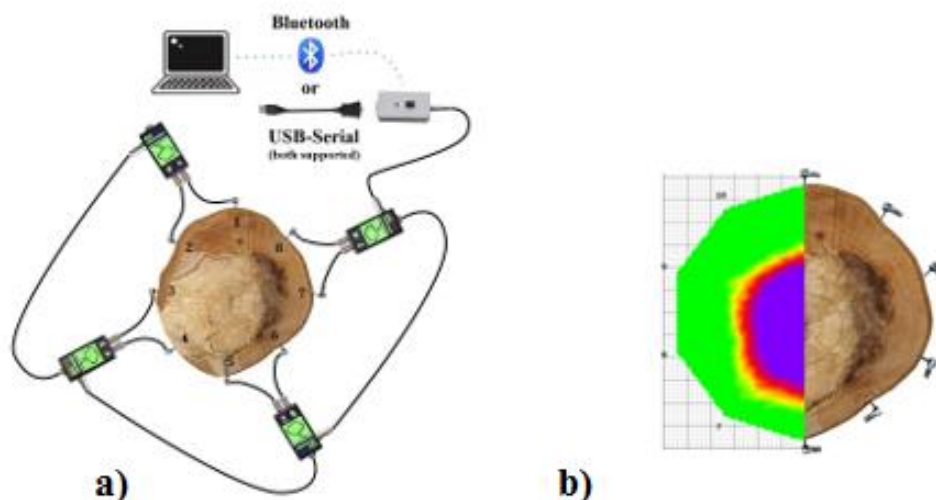
Figure 5 – Acoustic tomography (Major & Divos 2015)

Several versions of acoustic tomographs have been developed and evaluated over the past two decades. It was successfully applied to detect internal decay hidden

`

from view within the trunk of trees (Nicolotti et al. 2003, Gilbert and Smiley 2004, Wang and Allison 2008, Wang et al. 2009.) Some versions of the available evaluation software is also capable of creating 3D maps by measuring several cross section layers of the same trunks at different height (Divos 2010).

2.2.5. Root Detection

The structure and condition of the root system has a very important effect on the health and stability of trees. Unfortunately, the position and condition of roots is very difficult to assess without excavating. Attempts to use nondestructive assessment included the use of ground penetrating radar (Guo et al. 2013) and nd electric resistivity tomography (Amato et al. 2008; Zenone et al. 2008).

More recently, an acoustics-based approach was presented for determining the location and orientation of the roots in the soil (Buza and Divos 2016). It works based on sound velocity measurements between a sensor attached to the trunk and a soil sensor placed close to the root (**Figure 6**). By adjusting the position of the soil sensor while keeping a constant distance from the trunk enables operator to map major roots that run close to the surface (**Figure 7**). The benefit of this method is that other trees' roots, pipes or other buried materials do not affect the measurement. (Divós et al. 2009)

`

Figure 6 – Photograph showing the measurement principle used for root detection
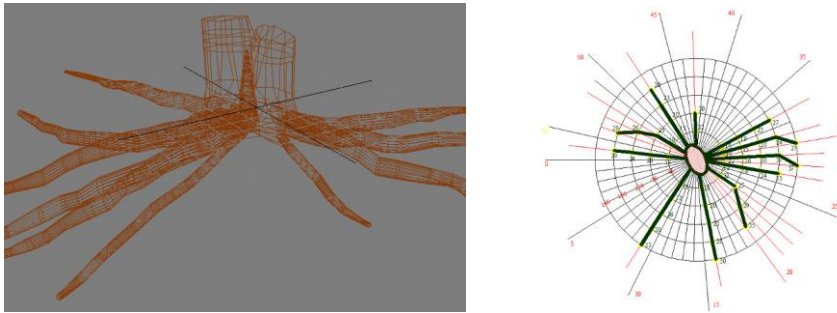
Figure 7 – Demonstration of the results obtained from a root detector (Divós et al. 2009)

2.2.6. The pulling test

This technique is based on attaching a cable to the tree (at the approx. center of the crown), and exerting increasing lateral loads on the tree, while measuring the inclination of the root collar and/or the deformation of the trunk. The loading test is terminated at an inclination of 0.2 degrees, well before any damage could be caused to the tree. From the load-inclination or load-deformation curves, the uprooting or trunk failure moment can be estimated, and the safety of the tree concerning uprooting or breakage can be calculated, respectively, based on tree geometry and other factors.
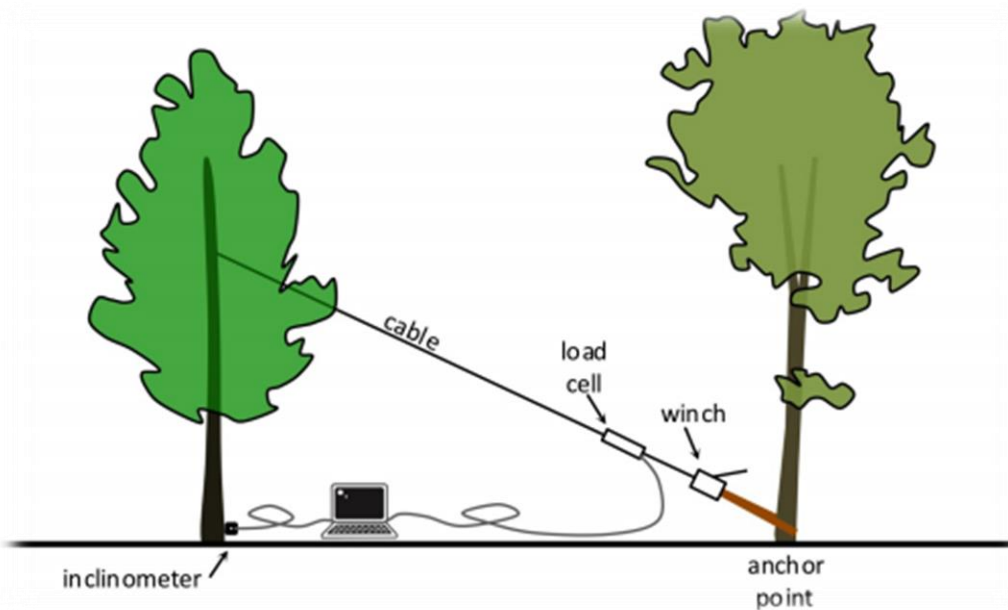
Figure 8- Schematic view of the pulling test (Buza & Divós 2016)

`

The pulling test technique has been in use since the early 1990's. Plenty of excellent papers are available on the implementation and the usage of these tests. **Figure 8** (Bell et al. 1991; Wessolly 1991; Rodgers et al. 1995; Ray and Nicoll 1998; Neild and Wood 1999; Moore 2000; Peltola et al. 2000; Silins et al. 2000; Brudi and Wassenaer 2002; Clair et al. 2003; Lundström et al. 2007a, 2007b; Kane and Clouston 2008; James and Kane 2008; Sani et al. 2012; Siegert 2013; James et al 2013; Rahardjo et al. 2014, Buza and Divos 2016).

At present, the pulling test is the most accepted method for evaluating the safety and stability of the root system. The advantages of this technique are discussed in chapter 1.2. Since this technique was used in our investigations, and because it is the basis of the dynamic tests as well, a detailed description of the theoretical background of this test is included in chapter 3.2.

`

2.3. Dynamic tree stability assessment

As shown in chapter 2.2, the currently accepted method of tree stability assessment is the static pulling test, despite its many disadvantages; chief among them is that it is a poor way of modeling the response of trees to actual wind loads (Moore and Maguire 2004). The reason for this is that the behavior of trees under actual wind load conditions is far from straightforward. Trees – especially open-grown trees, typical of urban situations – constitute a complex system of trunk, primary and secondary branches, twigs and leaves (James et al. 2006, 2014). Wind loading produces a chain reaction in these components in reverse order. Due to the complex interaction of the different components, the actual response of the tree is practically impossible to model or predict at our current scientific capabilities (Sellier and Fourcaud 2009). Further factors, like erratic wind gust intensities, natural variation of the material characteristics of the wood comprising the tree, etc. further complicate the situation.

In a relatively recent review article, James et al (2014) compiled a very thorough analysis of the available literature on the dynamic behavior of trees. In their study, they identified a number of hurdles that hamper the efforts to determine the mechanisms by which trees respond to wind loads, including:

- the viscoelastic nature of wood, which results in non-linear deformations (Vogel 1996, Miller 2005);
- exact material parameters are impossible to determine due to natural variation (Niklas 1992);
- trees and other biological materials acclimate and can change their material properties as they age and grow (Lindström et al. 1998; Lichtenegger et al. 1999; Reiterer et al. 1999; Brüchert et al. 2000; Spatz and Brüchert 2000; Lundström et al. 2008; Dahle and Grabosky 2010b; Speck and Burgert 2011)
- Dynamic analysis is complicated because it includes all the static forces and additional components of inertial forces due to the motion, the damping

`

forces and the dissipation of energy, the displacement and phase differences, the natural frequencies, and the consequent changes in motion (Den Hartog 1956)

- Damping is usually not well understood in vibrating structures (Clough and Penzien 1993) especially when it is complicated by non-linearity (Miller 2005)

- Twigs, branches and trunk comprise a multi-degree of freedom system. A multimodal analysis is required to account for complex dynamic interaction of these components (de Langre 2008; Rodriguez et al. 2008)

In their study of tree aerodynamic behavior, Sellier and Fourcaud (2009) concluded that material properties play only a limited role in tree dynamics, while small morphological variations can produce extreme behaviors, such as either very little or nearly critical dissipation of stem oscillations. Indeed, ontogenetic morphological differences tend to have a major impact on the tree's response to wind loading (Dahle and Grabosky 2010b; Speck and Burgert 2011).

In spite of the above issues, researchers employed various strategies to predict the behavior of trees in the wind. These include the following (based on James et al. 2014):

a) statistical evaluation of economic losses due to wind damage in forests (Moore and Maguire 2005; Peltola 2006);

b) assessment of the expected global behavior of trees under wind loading, e.g. visual tree assessment (Mattheck and Breloer 1994), tree risk assessment methodology (Smiley et al. 2011), quantified tree risk assessment (Ellison 2005), and statics integrated methods that combine static pulling with dynamic wind load assessment (Wessolly 1991; Brudi and van Wassenaer 2002; Detter and Rust 2013).

c) wind tunnel testing (Peltola 2006); and

d) dynamic tree modeling.

`

Unfortunately, the first three methods have their limitations in terms of accuracy. Statistical economic evaluations cannot predict the behavior of individual trees at all, global tree behavior assessment methods tend to over-simplify tree behavior, and the limited size of wind tunnels allows the testing of scale models only, rather than actual trees, where the up scaling is complicated in terms for elastic, deformable bodies like trees, and loading tends to be static, rather than dynamic.

Dynamic modeling has the most potential to accurately recreate the dynamic loading situation that occurs in real life. Three types of models have been employed to simulate the dynamic behavior of trees, including the following:

- The *lumped-mass procedure*, which assumes that the mass of each tree component is concentrated at a discrete point as it oscillates dynamically. Components are regarded as interconnected spring-mass-damper systems (**Figure 9**). In its simplest form, the whole tree is regarded as a single system (e.g. Milne 1991; Miller 2005). However, realistic modeling requires a complex model of multiple interconnected lumped-mass components (James et al. 2006; Theckes et al. 2011; Murphy and Rudnicki 2012). Such systems tend to become very complex very fast, and their behavior exhibit multi-modality, which means that the harmonic movement of individual components may amplify or cancel each other out in a manner which is very difficult to predict. Nevertheless, the relative simplicity of the lumped-mass procedure is very helpful, particularly in describing the frequency-dependency of the trees' behavior in dynamic loading scenarios (James 2010).

`
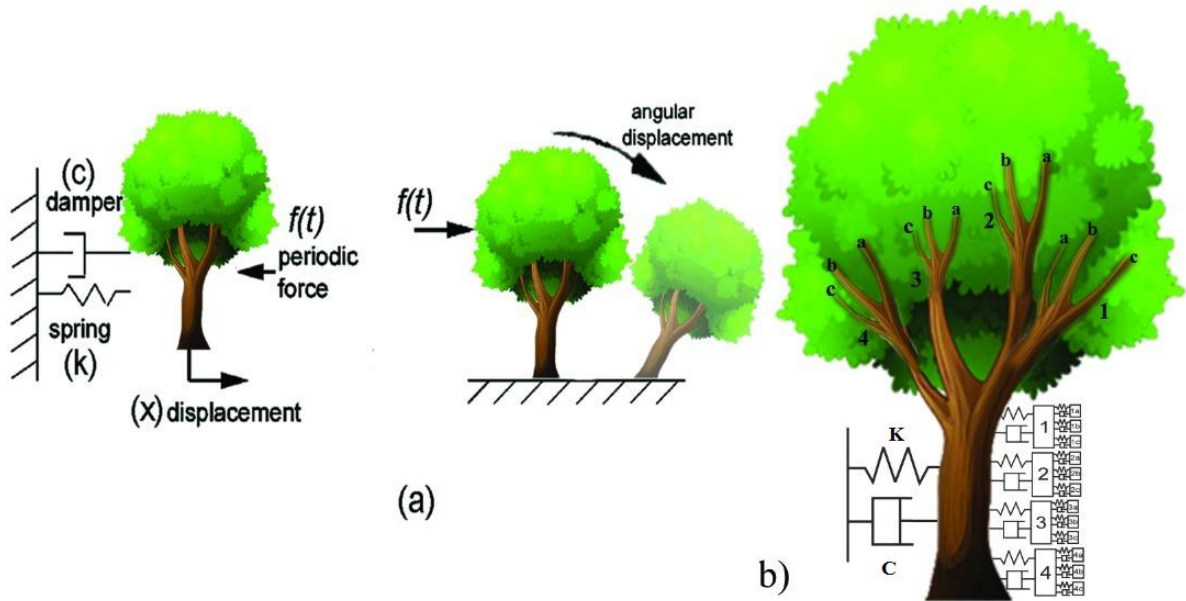
Figure 9– Dynamic models using a spring-mass-damper system representing: (a) a tree as a single mass (Miller 2005), and (b) as multiple masses with a trunk and branches (James et al. 2006).
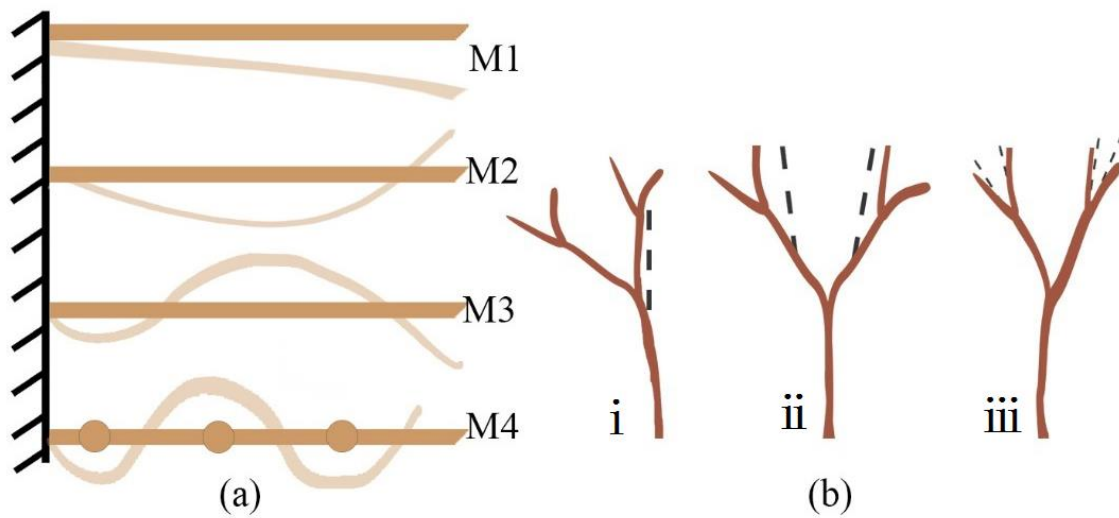
Figure 10 – Dynamic modes applied to trees: (a) modes of a beam (Schindler et al. 2010) and (b) modes ofbranched structures (Rodriguez et al. 2008).

- The *uniformly distributed mass model* provides a more accurate representation of tree components by treating each component as a beam

with distributed mass (**Figure 10**). However, it also makes the computations much more complicated, since not only does the interaction of the components exhibit modality, but each component may oscillate in different modes, which adds another level of complexity to the model. The groundwork for this method – the simple pole model – has been laid down as early as 1881 by Greenhill. The simplest model – a single beam with distributed mass – proved to be useful for analyzing the dynamics of trees growing in closely spaced plantations or forests (e.g. Bruchert et al. 2003). However, the conspicuous lack of studies that would employ a more complex model to simulate tree behavior bears witness to the considerable complexity of this method.

- Finally, *Finite Element Modeling* (FEM) combines the features of both the lumped mass and uniformly distributed mass procedures. It can handle any kind of structure (including trees), by breaking them down into smaller elements, and offers a good deal of flexibility. It can accurately represent relatively complex tree geometries, and has been successfully used to simulate various wind loading scenarios (e.g. Sellier et al. 2008; Sellier and Fourcaud 2009). On the other hand, its application requires accurate empirical measurement of many parameters particular to the tree and loading conditions to produce reliable results. It is a promising technique, but, again, realistic modeling requires a lot of computing power, and small inaccuracies in the initial/boundary conditions may lead to widely different simulation results.

Regardless of the particular modeling technique used, when representing complex entities like trees, a large number of parameters are needed to describe the material characteristics, morphology, the connections and mechanical behavior of trees, even in a relatively simple case. Also, the computing power required for modeling a given scenario is often prohibitive.

`

For this reason, any kind of modeling requires a good deal of simplifying assumptions, which introduces a certain amount of calculated inaccuracy or uncertainty in the simulation. This is generally acceptable in most modeling or simulation studies. However, as mentioned before, when modeling trees, even small morphological variations or inaccuracies can lead to widely divergent results, and the same is true for small differences in the boundary conditions.

In fact, the behavior of the various components − trunk, branches, twigs − is not unlike that of a multiple damped pendulum (Bejo et al. 2017). The branches and the trunk constitute a nonlinear vibrating system that behaves very erratically. The behavior of such systems is extremely sensitive to the initial boundary conditions, and is virtually impossible to predict long term. This type of behavior is called chaotic motion, and multiple pendulums are also dubbed chaotic pendulums for this reason.

The reason that the dynamic modeling techniques mentioned earlier generally fail to adequately describe the behavior of trees is that unfortunately this type of nonlinear and chaotic system is virtually impossible to model by deterministic methods. This is the reason why there appears to be no direct relationship between momentary wind velocity and the inclination of the trunk. In fact, in high wind gusts the tree often remains relatively stable, while sometimes in a relative lull significant loss of stability is observed (see **Figure 11**). This phenomenon goes well beyond a simple time lag; it appears almost completely random (Divos et al. 2015).

`
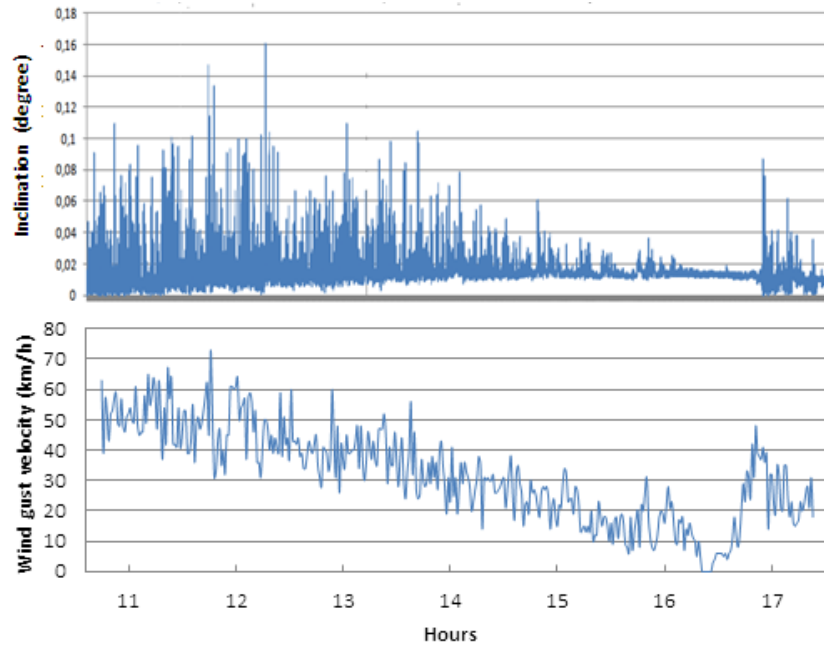
Figure 11 – Simultaneous inclination and wind velocity data showing no immediate correlation between the two factors (Bejo et al. 2017.)

However, chaotic systems may be studied using statistical methods (Strogatz 2014). In the long run, such systems will realize all possible states, and the statistical parameters of the measured variables over a certain period provide meaningful information. E.g. while there is no direct relationship between momentary wind load and inclination, average wind speed and average inclination values taken over longer periods (e.g. 1, 5 or 10 minute intervals) exhibit a similar relationship as that found between load and inclination during static testing.

This is the principle behind the dynamic tree stability assessment technique used in our study. A more detailed description of the measurement principle will be presented in chapter 3.3.

`

2.4. Factors influencing tree stability

Water, carbon dioxide, soil, sun, mineral nutrients and etc. are elements that trees need for growth. Deficiencies of these raw materials affect the health and stability of trees. The location of the trees also plays an important role in the stability of the trees.

Sunlight is the biggest source of energy for the trees. However, sunlight is not equally distributed around the globe. This means that trees do not receive the same amount of sunlight in their different parts. Sometimes even they grow up with angle to reach to sunlight and when they become taller and taller they'll have problem with self-weight and it make problem for their stability. On the other hand, as clear in the forest (not planted) the trees are somehow very close to each other in this case they start to competition together to reach sunlight. Only trees that succeed in growing towards sunlight will be able to survive.(Wessolly and Erb 2016)

The other impact is wind load. Wind is depending to 2 quantities: velocity and pressure. Three different conditions determined these two parameters: geographical situation, topographical situation and seasonal and meteorological influences (Wessolly and Sinn 1989).

Asymmetric tree crown is another element that may decrease tree stability. This may occur when trees grow on a slope, around an obstacle or in close proximity if buildings (Coomes & Allen 2007).

The root system has a crucial effect on the stability of trees. There are 3 types of root systems depending on species; surface root, heart root and taproot system. Furthermore, there are different soil properties, such as moist, rock, sandy soils, clay soils, pot plant effect and the effect of fertilization could affect the stability of trees (Wessolly and Erb 2016).

Several problems could pose risks for the stability of the trees that are caused by natural events like stroke of lighting, forest fire, floods, snow breakage, ice

`

breakage, sun scald, frosts, climbers and the dieback of main roots, tree bark parasites, bark beetle, vascular diseases, root parasites. Some more problems happen by human interference. This kind of problem usually happens in urban areas where trees are in touch with human life. These problems include construction work, changes in the water table, trees suddenly becoming solitary, demolition of a wall above the root zone close to the tree trunk, compacted soil in the root zone – reduced oxygen content in the root zone, soil sealing, backfilling, soil excavation, excavation with or without machinery, root cutting, injuries, thermal radiation emitted by buildings, construction damage, car accident by tree, pollution, bonfires, compost heaps, natural gas, vandalism, crown reduction, tree surgery. (Chodak 2019)

Species have a very important effect on the stability of trees. General categories include broad leaves and conifers, but these categories may be broken down furhter based on crown and root morphology and other factors. Each category has its own unique properties. (Barbier et al 2008)

Many studies on conifer seedlings show that root deflection in propagation containers can contribute to long-term growth problems after planting in the forest (Krasowski 2003). Wood and most materials that come from plants are described as viscoelastic because their mechanical behavior contains both elastic and viscous elements (Miller 2005). These properties result in nonlinear behavior. Evidence of the influence of tree architecture on wind firmness has also been shown by Fourcaud et al. (1999) who carried out mechanical studies on two rubber tree clones that had similar wood properties but dissimilar crown structures (Cilas 2004). The shape and structure of trees has an important impact on their mechanical stability under dynamic loading. As trees grow, the added biomass translates into greater dead weight, and the upper parts of the tree are exposed to higher wind speeds, creating larger bending moments at its base (Niklas & Spatz 2000).

`

Yang et al. (2010) explored the influence of root moisture content on the tensile resistance and strength with different root diameters and for different tree species. The results showed that root moisture content affected the tensile properties. A slight loss of root moisture content could enhance tensile strength, but too much loss of water resulted in weaker capacity for root elongation with tensile resistance. The main factors contributing to slope stability include soil shear strength, soil-root interactions, the quantity and distribution of roots, as well as root tensile properties (Genet et al 2005).

`

Chapter III. Theoretical background

3.1. Tree biomechanics

Brudi and Wassenaer (2002) provided a very detailed review of tree biomechanics, based on a statics approach. In their model, just like in the engineering design of man-made structures, wind loads acting on trees are counteracted by the load-bearing capacity of the tree, which is determined by material properties on the one hand, and the geometry of the tree on the other. This model can be applied both to the safety of trunk (or indeed, that of larger branches) against breakage, and to the stability of the tree against uprooting.

Of course, this very simple model becomes considerably more complicated when looking at the real life situation of trees. First of all, wind intensity and wind pressure depend on three different factors:

- Geographical location
- Topological situation
- Seasonal and meteorological influences.

Wind speeds are not constant, but increase with altitude following a parabolic profile. The exact wind speed distribution also depends on the surface roughness of the terrain. For practical consideration, trees are usually evaluated using these profiles, based on the expected maximum wind speed in the given geographical location.

Once the maximum wind speed (and, from that, the maximum wind pressure, or pressure profile) is established, maximum expected wind loads may be calculated for the tree. This load can be used to calculate the maximum bending moment the trunk of the tree is likely to experience, and also the maximum tipping moment

`

that the tree needs to withstand without uprooting. The latter is important for the purposes of our study.

Wind pressure is calculated from wind velocity using the simple equation below:

$$p_{wind} = {^\rho}/_2 \, v^2, \quad (1)$$

where ρ is the density of air, and v is wind velocity. We can calculate the wind load (lateral force) from the wind pressure, by multiplying it with the area of the crown. This is the force that acts on the crown of the tree, and creates torque on the tree trunk. This torque is maximal at the root collar, where the lever arm is the longest.

In actuality, of course, because of the uneven vertical distribution, different portions of the crown experience different wind pressures, and also the distance of these parts of the crown is different from the ground. **Figure 12**
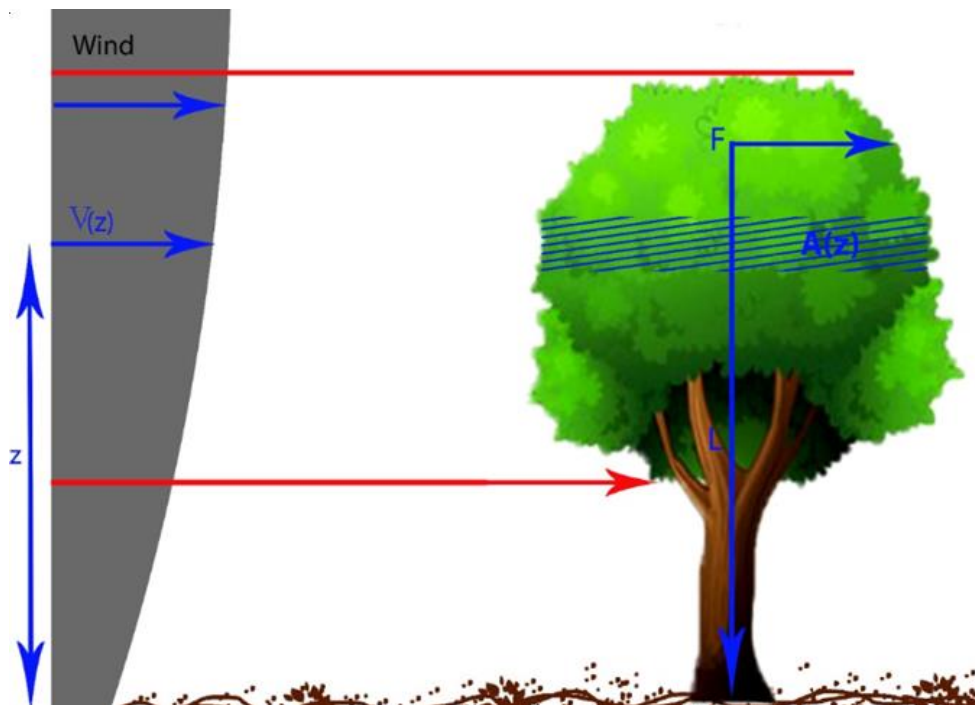
Figure 12- Influence of the load component (Wessolly 1998)

In this case, the moment can be determined using to the following formula:

`

$$M_{wind} = {}^{\rho}\!/_2 \sum v(z)^2 \times A(z) \times z, \qquad (2)$$

where: A – surface area of a portion (a horizonatal "slice") of the crown

z – vertical position (distance from the ground).

In practical investigations the above formula is typically too tedious, and the vertical pressure distribution is replaced by a constant effective pressure value, and the equation is simplified, as follows:

$$M_{wind} = p_{wind} A_{crown} h_{cent} = {}^{\rho}\!/_2 \, v^2 A_{crown} h_{cent} \quad (3)$$

where: A_{crown} – crown surface area

h_{cent} – crown centerpoint height.
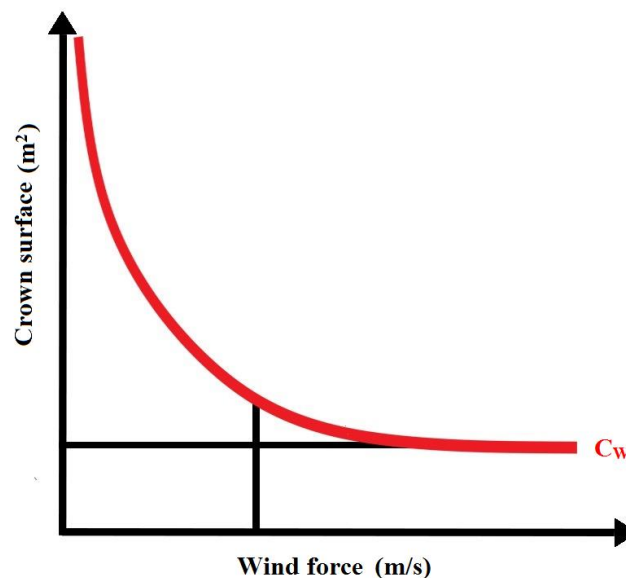
Figure 13 – Wind resistance of tree crowns and the aerodynamic drag factor (c_w)
(based on Davenport, 1965)

The situation is further complicated by the fact that strong winds can deform the crown of the tree, whose area and center point height are also significantly altered. This is handled by introducing a so-called aerodynamic drag factor (c_w) in the

`

equation. The value of this factor depends on wind intensity (see **Figure 13**), and is also species-dependent. Therefore, the final equation for determining wind-induced torque on the root collar is, as follows:

$$M_{wind} = p_{wind} c_w A_{crown} h_{cent} = \frac{\rho}{2} v^2 c_w A_{crown} h_{cent}, \quad (4)$$

Substituting maximum wind pressure/velocity (p_{max}/v_{max}) in the above equation allows the calculation of the maximum moment (M_{max}), i.e. the largest level of torque the tree needs to withstand without uprooting. Drag factor values for different species have been determined through extensive experimentation, and can be found in the work of Brudi and Wassenaer (2002).

3.2. Traditional tree stability assessment

As mentioned in chapters 1.2 and 2.2, the traditional method of assessing tree stability is the pulling test. This test was developed based on the engineering principles outlined in chapter 3.1.

The test involves fixing a rope in the tree crown, approx. at centerpoint height, and achoring it somewhere close to the ground. After that, a gradually increasing pulling load is applied through the cable, while measuring the inclination of the root collar. This provides a load-deflection curve, which follows a special tangential relationship (**Figure 14**), according to equation (5):

`
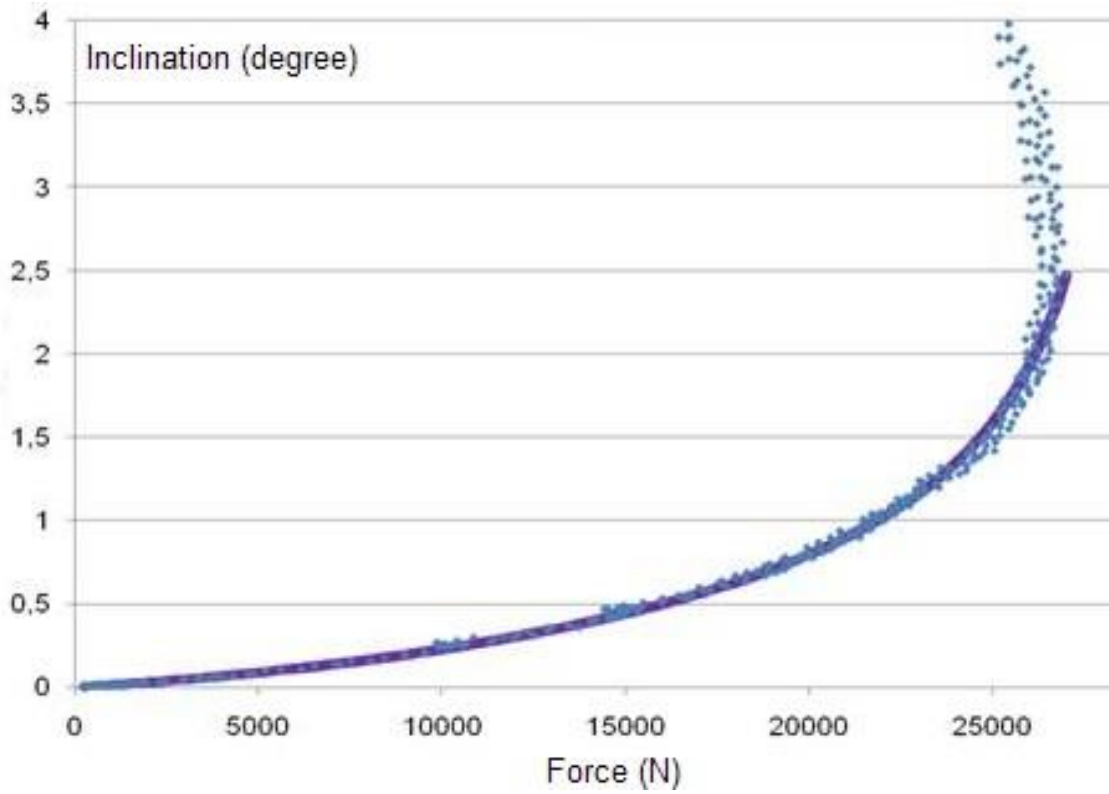
Figure 14 – The tangential relationship between load and inclination experienced during the pulling test (Bejo et al 2017)

`

$$\varphi = \frac{1}{3}\tan\left(\frac{100}{73.85}\frac{F}{F_{crit}}\right) + \frac{1}{3}\left(\frac{F}{F_{crit}}\right)^2 - \frac{1}{10}\frac{F}{F_{crit}}, \quad (5)$$

where: φ – the inclination of the root collar,

F – horizontal load,

F_{crit} – critical horizontal load (uprooting force).

The above relationship has been verified by testing a large number of trees that all followed this behavior (Brudi and Wassenaer, 2002).

Naturally, trees are not tested all the way to uprooting, but released after an inclination of 0.2 degrees is reached, well before any damage could be done to the tree. F_{crit} is then estimated through extrapolation by fitting the relationship described by eq. (5) to the measured data point. From F_{crit} and the height at which the cable has been attached to the tree, M_{crit} (the uprooting moment) can be calculated. This is the torque required to uproot the tree.

Finally the stability of the tree is characterised by the so-called Safety Factor (SF), determined as the ratio of M_{crit} and the maximum moment (M_{max}) determined from the critical wind pressure using eq. (4):

$$\text{SF} = \frac{M_{crit}}{M_{max}}, \quad (6)$$

Note that M_{max} is always determined relative to a certain reference wind velocity level (the highest wind likely to occur at the given geographical area). Theoretically, as long as $M_{crit} > M_{max}$, (i.e. SF > 1) the tree is safe at the reference wind velocity. However, since M_{crit} is only a prediction (albeit usually very accurate), and because of possible uncertainties in the determination of the reference wind velocity and the geometric parameters, the tree, by convention, is considered safe if SF > 1.5 and unsafe if SF < 1. Between 1 and 1.5 there is a region of uncertainty, and one should exercise caution (Brudi and Wassenaer 2002).

`

3.3. Dynamic tree stability assessment

Dynamic testing is based on the same principles as the static test, except the static horizontal load is replaced by actual wind loading. However, as mentioned in chapter 2.3, there is no direct relationship between momentary wind pressure and the inclination of the root collar, due to the chaotic response of trees to dynamic wind loading. However, while there is no immediate relationship between these parameters, statistical methods can often be employed on chaotic systems to find meaningful relationships (Strogatz 2014). For example, the wind load and inclination diagrams introduced in **Figure 1** can be broken down into longer intervals, and statistical parameters (e.g. the average over a 5 or 10-minute period) can be calculated, as shown in **Figure 15.** It is evident from these diagrams that, while momentary values cannot be correlated, the averages (indicated by red lines in the figure) are in relatively good agreement.
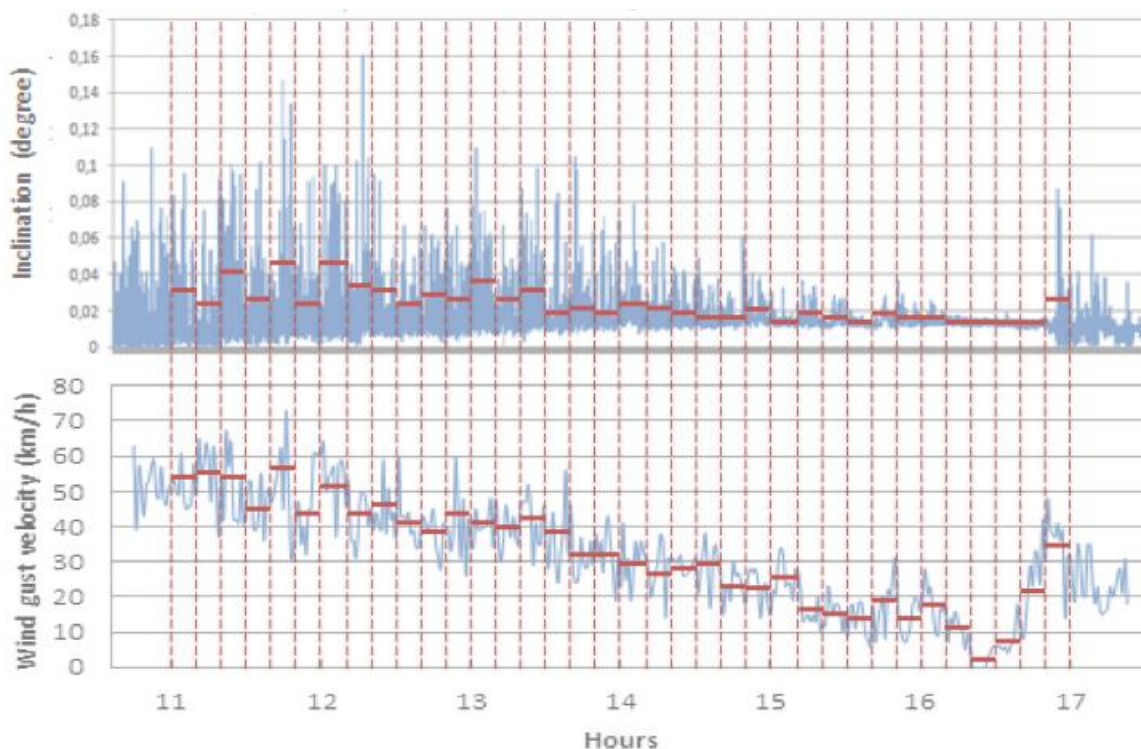
Figure 15 – Breaking down dynamic wind load and inclination data into batches
to calculate statistical parameters

By measuring the wind intensity and root collar inclination over longer periods of several hours, grouping them into batches of several minutes, and calculating the

`

averages, similar load and inclination data pairs can be obtained as the ones used for evaluating pulling test results. There are only two important differences:

1. Data points are not consecutive but random
2. Instead of horizontal force, wind velocity or wind pressure is measured

The first issue is inconsequential since curve fitting can be executed regardless of the order of the points, as long as enough data points are available. The second issue means that the calculation of the Safety Factor is slightly different, since wind load is substituted for the static load employed to determine M_{max}. Therefore, equation (6) can be expressed, as follows:

$$SF = \frac{M_{crit}}{M_{max}} = \frac{Ap_{crit}c_w h_{cr}}{Ap_{max}c_w h_{cr}} = \frac{p_{crit}}{p_{max}}, \qquad (7)$$

Notice that by substituting wind pressure for the calculation of the critical and maximum moments, the crown area and crown center point height cancel out in the equation, since these parameters are the same whether we are considering maximum or critical wind pressure. The situation is less straightforward in case of the drag factor, which depends on wind intensity, and does not affect the low-wind section of the curve as much as the high wind area. However, using the same, high c_w value throughout the curve results in conservative estimation, and allows the drag factor to cancel out too.

Thus, the equation is reduced to the ratio of critical wind pressure to maximum wind pressure (the wind pressure belonging to the highest expected wind velocity). Critical wind pressure (p_{crit}) is determined from the pressure-inclination curve the same way as F_{crit} is determined from the load-inclination curve. The safety factor determined this way is not only simpler to calculate, but likely to be more relevant to the dynamic loading situation that trees experience in the wind.

3.4 Factors influencing tree stability

`

There are many factors that influence tree stability (i.e. the tree's resistance against uprooting). Some of these, like crown shape and surface area, age, etc. are intrinsic properties of the tree, and are taken into consideration when assessing the stability of the trees. There are also external factors that impact the stability significantly. The most important of these natural and anthropogenic factors are discussed in this chapter.

3.4.1 Seasonality

In temperate climates, the seasons affect the growth, metabolism and general activity of trees. This also influences the stability of trees in several different ways, as follows:

3.4.1.1. Foliage changes

The changing of the seasons has a major effect on the foliage of broadleaved species. This also has a major impact on tree stability, since leaves significantly increase the crown surface, and transfer much of the wind loads to the system of twigs and branches, and eventually, through the crown, to the root system. On the other hand, leafy crowns suffer more deformation in the wind, which may decrease the crown surface, as expressed by the aerodynamic drag factor.

In conifers, this effect is much less pronounced, or may be altogether absent, since their crown surface area and aerodynamic drag factor do not change dramatically in the winter (except for some rare exceptions, like larch, which sheds its needles in the winter).

`

3.4.1.2 Biological activity

In general, trees are biologically much more active in the spring and summer, and tend to decrease their activity, and eventually go dormant in the winter. This affects the root system, which tends to swell and be more firmly anchored in the soil in the spring and summer, due to the increased sap flow, and become somewhat looser in the autumn and winter. This affects the stability of all trees adversely, albeit not nearly as strongly as the foliage change in broadleaved trees. (Bieker et all 2010)

3.4.1.3 Other seasonal factors

Seasonal changes also affect tree stability through changes in temperature. Particularly, the frozen soil in the winter may become much more resistant against uprooting, which will positively influence the stability of the tree. The nature of precipitation also tends to change in the winter, but this will be discussed in the next chapter.

3.4.2 Precipitation

Precipitation will also affect the stability of trees. The effect is markedly different depending on the form of precipitation.

3.4.2.1 Rain

Rainy weather – especially when it's prolonged – affects both the tree and the soil. Rain-covered foliage will have a somewhat increased inertia, but the effect is much more pronounced in the soil. Rainwater penetrates the ground, and loosens the soil, which will therefore allow more movement, and become less resistant to uprooting. Both of these effects will act towards decreasing tree stability.

`

3.4.2.2 Snow

Snow will also tend to decrease tree stability, but through a different mechanism. Snow will not penetrate and loosen the soil. Instead, it will accumulate on the branches (and, in the case of conifers, needles) of the tree. Sometimes the accumulation can be quite significant, and the weight of the snow will considerably increase the inertia forces, when the tree is moved by wind, and will therefore lead to increased loads. The weight of the snow will also push the tree into the ground and help anchor it, which will alleviate the increased loading to a certain extent. Nevertheless, snow loads tend to decrease tree stability, although not as much as the seasonal foliage changes. (Sleet will also have a similar effect.)

3.4.3 Wind direction

The wind direction in most locations is not completely random. Each geographical area will have a so-called prevailing wind direction, i.e. the point of the compass where the wind most frequently blows from. During its development, this is the wind that the tree most frequently experiences, and therefore this is the direction in which it will develop the highest resistance against breakage and uprooting.

3.4.4 Root damage

Root damage is most often an anthropological issue. It occurs most frequently in urban environments, when various structures like roads or buildings are built in the vicinity of trees. Cutting the roots has a twofold consequence. On the one hand, roots absorb water and nutrients from the soil, and some of this is interrupted when roots are damaged. On the other hand, roots serve as anchorage for the tree; cutting the roots therefore obviously decreases the stability of the tree.

For significant stability loss to occur, a considerable portion of the roots needs to be cut. This also depends on the root system structure; trees with extensive, superficial roots are affected more badly by relatively shallow structures (e.g. when

`

constructing roads or pipelines running close to the surface), while deeper, taproot systems are less susceptible to this, and are only affected when constructing underground structures underneath them.

3.4.5 Pruning

Pruning is another type of artificial intervention, done to the tree intentionally. It is a silvicultural practice that is used to improve wood quality. Pruning is also used in urban environment, sometimes for aesthetic reasons, or to remove branches that interfere with manmade structures, or sometimes to improve trunk safety and stability by reducing the crown area.

The reduction of the crown surface means that there is a smaller area for the wind to act upon. This results in lower loads at the same wind intensity, and, ultimately, improved safety and stability. The effect of pruning is different from the effect of defoliation of broadleaved trees in the autumn in that in this case the branches are also removed, in addition to the leaves.

`

Chapter Ⅳ. Equipment and Methods

Research objectives were fulfilled via various experiments, as follows:

- comparing the results of the traditional static pulling test with those of the new dynamic method, and validating the results against the uprooting moment required to pull up some diseased trees;

- measuring trees in different weather and seasonal conditions to build a database and draw conclusions regarding the influence of various factor on the stability of coniferous and deciduous trees;

- assessing the influence of anthropogenic factors such as pruning and root system damages on the stability of trees.

In this chapter, both the equipment and the experimental methods will be described.

4.1. Equipment

In the research work two different pieces of equipment were used: the DynaRoot system and pulling test.

The DynaRoot system is completely nondestructive method, while in the case of pulling test, the force is exerted mechanically, but, in normal cases, it does not cause any damage to the tree. When the pulling test is prolonged, it can be used for uprooting the tree when using a high level of force. In this chapter a detailed explanation about the two kinds of equipment, as well as the Arborsonic software will be given.

`

4.1.1. Pulling test

The pulling test (**Figure 16**) consists of:

- Cable and winch: our system contains a 20-meter length of high capacity metal cable with a 1.6 metric ton manually operated winch. The winch has a ratchet mechanism that multiplies the force of the operator to exert sufficient tension on the cable. The cable and the winch were equipped with safety hooks and two soft belts for fitting it around the tree trunk and the anchor point.

- Load cell: calibrated cable-mounted load cell, 5T capacity with a sampling rate of 1 Hz.

- Inclinometer: biaxial inclinometer sensor, ST-015 mounted on the tree collar with a measurement range of ± 2 degrees, and a resolution of 0.001 degree.
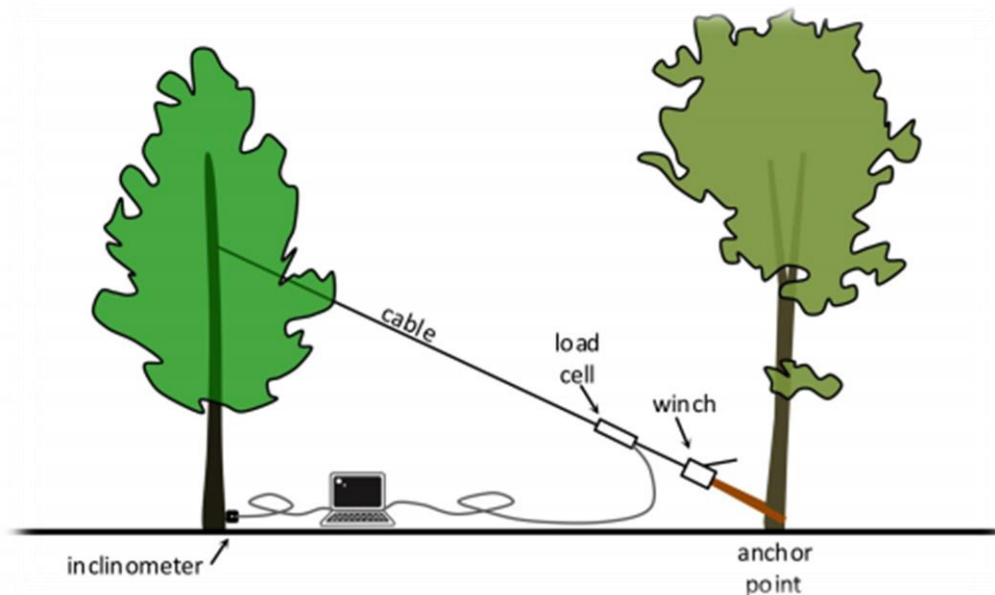
Figure 16 – Schematic view of the pulling test

`

The pulling test is based on affixing a cable at approximately mid-height to the tree to be evaluated, and applying a moderate load, while measuring the inclination at the base of the trunk. The induced inclination is slight (less than 0.2 degrees), to make sure that the test itself does not damage or start uprooting the tree. Installing the cable typically requires a ladder, or climbing the tree to the appropriate height. The metal cable was attached to the trunk, via a soft belt to avoid damaging the tree. The other end of the cable entered the winch, which was affixed to an anchor point. The anchor point can be any object that is safely secured to the ground, most often a stump or the bottom of another tree. Whenever another tree was used, we were careful not to damage the bark. The winch applies tension to the cable. A load cell was attached to the cable to measure the tensile load.

Measured load and inclination data was sent to a computer, using a sampling frequency of 1 Hz. The data was recorded and analyzed in real time, using FAKOPP's pulling test software (FAKOPP Enterprise 2018). The software evaluates data and provides the load-inclination curve in real time. Data evaluation requires information such as species, height of the tree, rope height on the tree, anchor-tree level difference, anchor-tree distance, drag factor, critical wind speed, crown area and crown center point height. Tree height, crown surface area and crown center point height were calculated from images of the examined trees using the Arborsonic 3D software (see chapter 4.1.3).

During measurement, load is applied on the cable slowly and evenly using the winch. Measurement is continued until an inclination of 0.2 degrees is reached. After this, the load is released, and the software evaluates the inclination curve. The load-inclination relationship is approximated using a special tangential function. The maximum load (F_{max}) – and from that, the maximum torque (M_{max}) required for uprooting the tree can be estimated by extrapolating this curve, as explained in chapter 3.2. The software also calculates the the critical moment (M_{crit}), and from that the Safety Factor (SF) value.

`

4.1.2. The DynaRoot system

The DynaRoot system consists of three components (**Figure 17**):

- Anemometer: an instrument for measuring wind velocity at or near the tree to be evaluated. The closer the anemometer is to the tree the better, but, depending on wind velocity DynaRoot may provide reliable data even with measurements taken several kilometers away. Ideally the anemometer should be clear of buildings or other objects that may obstruct the wind, at a height of at least 10 m.

  When measuring trees in the University's botanical gardens, we used a modified TX20 ball anemometer permanently mounted on top of one of the University buildings (no farther than 800 m from the measured trees), with a sampling rate of 1 Hz. This instrument is set up to send the data directly to a web server, whence it can be retrieved later.
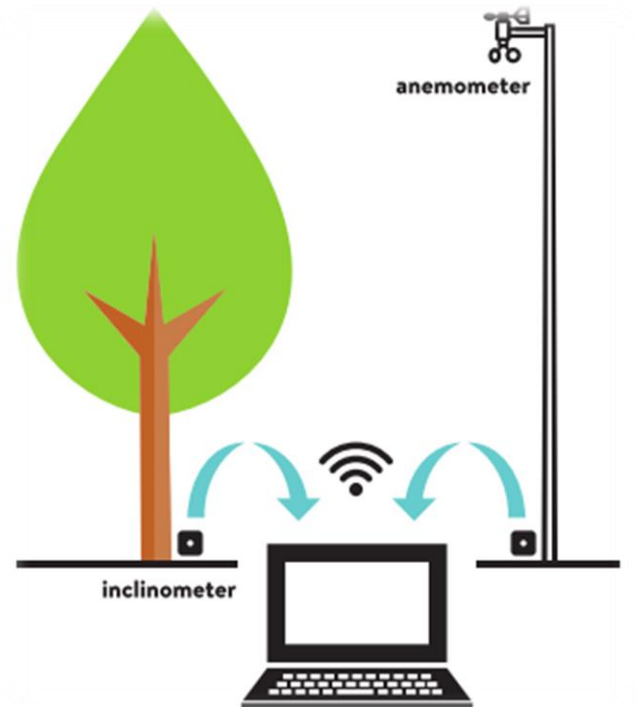
Figure 17 – Schematic of the DynaRoot system (with mobile anemometer tower)

`

For measurements taken outside University grounds, a FAKOPP mobile ultrasonic anemometer was used. The anemometer, which had a 1 Hz sampling rate, was set up no farther than 300 m from the examined trees. The anemometer is equipped with a GPS receiver and a data logger, and records the data, along with the exact time of measurement on a data card.

- A biaxial inclinometer (the same type as used in the pulling test). The sampling frequency for inclination was 10 Hz. The type of the inclinometer is a DPN series dual axis inclinometer manufactured by company MAES. Inclination data is also recorded on a data card along with the exact time of measurement.

- Evaluation software: a PC software for evaluating wind velocity, x and y inclination. The data, recorded over periods of several hours (varies depending of weather conditions), are transferred from the anemometer and inclinometer on memory cards or wirelessly. Both wind velocity and inclination should be recorded at the same time, and synchronized exactly; otherwise no meaningful correlation can be detected. In this case, the software the software recognizes the inconsistency and registers an error. Exact measurement times were recorded along with the measured velocity and inclination for the accurate correlation of the data

  The software groups the velocity and inclination data into batches based on intervals of several minutes and calculates statistical parameters for each batch. Instead of momentary velocity and inclination, these statistical parameters are used for the tree stability evaluation.

The Safety Factor calculation is similar to that in the pulling test, except, in this case, wind pressure is used instead of force, and statistical parameters are used, instead of the momentary wind pressure and inclination values

The following conditions were observed during the measurements:

`

- The distance between the measured trees and the anemometer, was less than 1 km.

- Wind velocity, was more than 25 km/h in every case.

- Wind load and inclination statistics were calculated based on 10 min intervals.

The reference wind velocity for the safety factor calculation was 33 m/s (approx. 120 km/h).

4.1.3 The ArborSonic software

Pulling test Safety Factor calculations required crown surface area and crown center point height determination. The crown surface area was also important for the evaluation of the results of dynamic measurements, especially when determining the effect of foliage changes.

Crown geometry was evaluated using FAKOPP's ArborSonic 3D software. Arborsonic evaluates tree parameters through image analysis. This requires a taking a clear photograph and uploading it in the software. Arborsonic 3D is also capable of evaluating the SF for trunk breakage after using the Arborsonic 3D tomograph to create a tomogram of the trunk, and entering additional parameters (critical wind velocity, species, drag factor, etc.) For the purposes of our investigations, only the image analysis capabilities were used.

Figure 18 shows the Biomechanics screen of the software. Crown area may be entered manually, calculated from basic crown dimensions using a shape factor, or obtained from the image, chosen from the image container. In the last case, after choosing image, the user needs to mark the contour of the crown manually, and also mark a reference line of known length (e.g. the height of an object close to the tree) – the longer the better (best if the height of the tree is known.) The length of this line is

`

entered by the user, and is used as a reference for determining the dimensions of the crown.
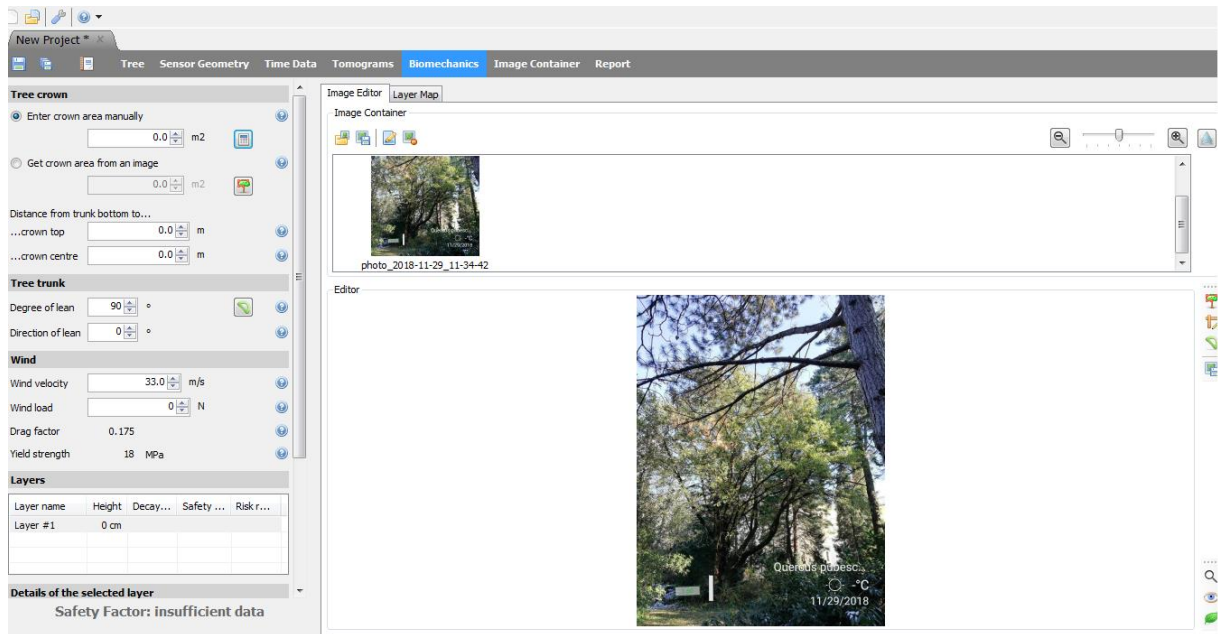
Figure 18 – The Biomechanics input screen of Arborsonic 3D

Figure 19 – Image of a tree with the crown contours (red) and a reference length (in this case, the height of the tree, blue) marked.

Figure 19 shows a sample image where the crown and the reference length have been marked. After this, the software is capable of calculating the crown area, total height and crown CenterPoint height. Note that the software does not actually recognize the foliage, and simply calculates the area inside the contour.

4.2. Experimental methods

According to the research objectives, three different studies were set up to further verify the applicability of dynamic testing for tree stability assessment, and to study the effect of natural and anthropogenic factors on the stability of trees.

In the first part of this research. 10 decayed ash trees were chosen in a forest in Donaudorf, Austria. The stability of the trees was measured in the same day using the DynaRoot system. This means that soil moisture content, species, wind load and temperature were considered constant. After the dynamic measurement, all ten trees were measured by the pulling test as well. Pulling test was not stopped at 0.2 degrees of inclination as is customary; instead, trees were tested to failure by uprooting. This allowed the comparison of the critical loads estimated from the static and dynamic test results with the actual critical load obtain by uprooting. Chapter 4.2.1 describes the details of this part of the research project.

Tree stability was measured on several tree specimens and different years in the Botanical Gardens of the University of Sopron. Several conifers and broadleaved trees were chosen and tested in different seasons and under different conditions. This allowed us to assess the effect of changing the foliage, weather, temperature and other seasonal variation in various trees. This portion of the project was executed using DynaRoot, with the permanently installed anemometer described in chapter 4.1.2. Details of this investigation will be described in 4.2.2.

`

4.2.1 Comparing the DynaRoot and pulling test results on diseased trees

In this part of research, severely decayed ash trees were evaluated whose SF was likely to be low at the reference wind velocity. Measurements were conducted in a diseased forest stand in Donaudorf, Austria (48°11'26.5"N 15°03'17.3"E), that was attacked by a fungal infection (**Figure 20**).

Figure 20 – Fungal attack causing the decay in ash trees

This part of the research was carried out in cooperation between the FAKOPP enterprise, Forest Training Centre Traunkirchen, and the University of Sopron. First, approx. 100 trees were identified, and classified according to level of decay (see **Figure 21**). 10 trees with moderate (<10%) decay were chosen for stability evaluation.

`

UP TO 10%   >10 TO 25 %   >25 TO 50%   >5 50 TO 90%   > 90% TO <100%
                                                          Photos: Kirisits T., Schwanda K.

Figure 21 – classification of the decayed ash trees (Forest Training Centre Traunkirchen, Austria)

First, pulling test was executed on the chosen trees. Before the analysis of the pulling test results, the crown surface and crown center height values were calculated using the ArborSonic 3D software (see chapter 4.1.3). One of the trees was accidentally pulled over during the pulling test; this meant that, dynamic testing could not be executed on this tree. The rest of the trees were later tested dynamically using FAKOPP's DynaRoot system, using the mobile anemometer described in 4.1.2. These measurements were conducted on a windy day (<90 km/h). Measurement duration was approximately 3-4 h for each tree.

Uprooting tests were carried out approx. 3 months later by DI Nikolaus Nemestóthy of the Federal Research and Training Centre for Forests, Natural Hazards and Landscape, Forest Training Centre, Traunkirchen, 4810 Gmunden, Austria. He supplied the uprooting torque values (M_u) used for our analysis.

4.2.2 Comparing the stability of the trees in different seasonal and weather conditions

`

For evaluating the effect of natural variations in soil moisture content, wind direction and seasonal changes, a number of tree specimens were chosen in the Botanical Gardens of the University of Sopron, Hungary (47°40'47.2"N, 16°34'30.4"E). The examined specimens included a wide range of species with different morphological characteristics, including the following:

Broadleaved species:

- Beech (*Fagus spp.*),

- Linden tree (*Tilia platyphyllos*),

- Tulip tree (*Liriodendron tulipifera*),

- White poplar (*populus alba*),

- Sessile Oak (*Quercus petraea*)

- Horse chesnut (*Aesculus hippocastanum*),

- Japanese zelkova (*Zelkova serrata*),

- Black ash *(Fraxinus nigra)*

- Hornbeam *(Carpinus)*

Coniferous species:

- Port-Orford-cedar (*Chamaecyparis lawsoniana*),

- Giant sequoia (*Sequoiadendron giganteum*),

- English Yew (*Taxus baccata*),

- Grand fir *(Abies grandis)*

- Black pine *(Pinus nigra)*

- Douglas-fir (*Pseudotsuga menziesii)*

- Needle-fir (*Abies holophylla*)

- Noble fir *(Abies procera)*

- Spruce *(Picea abies)*

One specimen of each species was chosen for investigation. Data was collected over a 2.5 year period (19.04.2017 to 24.11.2019), during which trees were measured in

`

different conditions, i.e. in the winter, when broadleaved trees lose their foliage and frozen ground conditions are likely, and in autumn and spring. With the dynamic method, there is a limitation on how well measurement conditions can be controlled. Measurements can only be taken in windy weather. Wind intensity and direction cannot be controlled, and sometimes there is no wind to measure trees in the chosen conditions. Nevertheless, we made an effort to build a considerable database by taking a total of 73 measurements (2 to 7 measurements per tree) of the above trees in different conditions.

Tree inclination and wind velocity were measured using the DynaRoot system. Wind measurement was monitored in one central place (on top of the NRRC building of the University of Sopron, Hungary), while tree inclination was measured using inclinometers affixed to the root collar of each tree. Inclinometer and anemometer readings were uploaded in the DynaRoot evaluation software, which calculated the Safety Factor, critical wind pressure for each measurement.

Metadata for analyzing the results included crown area, wind direction and soil moisture content. Unfortunately, there were no soil moisture content and crown area measurements taken during earlier tests (before spring 2018). Therefore, dynamic measurements and the resulting SF values could only be compared to wind direction, and the database for the effect of moisture content and crown area was smaller.

The crown surface and crown center height values were calculated using the ArborSonic 3D software, based on photographs taken of each tree at the time of the dynamic measurement. The height of the trees was measured by laser technology, using a TruPlus 200 instrument, and used as a reference for the image analysis. In addition to wind intensity, the anemometer also collects wind direction information, which yielded the average wind intensity used in our analysis. Finally, soil moisture content was also measured by taking a soil sample of approx. 500g at the time of measurement in the vicinity of the measured trees, at a depth of approx. 25 cm. Moisture content was determined by drying the soil sample for approx. 24 h at 100 °C, until completely dry, and comparing the initial weight to the oven dry weight.

`

4.3.3 the effect of reducing the crown and cutting the roots on the stability of trees

2 pine trees close to one another were chosen in University Botanical Gardens. First, the original stability of the trees was measured using DynaRoot at two different times, before modification. Dynamic tree stability measurements were executed the same way as described in chapter 4.3.2, except measuring the crown surface, which was not possible, since a clear photograph of the trees could not be taken because of their situation.

After the initial assessment of the dynamic safety factor, the root system of Pine tree nr. 1 was examined. This was done by acoustic root mapping, which is based on sending acoustic signals from the tree trunk, and measuring the response using sensitive sensors around the tree, at the same distance (approx 1m) around the tree. Since roots are much better conductors than soil, the signal is much stronger in the vicinity of the roots.

The results of this measurement are shown in **Figure 22a**, where the wooden pegs mark the probable location of the roots. One of the groups of roots was chosen at random, excavated and roots were cut close to the trunk (**Figure 22b**). After that, the stability of the tree was measured again two more times using the Dynaroot system.

a   **b**
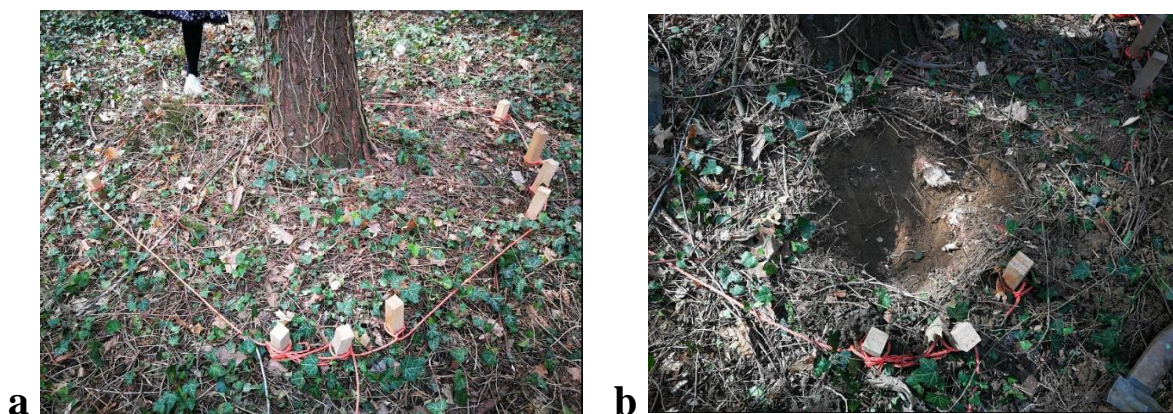
Figure 22 – Root mapping and cutting: (**a**) wooden pegs indicating root locations, (**b**) one of the groups of roots were excavated and cut

`

a b

Figure 23 – Pruning Pine tree nr. 2: (**a**) Before pruning, (**b**) After pruning

In the case of Pine nr. 2, the crown was pruned after the initial measurement. Crown area was reduced by approx. 50% (**Figure 23**), by climbing the tree and cutting the lower branches. After pruning the crown, the stability of the tree was, again measured twice using the DynaRoot system.

The original intention was to keep cutting more roots and reducing the crown in several stages, but unfortunately time constraints and weather did not permit that. Therefore, only the effect of this one-time change could be evaluated.

`

Chapter V Results and Discussion

5.1 Comparing the results of dynamic and static stability assessment

As described in chapter 4.2.1, all 10 trees were evaluated by the pulling test, and the 9 remaining trees were measured by the dynamic test, and finally uprooted to determine the actual load required to drop the tree. **Figure 24** shows sample output information from the Arborsonic software (crown surface determination), the pulling test and the DynaRoot system.

Table 1 shows the dynamically predicted critical wind pressure and SF values, critical moment and SF predicted from the pulling test, and finally, the torque required for uprooting the trees. In addition, the critical moment has been determined from the dynamic testing results as well, to facilitate comparison with the pulling test and actual uprooting torque.

Table 1 – Crown geometry, pulling test and dynamic stability evaluation results of 10 diseased ash trees in Donaudorf, Austria

Nr.	Pulling test		Dynaroot			Uprooting torque (kNm)
	Mmax (kNm)	SF	pcrit (Pa)	R*	SF	
1	62.8	1.06	1043	0.68	1.1	66.0
2	64.4	0.9	572	0.76	0.64	60.1
3	116.7	2.07	1460	0.84	1.61	119.0
4	70.7	1.23	1214	0.82	1.46	117.4
5	30.8	1.27	476	0.84	0.57	48.5
6	77.8	1.4	1453	0.81	1.71	117.7
7	24.7	0.69	1329	0.57	0.44	41.0
8	25.5	0.84				30.8
9	16.9	0.41	722	0.57	0.73	20.3
10	13.1	0.34	511	0.45	0.46	24.5

*Correlation coefficient of the pressure-inclination curve

`
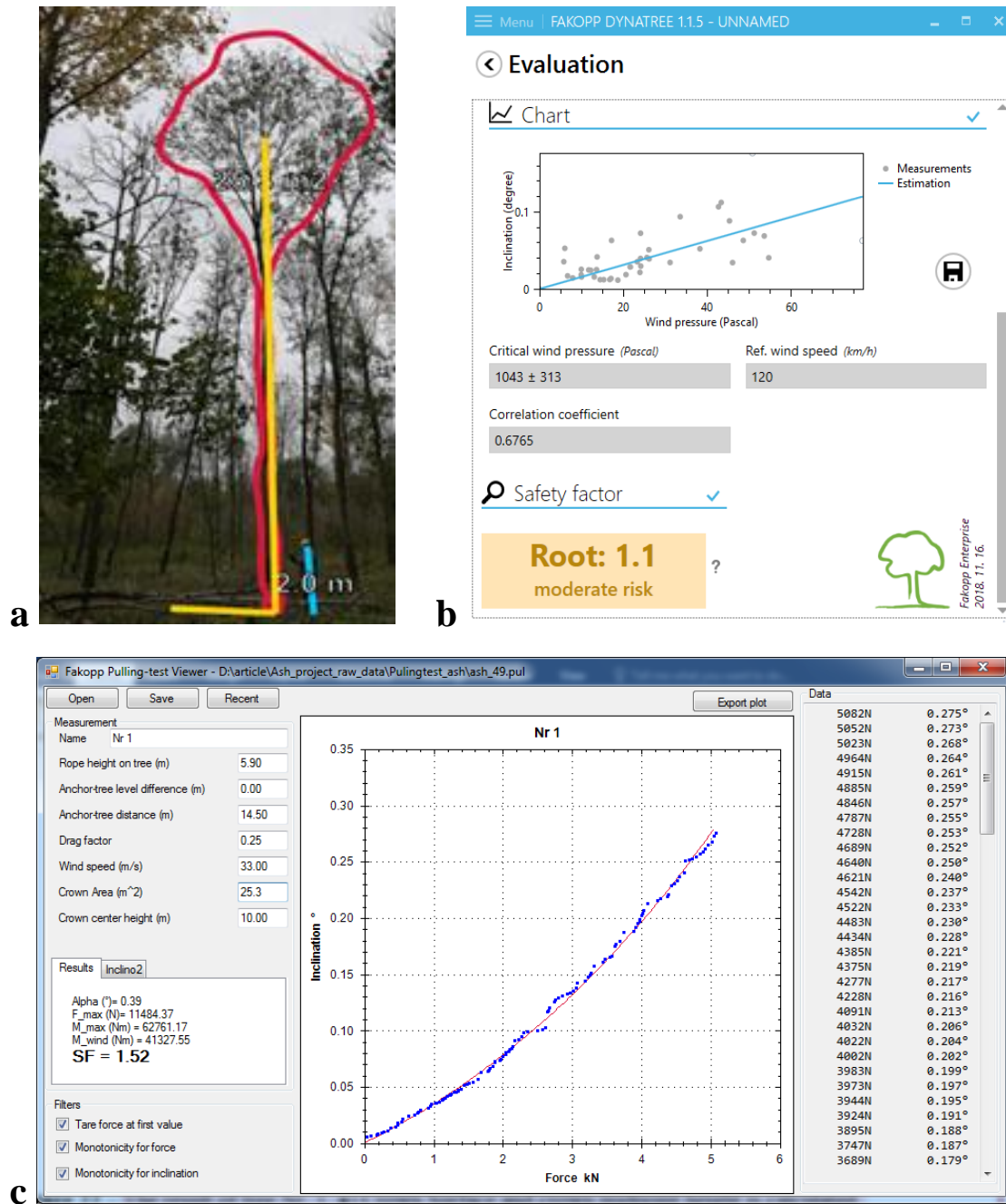
Figure 24 – The result of tree Nr. 1.
a) Crown Surface and crown midpoint height is calculated using the Arborsonic software
b) DynaRoot results analysis **c**) Pulling test curve analysis
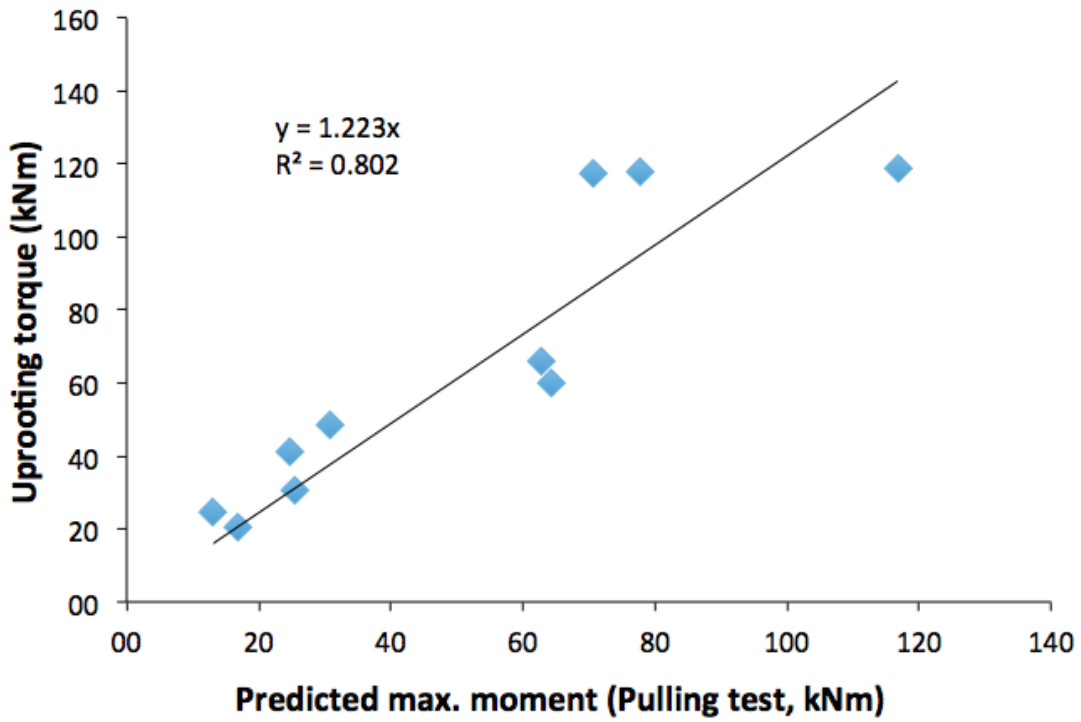
a.
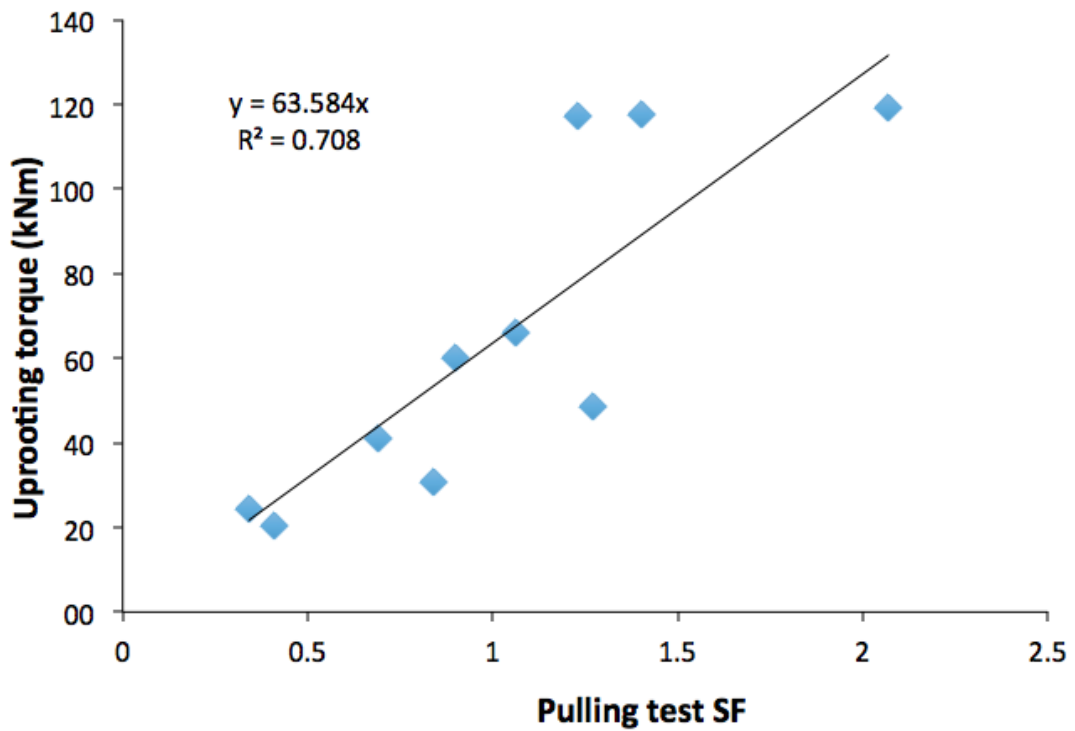
b.

Figure 25 – The reliability of the pulling test for predicting tree stability: the relationship between the predicted and actual uprooting torque (**a**), and between the SF and uprooting torque (**b**)

Figures 25a and **b** demonstrates the reliability of the pulling test. **Figure 25a** shows the relationship between the maximum torque predicted from the pulling test, and the

actual torque that was measured by uprooting the tree. As the high r^2 value (0.8) indicates, the pulling test estimates the uprooting moment with a very high level of accuracy. The slope of the curve is somewhat higher than 1, which means that the uprooting test slightly underestimated the torque required to uproot the tree. This is actually beneficial, since this means that the test tends to err on the side of safety.

The diagram in **Figure 25b** shows the relationship between the pulling test SF and actual uprooting torque. Again, the relationship is very strong ($r^2 = 0.71$) which is a good indication that the pulling test Safety Factor is a reliable parameter for predicting the stability of trees.

The results of the dynamic SF determination are shown in **Figure 25**, where the dynamic SF is compared to the uprooting moment. Surprisingly, in this particular case, the dynamic SF predicted the ultimate uprooting moment even better than the static value, with an r^2 value of 0.86. This may just be a coincidence, because the dynamic pressure-inclination curve is actually a measure of the ultimate load that is required to uproot the tree in a dynamic loading situation, which is expected to be somewhat different from the static loading case. Unfortunately, there is no objective way to measure this; thus, we can only compare the dynamically measured SF to the static uprooting torque. In any case, the good correlation is an encouraging sign concerning the reliability of the dynamic method.

`
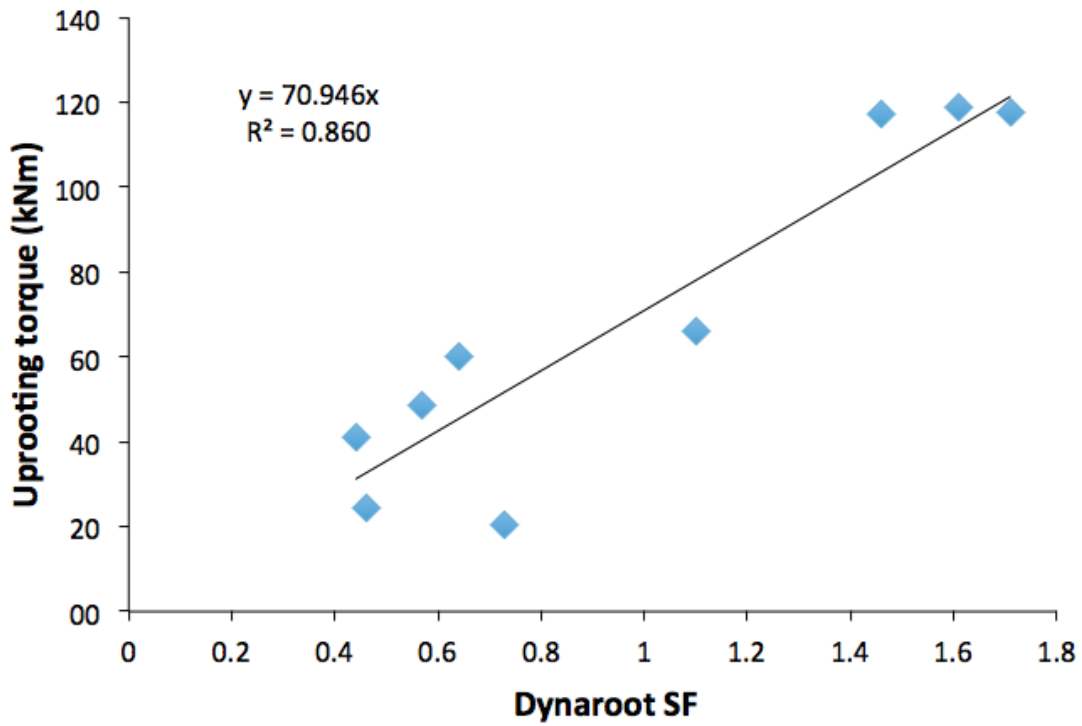
Figure 26 – The relationship between the dynamically measured SF and uprooting torque
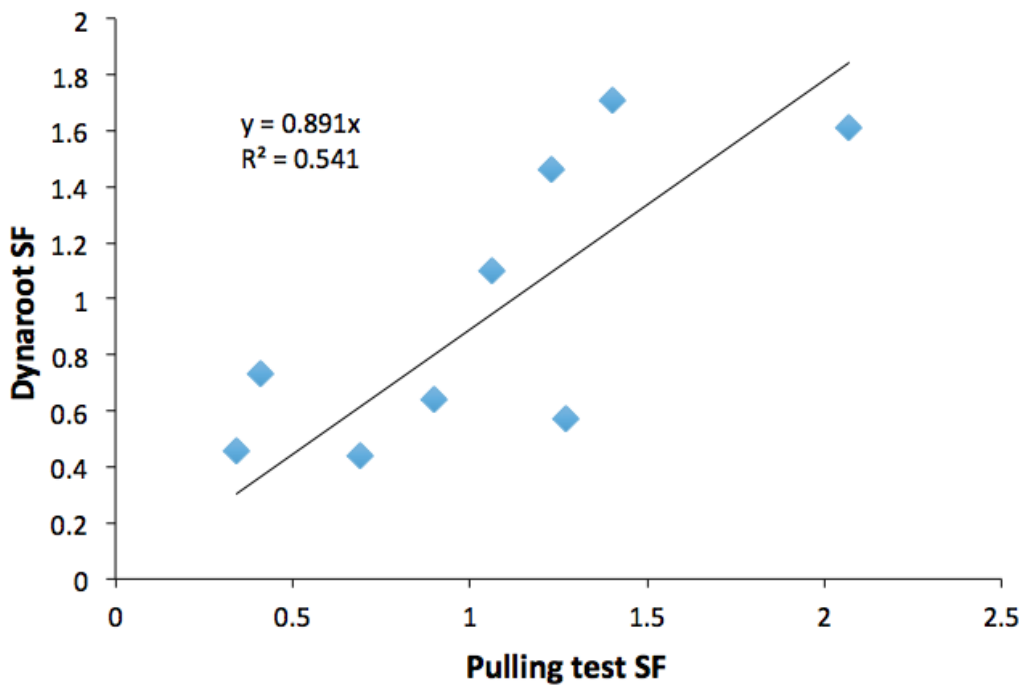
Figure 27 – The relationship between the measured static and dynamic SF values

Finally, **Figure 27** shows the correlation between the Safety Factor values determined by the pulling test and through dynamic measurement. The relationship is not very strong, but the r^2 value is still above 0.5, which is acceptable in biological materials. The relatively week relationship shows that the two different Safety Factor values are not completely interchangeable, as one measures tree behavior in a static loading scenario, while the other describes its dynamic response. Nevertheless, both are closely related to the uprooting moment, and both may be recommended for assessing tree stability. This confirms the preliminary findings outlined in Divos et al. 2015 and Bejo et al. 2017.

Notice that the regression lines were forced through the origin in all diagrams presented in **Figures 25** through **27**. This kind of relationship is likely to describe reality better, and eliminating the y-intercept did not significantly reduce the r^2 values and caused a significant change in the slope of the line in **Figure 27** only.

5.2   The effect of seasonal and weather conditions

Measurements on different trees were taken in the autumn, winter and spring over a period of 2.5 years (spring 2017 through autumn 2019). Testing required wind velocities of at least 25 km/h, which limited the number of measurements. There were sometimes also technical difficulties with the anemometer that failed to send wind data, and also faulty inclinometers, and – in one case – deliberate vandalism. Because of these limitations and problems, a total of 73 measurements were taken on 18 trees in different weather and seasonal conditions. Since there was no way to control measurement conditions, these measurements include a wide variety of soil moisture content, wind velocity and direction, as well as diverse foliage conditions in the case of broadleaved trees.

`

Tables 2 and **3** show the measurement data of the 9 conifers and 9 broadleaved trees, respectively. Crown surface area (A_{crown}) was determined from photographs taken of each tree at the time of measurement, as illustrated in **Figure 28** in the case of beech. **Appendix 1** shows the photographs of all trees at the time of measurement. (Since there is no significant seasonal foliage change, conifers were only photographed once.)

Table 2 – The stability of conifers measured under different weather and seasonal conditions

Species	Date	Soil MC (%)	WD (°)	A_{crown} (m²)	SF	r (%)	p_{crit} (Pa)	Height (m)	DBH (cm)
Cedar	08/06/18	20.1	294	159	7.69	83	6565	24.5	159
	08/12/18	20.9	262	159	7.33	71	6676		
	07/03/19	16.6	169	159	6.37	72	6410		
Sequioa	20/04/17		306		6.08	89	4971	29.7	118
	18/11/17		333		6.50	83	5571		
	20/11/17		315		8.56	93	7118		
	09/06/18	23.8	146	265.0	9.86	60	8721		
	29/11/18	28.9	91	265.0	10.23	59	9000		
	27/02/19	17.8	290	265.0	6.17	70	5366		
Spruce	08/05/17		45		4.89	74	3900		
	05/11/17		148		2.33	89	2002		
	02/03/18		133		6.58	92	5015		
Needle fir	13/02/18		319		3.46	79	2680		
	26/04/18		325		3.48	89	3044		
Noble fir	15/03/18		131		4.50	87	3756		
	04/04/18		194		4.66	67	3909		
	30/10/18		124		4.45	85	3932		
Douglas fir	01/03/18		134		2.99	85	2692		
	14/03/18		331		3.84	98	2822		
	01/04/18		313		2.92	94	2379		
Grand fir	19/04/18	11.0	45	117	2.56	57	5471	31.0	70
	01/12/18	18.5	100	117	3.51	91	3051		
	09/03/19	18.8	136	117	3.78	79	3326		
Yew	03/12/17		333		4.98	95	3735	27.8	63
	08/02/18		328		6.10	88	4588		
	08/12/18	21.0	272	219.6	8.00	70	7652		
	07/03/19	16.6	153	219.6	5.47	90	4609		
	10/06/19	13.0	87	219.6	5.34	90	4667		
Black Pine	09/03/19	15.2	118	162.9	4.45	80	4384	23.6	67
	12/04/19	11.0	299	162.9	3.76	62	3264		
	23/11/19		77	162.9	2.81	94	2397		

Legend: MC = moisture content; WD = Wind direction; r = correlation coefficient; DBH = diameter at breast height

`

Table 3 – The stability of broadleaved trees measured under different weather and

seasonal conditions

| Species	Date	Soil MC (%)	WD (°)	A$_{crown}$ (m^2)	SF	r (%)	p$_{crit}$ (Pa)	Height (m)	DBH (cm)
Beech	26/02/18		319		8.40	70	6516	29.0	86
	13/03/18		337		6.08	91	5276		
	10/04/18		162		5.25	83	4381		
	30/10/18		115		6.67	53	6586		
	09/03/19	19.3	116	313.5	6.29	93	5429		
	20/05/19	26.5	91	461.7	11.13	68	12074		
	24/11/19	15.7	137	427.4	7.23	51	14096		
Lime	09/03/19	15.2	121	144.0	11.15	82	9741	15.5	65
	13/04/19	11.0	293	183.6	13.95	64	10657		
	26/11/18	28.3	272	272.0	6.36	80	6131		
Tulip	10/12/17		191		4.70	87	4192	30.0	73
	26/02/18		319		7.84	64	6035		
	11/04/18		173		5.50	60	4648		
	07/03/19	22.2	149	220.0	4.86	90	4171		
	23/04/19	10.7	80	290.0	3.24	80	3079		
	24/11/18	16.0	141	189.4	3.53	84	3794		
Ash	13/02/18		320		6.39	0.81	4950		
	26/04/18		328		3.51	0.63	4001		
	29/04/18		184		5.01	0.65	4811		
Poplar	27/04/18		156		4.02	62	3490	34.0	125
	13/03/18		333		6.01	95	4637		
	26/02/18		318		4.01	87	3247		
	09/03/19	15.2	260	458.8	12.05	77	13858		
	11/12/18	28.4	267	563.2	5.26	74	4281		
	19/05/19	23.0	90	595.8	2.32	84	2080		
Oak	12/02/19	20.7	283	166.2	14.01	90	11724	29.2	84
	05/05/19	25.4	289	255.6	5.54	50	4339		
Hornbeam	14/02/18		324		8.04	84	6198		
	26/04/18		329		5.18	54	5982		
	29/04/18		183		5.01	57	5136		
Horse chestnut	25/04/17		45		9.60	83	8234	16.9	74
	04/11/17		152		14.12	90	11744		
	20/11/17		319		6.69	84	6456		
	28/11/18	29.4	279	132.0	31.00	71	24884		
	13/02/19	25.6	275	84.7	23.80	81	21323		
	06/05/19	26.5	291	143.0	17.40	57	16057		
Zelkova	23/10/17		337		5.19	0,52	4379	23.0	67
	11/04/18		158		3.58	0,82	3361		
	08/02/18	27.8	328	168.3	4.19	66	3752		
	01/12/18	21.9	99	140.0	6.10	79	5710		
	06/05/19	17.2	291	219.6	3.81	60	3418		

Legend: see **Table 2**.

`
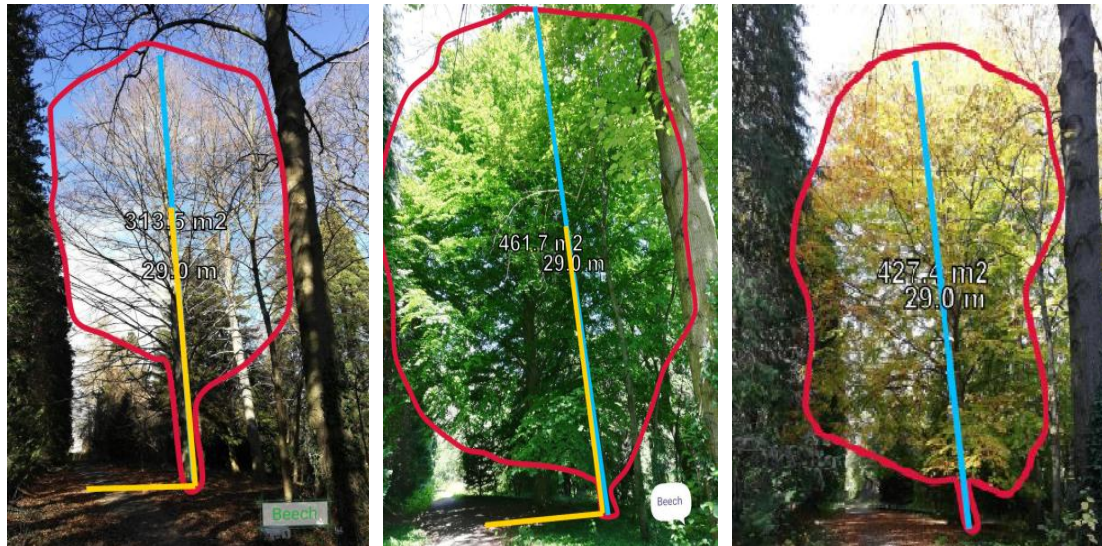
Figure 28 – An example of crown area determination using the Arborsonic 3D program
(From left to right: winter, autumn and spring, respectively)

Tree-by-tree analysis of the results delivers no clear trends. The Safety Factor increases with moisture content in some trees (e.g. tulip or yew), decreases in others (e.g. lime or oak), while there is no clear trend found for poplar and zelkova. In the case of broadleaved trees, foliage loss should increase the Safety Factor due to the decreased crown surface, which results in lower loads at the same wind pressure level. However, this trend was evident in Poplar and Zelkova only. For most of the other deciduous trees, there was no clear trend, and in the case of beech, Safety Factor decreased with reduced foliage. There is also no clear trend evident in terms of the effect of wind direction.

This apparent lack of relationship is partly because of the relatively small number of measurement in each tree, and also because of the complex interaction of various factors (some of which, like the effect of frozen ground, shading or differences in root structure, could not be measured and factored in). Combining the results of the individual trees may highlight trends and tendencies not evident in tree-by-tree analysis.

`

The results of different trees are not directly comparable. As shown in **Tables 2** and **3**, trunk diameter differed widely, as did the ranges of soil moisture content, wind direction and – in the case of broadleaved trees – variations in tree foliage. This resulted in much variation in the Safety Factor as well, with some trees averaging between 3 to 4, while others, like horse chestnut, reaching an average of 15 or higher. To facilitate comparison, the relative Safety Factor, moisture content, and crown surface was calculated instead, by comparing the measured values to the average of each tree, expressed as a percentage of the average. E.g., relative Safety Factor variation was calculated for each measurement, as follows:

$$RSF_{ij} = \frac{SF_{ij} - \overline{SF}_i}{\overline{SF}_i}, \quad (8)$$

where RSF_{ij} is the relative safety factor and SF_{ij} is the jth actual SF value measured on tree i, and $\overline{SF}_i$ is the average of all (2 to 7) SF values measured on tree i.

Since the moisture content range and crown surface also varied considerably between trees, the relative change in these parameters, rather than their absolute values, should be considered again. The calculation of their relative value is analogous to the relative safety factor calculation shown in equation (8). On the other hand, wind direction was not normalized using eq. (8), but instead calculated as the deviation from the prevalent wind direction (NW, or 315°) in degrees.

The parameters calculated above allows us to compare the relative changes in Safety Factor to the changes in moisture content, crown area and wind direction, regardless of individual differences between trees. The following analysis is based on these relative parameters (except in the case of wind direction).

`

Figure 29a compares the changes in the Safety Factor caused by soil moisture content variation for all trees. Based on this diagram, the effect of soil moisture content appears completely random. However, separating the results to broadleaved species and conifers results in a more meaningful analysis.

Figure 29b shows the effect of soil moisture content in the case of broadleaved trees. In this case a weak negative correlation emerges, but the trend is not straightforward. Particularly in the case of beech and tulip trees, increasing soil moisture content resulted in increased Safety Factor values. There is a strong likelihood that other factors – like seasonal foliage changes or gross anatomical differences – particularly those of the root system – have a more important effect on the stability of broadleaved trees.

The effect of soil moisture changes on the stability of conifers is shown in **Figure 29c**. In contrast to broadleaved trees, moisture content had a very significant positive effect on the dynamic stability of these trees. Moisture content appears to account for almost 80% of the variation in tree stability, while the remaining 20% may be caused by various other factors like wind direction, frozen ground, snow, etc. On the one hand, this is to be expected, since coniferous trees tend to be more similar in their gross anatomical features, and there is also no significant foliage change between seasons. However, the results contradict the expectation that moisture tends to loosen the soil, and therefore decrease tree stability.

The positive effect of soil moisture content increase on the stability of coniferous trees is most likely due to the root structure of the trees. Many coniferous trees (like pines and fir) have a taproot system, with the main root reaching deep into the ground. The compaction of the lower soil layers by the added weight of the topsoil may stabilize deep-reaching roots. Other trees (like sequoia) have a dense, matted root system, which incorporates large amounts of soil. The added weight of this soil helps anchoring the tree and, again, improves stability (Fathi et al. 2020).
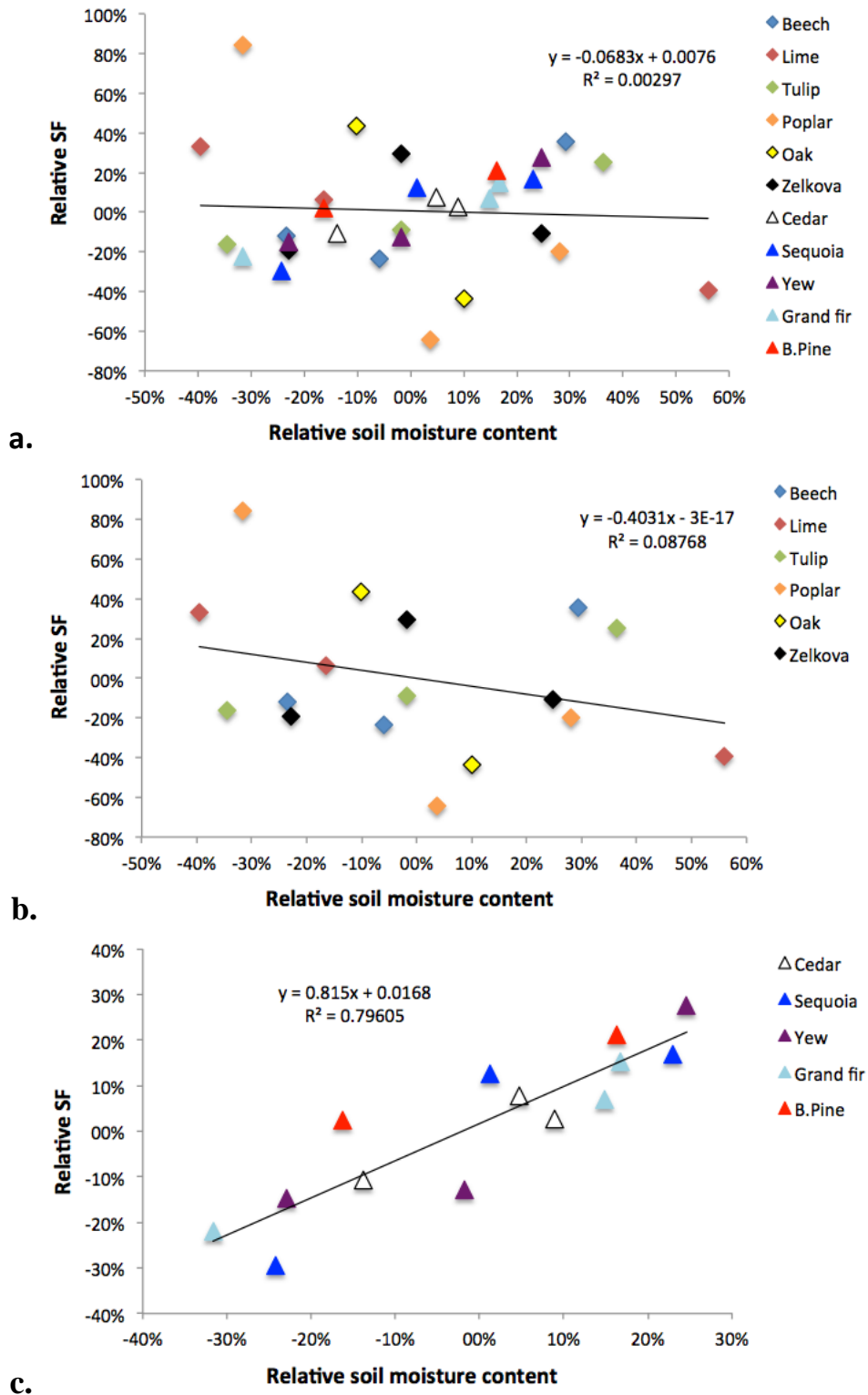
`

Figure 29 – The effect of changes in soil moisture content on the Safety Factor of all (**a**), broadleaved (**b**) and coniferous (**c**) trees

As explained in chapter 3.4.3, wind direction also plays an important role on tree stability. Trees tend to be strongest in the prevalent direction, and get progressively less resistant as we move away from that point in the compass. This is why the effect of wind direction was assessed in terms of deviation from the prevalent direction. **Figure 30** shows the results.

As apparent from **Figure 30a**, there was, again, no appreciable trend in terms of the effect of wind direction. This remains true even after separating the data to broadleaved and coniferous trees (**Figures 30b** and **c**, respectively). A closer look at the diagrams reveals that wind direction was mostly either relatively close to the prevailing direction (0°), or in the opposite direction (180°). There were only three data points measured in true crosswind. All of these resulted in low relative SF values (below 0%).

One question that arises from the analysis of the effect of wind direction is weather this parameter (the deviation from the prevalent direction) is in fact the best way to examine the effect of wind orientation. It may in fact be, that trees get weaker as we approach crosswind direction (i.e. as we go from 0 to 90° of deviation from the prevalent wind), and gradually get more stable again in winds opposite the prevalent direction (i.e. in the range of 90-180° of deviation). However, when we examine the Safety Factor as a function of deviation from crosswind, there is still no clear tend detectable in the data (**Figure 31a**, **b** and **c**). This may be because of the low number of data points measured in crosswind (below 30° deviation from the crosswind direction.

Be that as it may, the relationship between wind direction and safety factor is weak. Other factors are likely to be more influential on tree stability, which is actually good news for arborists, since they don't need to worry too much about the influence of non-prevalent wind directions when assessing tree stability.

`
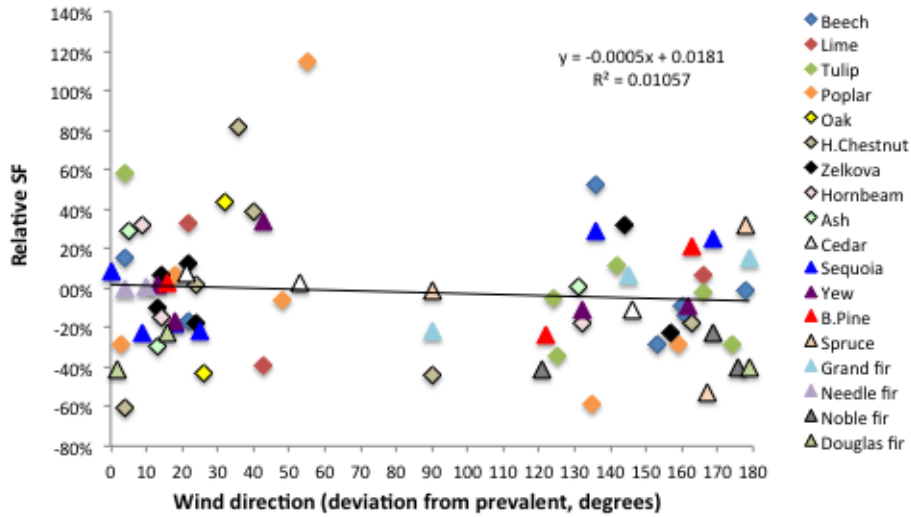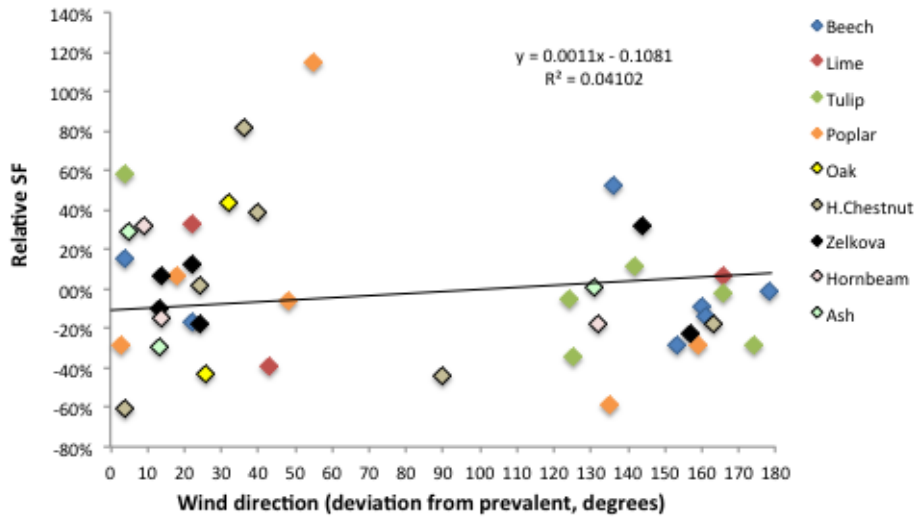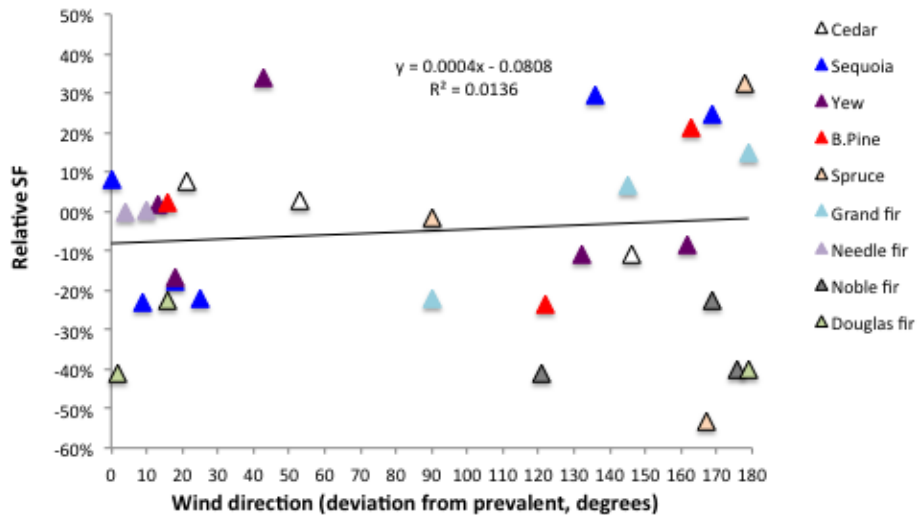
Figure 30 – The effect of the changes in wind direction (deviation from the prevalent direction) on the Safety Factor of all (**a**), broadleaved trees (**b**) and conifers (**c**)

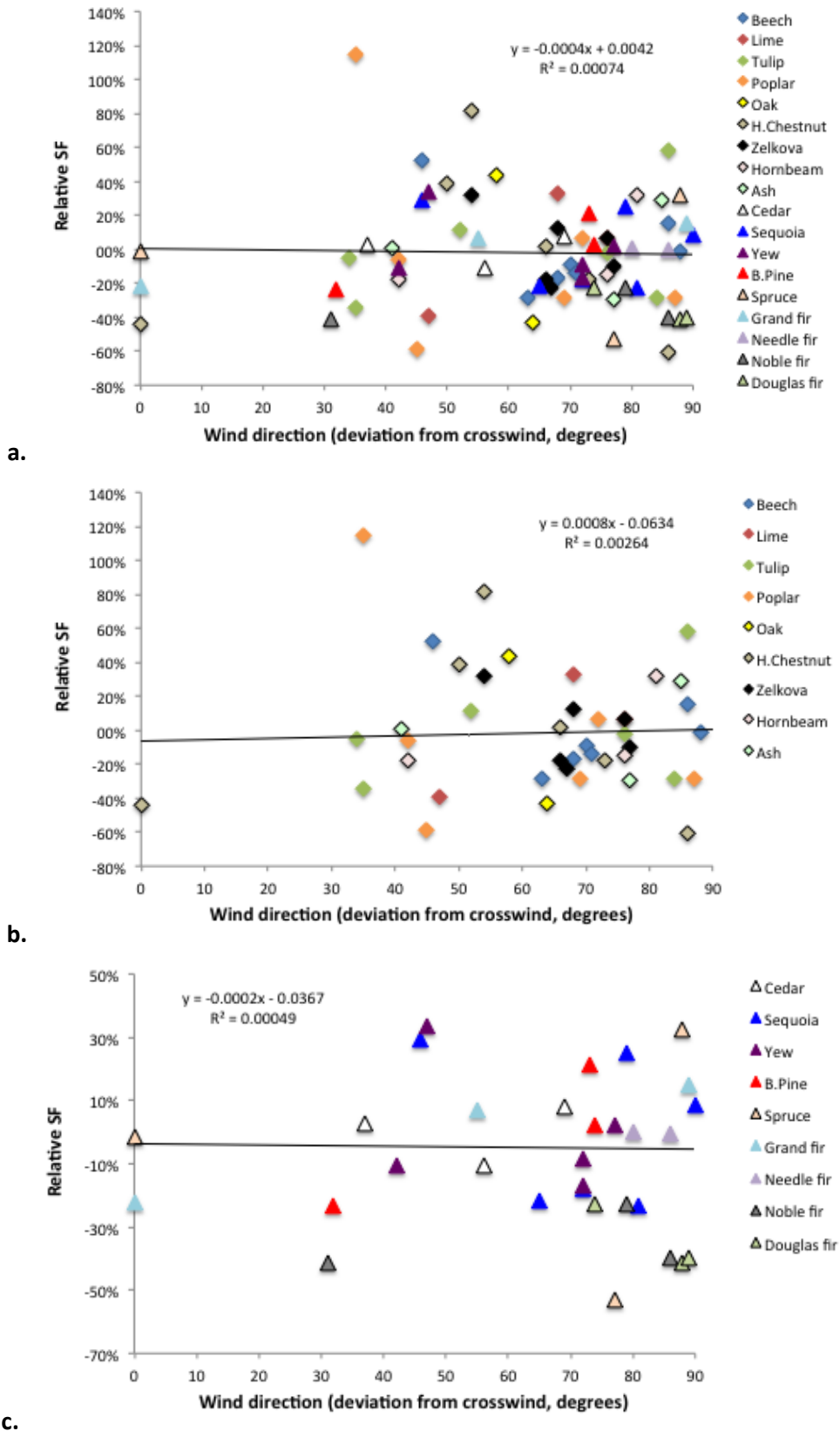**Figure 31** – The effect of the changes in wind direction (deviation from the crosswind direction) on the Safety Factor of all (**a**), broadleaved trees (**b**) and conifers (**c**)

The figure shows a scatter plot with "Relative SF" on the y-axis (ranging from -80% to 100%) and "Relative crown area" on the x-axis (ranging from -40% to 40%). The trend line equation is y = -1.0686x - 4E-17, R² = 0.30245. Legend: Beech, Lime, Tulip, Poplar, Oak, H.Chestnut, Zelkova.
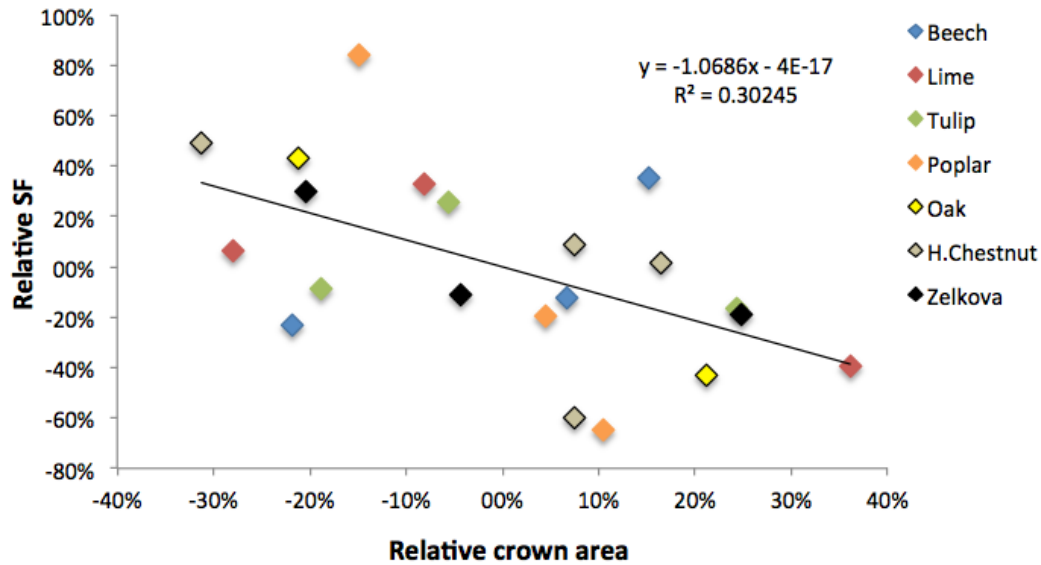
Figure 32 – The effect of foliage changes on the safety factor of broadleaved trees

Finally, **Figure 32** shows the effect of foliage changes on the stability of broadleaved trees. (This analysis did not include conifers, where seasonal foliage changes are minimal to nonexistent.) As expected, there is a negative relationship between crown surface area and the Safety Factor, i.e. trees get more stable after losing their leaves. However, the relationship is not very strong ($r^2 = 0.30$), and some trees (esp. beech) exhibited an opposite trend.

While one individual tree's inconsistent results may be attributed to a possible unfavorable combination of other factors that masked the effect of foliage in this particular case, the low overall correlation is somewhat surprising. One explanation for this is that, while a loss of foliage significantly decreases the surface of the crown, which would result in lower wind loads, in the meantime the drag factor increases. Since the wind load is calculated as a product of wind pressure, crown surface and the drag factor, the increase of the latter parameter may alleviate – and in some cases completely counteract – the effect of crown surface reduction. Indeed, in a recent presentation German researchers reported increased movement of broadleaved species in the winter, when the leaves are

missing. (Rust et al. 2019; results presented at the 21st Wood NDT Symposium in Freiburg, data unpublished.)

In any case, the low correlation indicates that other factors may, in fact, affect tree stability more than foliage changes do. Since neither wind direction, nor moisture content had a strong effect, there are probably other factors at play that are more important. Broadleaved trees are more variable in terms of their gross anatomical features than conifers, and characteristics like crown and root system size, shape and structure may determine the stability of trees in a complex interaction with the factors considered in our study. Unfortunately, the detailed examination of these factors goes beyond the scope of our project, and would require measuring more trees of each species to detect trends for each species and separate the effect of species-specific and ontogenetic morphological differences.

5.3 The effect of anthropogenic interference on the stability of conifers

Various anthropogenic factors may also influence the stability of trees. Such factors include shading due to nearby artificial structures, man-made obstacles to branch or root development, air or soil pollution that may hinder growth, etc. Two of the most typical types of interference is the pruning of the tree crown (this is typically a deliberate measure for silvicultural purposes or to improve the stability in urban settings), and cutting some of the roots (this is an unintended but frequent occurrence when building various structures like roads or buildings in the vicinity of trees). These may both majorly influence the stability of trees. The purpose of this part of the research was to assess the effect of pruning and root damage on the stability of trees.

`

Table 4 – The effect of pruning and cutting the roots of pine trees on tree stability

Tree	Date	WD	SF	r	Pcrit (Pa)	Soil MC (%)	Remark
Pine nr. 1	2/25/2019	286	1.89	67	1616	18.61	before root damage
	3/7/2019	114	1.26	52	1277	13.46	before root damage
	5/5/2019	291	1.7	54	1364	24.5	after root damage
	5/14/2019	299	1.55	51	1251	19.48	after root damage
Pine nr. 2	2/25/2019	286	1.75	57	1586	18.46	before pruning
	3/7/2019	114	1.43	52	1507	15.27	before pruning
	4/28/2019	293	3.07	85	2372	9.7	after pruning
	5/15/2019	286	2.41	52	1881	18.4	after pruning

The investigation was carried out by cutting the roots and pruning Pines nr. 1 and 2 respectively. This included cutting a few roots of pine nr. 1 at random, and also pruning approx. 50% of pine nr. 2, as described in chapter 4.3. Both trees were measured twice before, and twice after the respective interventions. The results are shown in **Table 4**.

As the data shows, artificial root damage did not cause significant changes in the Safety Factor of the examined pine tree. The average Safety Factor was close to 1.6 both before and after the intervention. This was not unexpected, since the root damage was relatively small, and affected the superficial roots only. Since pines, like many other coniferous trees, have a taproot system (Wessolly and Erb 2016), even cutting most of the superficial roots may not have a significant effect on their stability. More extensive studies, cutting more of the superficial roots, and possibly conducted on trees with a more fibrous root system could shed more light on the effect of root damage.

`

As opposed to root damage, the pruning of the crown evidently caused a serious improvement in the stability of Pine nr. 2. On average, the SF value increased by more than 50%, due to an estimated reduction of 50% of the crown surface area appendix. This shows that pruning is an effective tool for improving the stability of urban trees.

The results of the pruning study may seem to be in contrast with the results in chapter 5.2, concerning the effect of seasonal change in foliage for broadleaved species. In the case of foliage loss, the relationship between the reduction of the crown surface area in the winter, and the SF increase was not very strong (see Figure 5.2.6). However, in those cases the branches were not removed, only the foliage changed. When trees are pruned, the branches are also removed, so the drag factor is not significantly affected, only the crown surface changes.

While the results concerning the effects of pruning are encouraging, the study was not completed. More measurements, including the removal of branches in several stages, and involving more trees and several species are recommended for a more in-depth analysis of the relationship between pruning and tree stability. Our current results are, at best, preliminary, but will hopefully inspire further research in this area.

`

Chapter VI. Summary and conclusions

The PhD investigation described in this dissertation yielded the following conclusions:

6.1 The comparision of the pulling test and dynamic testing for tree stability assessment

- The maximum moment (M_{max}) and Safety Factor (SF) derived from the pulling test predicted the actual uprooting torque of diseased ash trees accurately. This confirms that the pulling test is a reliable tool for assessing static tree stability.

- Dynamically measured Safety Factor proved to be an even better predictor of the uprooting moment. This is a strong confirmation of the reliability of the new stability assessment method.

- The relationship of the pulling test and dynamically measured Safety Factors show an acceptable, but not very strong correlation. Based on this, both of the methods are reliable for stability measurement, but differ because they measure different things. It stands to reason that the dynamic loading used for the latter provides a better prediction for the tree stability in wind.

6.2 The effect of natural factors on the dynamic stability of trees

- Soil moisture content has a strong positive correlation with the dynamic Safety Factor of coniferous trees. This is most likely explained by the root structure of these trees. On the other hand, there was no strong correlation between soil moisture content and the SF of broadleaved trees.

- Wind direction variation had less of an effect on the stability of broadleaved and coniferous trees than expected. It is likely that other factors are more influential on dynamic stability. This is an advantage from a practical application point-of-view, where arborists and other experts do not have to worry about the effect of wind direction variations.

`

- Seasonal foliage loss had a weak positive effect on the stability of broadleaved trees. When trees loose their leaves, there is less crown area for the winds to act upon, which improves stability, but, in the meantime, the drag factor also increases which influences the results; this is why the correlation is relatively weak.

6.3 The effect anthropogenic influences on dynamic tree stability

- The effect of root damage could not be established from our results. Dynamic SF did not change, most likely because the modifications were not extensive enough to seriously affect tree stability.

- Pruning approx. 50% of the tree crown led to a significant improvement in tree stability. Pruning decreases the available crown area for the wind to act upon, while does not affect the drag factor. This confirms that pruning is indeed a useful tool to improve tree stability and safety.

6.4 Recommendations for further research

The conclusions in chapter 6.1 show that dynamic tree stability evaluation is a reliable and useful tool to evaluate the safety of trees. This opens up many more opportunities in this field. Specifically, the findings in our study suggest that the following areas are worth investigating:

- Assessing the effect of more variables on the stability of trees, especially broadleaved species. Investigating factors like ground temperature, frozen ground, snow loads, as well as anatomical variations may shed light on the hitherto unexplained variations in the stability of broadleaved trees.

`

- More extensive research into the effect of pruning, and especially that of root damage can increase the understanding of the effect of anthropogenic influences on tree stability. More tree species with different root system and crown architectures should be examined in several stages to gain more knowledge of these influences.

`

Chapter VII. Scientific statements

Based on the results and conclusions of my project, I have formulated the following scientific statements:

1. I have confirmed that dynamic tree stability assessment is a valid tool for assessing the stability and safety of urban and forest trees. Dynamic testing results showed very good agreement with traditional static testing results. Because of the dynamic loading scenario it is likely to be as good or better than the pulling test for this purpose.

2. I have shown that soil moisture content is an important natural factor that influences tree stability in coniferous trees. There is a strong positive correlation between soil moisture content and the dynamic safety factor.

3. I have concluded that, while seasonal foliage loss has some positive effect on the safety factor of broadleaved trees, their stability is determined by a number of factors in a complex interaction. This phenomenon needs to be further investigated to gain a better understanding of the stability of deciduous trees.

4. I have concluded that, contrary to expectation, wind direction does not significantly influence the dynamic Safety Factor of trees. Other factors are more influential in determining their stability. This is an advantage from a practical application point-of-view.

5. I have proved experimentally that pruning is an effective tool to improve the safety of urban trees, due to the significant improvement in the dynamic safety factor. Removing approx. 50% of the crown led to a significant improvement in tree stability.

`

Chapter VIII. References

1. Allison, R.B. and X. Wang. 2015. Nondestructive Testing in the Urban Forest. In: R.J. Ross ed. Nondestructive Evaluation of Wood. 2nd ed. General Technical Report FPL-GTR-238. USDA Forest Products Laboratory, Madison, WI., USA. pp. 77-86.

2. Amato, M., Basso, B., Celano, G., Bitella, G., Morelli, G., Rossi, R. 2008. In situ detection of tree root distribution and biomass by multi electrode resistivity imaging. Tree Physiology 28: 1441–1448.

3. Bejo, L., Divos, F, and Fathi S. 2017. Dynamic root stability assessment – basics and practical examples. Proc. 20th Int. NDTE Wood Symp. Sept. 12-15, 2017, Madison, WI pp. 262-269

4. Bell, H.J., Dawson, A.R., Baker, C.J. and Wright, C.J. 1991. Tree stability. In: Hodge, S.J. (Ed.), Research for Practical Arboriculture. HMSO, London, University of York. 94–101.

5. Buza, Á.K. and Divós, F. 2016. Root Stability Evaluation with Non-Destructive Techniques Acta Silv. Lign. Hung.,Vol. 12, Nr 2 125–134

6. Bieker, D. and S. Rust (2010) Non-destructive estimation of sapwood and heartwood width in Scots pine (Pinus sylvestris L.). Silva Fennica 44(2):267-273.

7. Bieker, D., Kehr R., Weber, G & Rust, S. 2010. Non-destructive monitoring of early stages of white rot by Trametes versicolor in Fraxinus excelsior, Annals of Forest Science volume 67, page210

8. Brashaw , B. K., Bucur, B. V, Divos, F., Gonçalves, R., Lu, J., Meder, R., Pellerin, F. R., Potter, S., Ross, R. J., Wang, X., and Yin, Y. 2014. Nondestructive Testing and Evaluation of Wood: A Worldwide Research Update, Fores Products Journal 59(3): (35-43)

9. Barbier, S., Gosselin, F. and Balandier, P. 2008. Influence of tree species on understory vegetation diversity and mechanisms involved—A critical review for temperate and boreal forests, Forest Ecology and Management 254(1):1-15

`

10. Brudi, E. and Wassenaer, P. V. 2002. Trees and Statics: Non-Destructive Failure Analysis, in How Trees Stand Up and Fall Down, Illinois, pp. 53–70.

11. Brüchert, F., Speck, O. and Spatz, H. 2003. Oscillations of plants' stems and their damping: Theory and experimentation. Philosophical Transactions of the Royal Society of London Series B-Biological Sciences 358(1437):1487–1492.

12. Brüchert, F., Becker, F. and Speck, T. 2000. The mechanics of Norway spruce [Picea abies (L.) Karst]: Mechanical properties of standing trees from different thinning regimes. Forest Ecology and Management 135:45–62.

13. Cilas, C., Costes, E., Milet, J., Legnaté, H., Gnagne, M. and Clément-Demange, A. 2004. Characterization of branching in two Hevea brasiliens is clones. Journal of Experimental Botany 55:1045-1051.

14. Clair, B., Fournier, M., Prevost, M.F., Beauchene, J., Barbet, S. 2003. Biomechanics of buttressed trees: bending strains and stresses. American Journal of Botany 90 (9): 1349–1356.

15. Clough, R.W. and Penzien, J. 1993. Dynamics of structures. McGraw Hill, New York, City, New York, U.S.

16. Cullen, S. 2002. Trees and wind: wind scales and speeds. Journal of Arboriculture 28: 237–242.

17. Coomes, D., Allen, R. B. 2007. Effects of size, competition and altitude on tree growth., Journal of Ecology 95(5):1084 - 1097

18. Conrad, W. 1895. Röntgen discovered "An Unknown Kind of Radiation about X-ray in NDT.

19. Chodak, E. R. 2019. Pressures and Threats to Nature Related to Human Activities in European Urban and Suburban Forests, FORESTS Journal., 10, 765, 26 pages

20. Davenport, A. G. 1965. The relationship of wind structure to wind loading. In: Proceedings of the Conference on Wind Effects on Structures. National Physical Laboratory (NPL United Kingdom), (ICWE-1), HMSO, p. 53.

`

21. Detter, A. and Rust S. 2013. Aktuelle Untersuchungsergebnisse zu Zugversuchen [Latest results in research on pulling tests] In: D. Dujesiefken (Ed.). Jahrbuch der Baumpflege (in press).

22. Dahle, G.A. and Grabosky, J.C. 2010b. Variation in modulus of elasticity (E) along *Acer platanoides* L. (Aceraceae) branches. Urban Forestry & Urban Greening 9:227–233.

23. Divos, F. and Szalai, L. 2002. Tree evaluation by acoustic tomography. In: Proc. 13th Int. Nondestructive Testing of Wood Symposium, August 19-21, 200. Berkeley CA, Madison WI, Forest Products Society. pp. 251-256.

24. Divos, F., Bejo, L., Toth, A. 2009. Instrument supported tree evaluation in Hungary. In: Zhang H., Wang X. (ed.) Proceedings of the 16th International Symposium on Nondestructive Testing of Wood. Beijing Forestry University, Beijing, China. 71–76.

25. Divos, F. 2010. Acoustic tools for seedling, tree and log selection. In: Proceedings of the Final Conference of COST Action E53 "The Future of Quality Control for Wood and Wood Products". Edinburgh (Scotland) 4-7 May 2010. Napier University, Edinburgh, UK. pp. 5.

26. Divos, F., Tóth, A., Takats, P. 2011. Nondestructive methods for in-service glulam beam evaluation, International Conference on Structural Health Assessment of Timber Structures - Lisbon, Portugal

27. De Langre, E. 2008. Effects of wind on plants. Annual Review of Fluid Mechanics 40:141–168

28. Den Hartog, J. P. 1956. Mechanical Vibrations. McGraw-Hill, New York City, New York, U.S.

29. Dubbel, V., Weihs, U., Krummheuer, F. and Just, A. 1999. Neue Methode zur zweidimensionalen Dar- stellung von Fäulen an Fichte. AFZ/Der Wald 26:1422–1425

30. Ellison, M. J. 2005. Quantified tree risk assessment used in the management of amenity trees. Journal of Arboriculture 31(2):57–65.

`

31. Fourcaud, T., Clément-Demange, A., Costes, E., Baillères, H., Gnagne, M. 1999. A mechanical analysis of the relationship between free oscillations of Pinus pinaster Ait. saplings and their aerial architecture

32. Montpellier, France: Compte rendu ATP CIRAD (internal report), 1–16.

33. Fakopp Ltd. 2018 DynaRoot Dynamic Root Evaluation System http://fakopp.com/docs/products/dynaroot/UserManualDynaRoot.pdf

34. Fathi, S., Bejo, L. and Divos, F. 2020. Investigating the Effect of Weather and Seasonal Factors on Root Stability Using Dynamic Measurements, Open Journal of Forestry 10:124–134

35. Genet, M., Stokes, A., Salin, F., Mickovski, S. B., Fourcaud, T. and Dmail J. F. 2005. The influence of cellulose content on tensile strength in tree roots. Plants and Soil. 278:1-20

36. Gilbert, E. A. and Smiley, E. T. 2004. Picus sonic tomography for the quantification of decay in white oak (Quercus alba) and hickory (Carya spp.). Journal of Arboriculture. 30: 277–280.

37. Greenhill, A. G. 1881. On the Flow of Viscous Liquid in a Pipe or Channel.

38. Goncz,. B, Divos, F. and Bejo, L. 2018. Detecting the presence of red heart in beech (Fagus sylvatica) using electrical voltage and resistance measurements, European Journal of Wood and Wood Products volume 76, P 679–686

39. Guo, L., Chen, J., Cui, X., Fan, B. and Lin, H. 2013. Application of ground penetrating radar for coarse root detection and quantification: a review. Plant and Soil 362: 1–23.

40. Hanskötter, B. 2004. Diagnose fakultativer Farbkerne an stehenden Rotbuche (Fagus sylvatica L.) mit- tels "Elektrischer Widerstandstomographie". Ph.D. thesis. Department of Forest Science and Ecology, Georg-August Univ. Göttingen, Germany. 133 pp.

`

41. IAEA 2001, Application of non-destructive testing and in-service inspection to research reactors, Results of a co-ordinated research project, Austria, Vienna

42. James, K. R., Haritos N. and Addes, P. K. 2006. Mechanical stability of trees under dynamic loads. American Journal of Botany 93(10):1361–1369.

43. James, K. R., Haritos, N. and Adesh, P. K. 2006. Mechanical stability of trees under dynamic loads. American Journal of Botany 93(10): 1522–1530.

44. James, K. R. and Kane, B. 2008. Precision digital instruments to measure dynamic wind loads on trees during storms. Agricultural and Forest Meteorology 148: 1055–1061.

45. James, K., Grabosky, J., Dahle, G. and Kane, B. C. 2014. Tree Biomechanics Literature Review: Dynamics Arboriculture & Urban Forestry 40(1): (1-15)

46. James, K. R. 2010. A Dynamic Structural Analysis Of Trees Subject To Wind Loading. Ph.D. thesis. University of Melbourne, Australia

47. James, K., Hallam, C. and Spencer, C. 2013. Measuring tilt of tree structural root zones under static and wind loading. Agricultural and Forest Meteorology 168: 160–167.

48. James, K. R., Haritos, N. and Ades, P. K. 2006. Mechanical stability of trees under dynamic loads. American Journal of Botany 93(10):1361–1369.

49. Just, A. and Jacobs, F. 1998. Elektrische Widerstandstomographie zur Untersuchung des Gesundheitszustandes von Bäumen. Tagungsband des VII. Arbeitsseminars „Hochauflösende Geoelektrik", Institut für Geophysik und Geologie der Universität Leipzig

50. Kane, B. and Clouston, P. 2008. Tree pulling tests of large shade trees in the genus Acer. Arboriculture and Urban Forestry 34 (2): 101–109.

51. Krasowski, M. J. 2003. Root system modifications by nursery culture reflect on post-planting growth and development of coniferous seedlings. Forestry Chronicle 79:882–891.

`

52. Lichtenegger, H., Reiterer, A., Stanzl-Tschegg, S. E. and Fratzl, P. 1999. Variation of cellulose microfibril angles in softwoods and hardwoods-a possible strategy of mechanical optimization. Journal of Structural Biology 128:257–269.

53. Lin, C. J., Chung, C. H., Yang T. H. and Lin, F. C. 2012. Detection of Electric Resistivity Tomography and Evaluation of the Sapwood-Heartwood Demarcation in Three Asia Gymnosperm Species. Silva Fennica 46(3): 415–424.

54. Lindström, H., Evans, J. W. and Verril, S. P. 1998. Influence of cambial age and growth condition on microfibril angle in young Norway spruce [*Picea abies* [L.] Karst.]. Holzforschung 52:573–581.

55. Lundström, T., Jonas, T., Stöckli, V. and Ammann, W. 2007A. Anchorage of mature conifers: resistive turning moment, root–soil plate geometry and root growth orientation. Tree Physiology 27:1217–1227.

56. Lundström, T., Jonas, T. and Kalberer, M. 2007B. The root–soil system of Norway spruce subjected to turning moment: resistance as a function of rotation. Plant Soil 300:35–49

57. Lundström, T., Stoffel, M. and Stöckli, V. 2008. Fresh-stem bending of silver fir and Norway spruce. Tree Physiology 28:355–366

58. Mattheck, C. and Bethge, K. A. 1993. Detection of decay in trees with the Metriguard Stress Wave Timer. J. of Arboriculture 19(6).375-378.

59. Mattheck, C., Bethge, K. and Schafer, J. 1993. Safety Factor in trees. Journal. Theor. Biol. 165:185-189

60. Major, B. and Divos, F. 2015. Glue laminated timber structure evaluation by acoustic tomography. In: Proc. Euromech colloqutum556, Theoretical, Numerical, and Experimental Analyses in Wood Mechanics. Dresden, Germany.

61. Miire, J. R. 2000. Differences in maximum resistive bending moments of Pinus radiata trees grown on a range of soil types. For. Ecol. Man. 135: 63–71.

`

62. Moore, J. R. and Maguire, D. A, 2004. Natural sway frequencies and damping ratios of trees: Concepts, review and synthesis of previous studies, ReaserchGate 18:195–203

63. Miller, L. A. 2005. Structural dynamics and resonance in plants with nonlinear stiffness. Journal of Theoretical Biology 234:511–24.

64. Mattheck, C. and Breloer, H. 1994. The body language of trees. HMSO, Department of the Environment, London, UK. 240 pp.

65. Moore, J. R. and Maguire, D. A. 2005. Natural sway frequencies and damping ratios of trees: Influence of crown structure. Trees 19:363–73.

66. Miller, L. A. 2005. Structural dynamics and resonance in plants with nonlinear stiffness. Journal of Theoretical Biology 234:511–24.

67. Murphy, K.D., and Rudnicki, M. 2012. A physics-based link model for tree vibrations. American Journal of Botany 99:1918–1929.

68. Milne, R. 1991. Dynamics of swaying of Picea sitchensis. TreePhysiology 9(3):383–399.

69. Moore, J. R., and Maguire, D. A. 2008. Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. Tree Physiology 28:75–83

70. Nicolotti, G., Socco, L. V., Martinis, R., Godio, A. and Sambuelli, L. 2003. Application and comparison of three tomographic techniques for the detection of decay in trees. Journal of Arboriculture. 29: 66–78.

71. Neild, S. A., Wood, C. J. 1999. Estimation stem and root-anchorage flexibility in trees. Tree Physiology 19: 141–151.

72. Niklas, K. J. 1992 . Plant biomechanics: An engineering approach to plant form and function. University of Chicago Press, Chicago, Illinois, U.S.

73. Niklas K.J., Spatz H.C. 2000 Wind induced stresses in cherry trees evidence against the hypothesis of constant stress level trees. Trees 14(4):230-237

`

74. Peltola, H., Kellomaki, S., Hassinen, A. and Granander, M. 2000. Mechanical stability of Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. Forest Ecology and Management 135(1):143-153

75. Peltola, H. M. 2006. Mechanical stability of trees under static loads. American Journal of Botany 93(10):1341–1351.

76. Pitarma, R., Crisóstomo, J. and Ferreira, M. E. 2018. Learning About Trees in Primary Education: Potentiality of IRT Technology in Science Teaching. In Proceedings of the EDULEARN18 Conference, Palma, Spain,; pp. 208–213.

77. Rahardjo, H., Harnasa, F. R., Indrawana, I. G. B., Leonga, E. C., Tanb, P. Y., Fongc, Y .K., Owc, L. F. 2014. Understanding the stability of Samaneasaman trees through tree pulling, analytical calculations and numerical models. Urban Forestry and Urban Greening 13: 355–364.

78. Ray, D., Nicoll, B. C. 1998. The effect of soil water-table depth on root-plate development and stability of Sitka spruce. Forestry 71 (2): 169–182.

79. Reiterer, A., Lichtenegger, H., Tschegg, S. and Fratzl, P. 1999. Experimental evidence for a mechanical function of the cellulose microfibril angle in wood cell walls. Philosophical Magazine A 79:2173–2184.

80. Rinn, F. (1990): Vorrichtung zur Materialprüfung, insbesondere Holzprüfung durch Bohr- bzw. Eindringwiderstandsmessung. Patent DE4122494B4, Prioritätsdatum 3. September 1990.

81. Rodgers, M., Casey, A., Mcmenamin, C. and Hendrick, E. 1995. An experimental investigation of the effects of dynamic loading on coniferous trees planted on wet mineral soils. In: Coutts, M.P., Grace, J. (Eds.), Wind and Trees. Cambridge University Press. 204–219.

82. Rodriguez, M., Langre, E. de. and Moulia, B. 2008. A scaling law for the effects of architecture and allometry on tree vibration modes suggests a biological tuning to modal compartmentalization. American Journal of Botany 95:1523–37.

83. Sani, L., Lisci, R., Moschi, M., Sarri, D., Rimediotti, M. and Vieri, M. 2012. Preliminary experiments and verification of controlled pulling tests for tree

`

stability assessments in Mediterranean urban areas. Biosystems Engineering, 112 (3): 218–226.

84. Saddik, G., 2015. Ultrasound Imaging System. Ph.D. thesis. University of California, Los Angeles, CA Bioengineering Department.

85. Siegert, B. 2013. Comparative Analysis of Tools and Methods for the Evaluation of Tree Stability Results of a field test in Germany. Arborist News april 2013: 26–31.

86. Silins, U., Lieffers, V.J. and Bach, L. 2000. The effect of temperature on mechanical properties of standing lodgepole pine trees. Trees 14 (8): 424–428.

87. Spatz, H. C. and Brüchert, F. 2000. Basic biomechanics of selfsupporting plants: wind and gravitational loads on a Norway spruce tree. Forest Ecology Management 135:33–44.

88. Speck, T, and Burgert, I. 2011. Plant Stems: Functional Design and Mechanics. Annual Review of Material Research 41:169–193.

89. Sellier, D., and Fourcaud, T. 2009. Crown structure and wood properties: Influence on tree sway and response to high winds. American Journal of Botany 96:885–896.

90. Smiley, E. T., Matheny, N. and Lilly, S. 2011. Best Management Practices Tree Risk Assessment. ISA, Champaign, Illinois, U.S.

91. Schindler, D., Vogt, R., Fugmann, H., Rodriguez, M., Schonborn, J., and Mayer, H.. 2010. Vibration behavior of plantation-grown Scots pine trees in response to wind excitation. Journal of Agri-cultural and Forest Meteorology 150:984–993.

`

92. Strogatz, S. H. 2014. Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering, Second Edition (Studies in Nonlinearity) 2nd Ed. CRC Press. ISBN-13: 978-0813349107

93. Sellier, D., Y. Brunet, and T. Fourcaud. 2008. A numerical model of tree aerodynamic response to a turbulent airflow. Forestry 81:279–97.

94. Theckes, B., de Langre, E., and Boutillon, X. 2011. Damping by branching: A bioinspiration from trees. Bioinspiration and Biomimetics 6:1–11.

95. Vogel. S. 1996, Blowing in the wind: storm resistancing features of the design of trees. Journal of Arboriculture 22(2): 92-98

96. Vizvari, Z., Kissa, T., Matheb, K., Odry, P., Ver, C and Divos, F. 2015. Multi-Frequency Electrical Impedance Measurement on a Wooden Disc Sample Acta Silv. Lign. Hung., 11(1):153–161

97. Weihs, U. 2001. Farbkerndiagnose am stehenden Elsbeerenstamm. AFZ/Der Wald 6:268-270

98. Weihs, U., Dubbel, V., Krummheuer, F. and Just A. 1999. Die elektrische Widerstandstomographie – Ein vielversprechendes Verfahren zur Farbkern-diagnose an stehenden Rotbuchen. Forst und Holz 6:166–170.

99. Wessolly, L. and Erb, M. 1998. Handbuch der Baumstatik und Baumkontrolle. Patzer, Berlin

100. Weihs, U., Hoffmann, N., Fitzner, S. and Schilling, M. 2005. Diagnose des Eschenbraunkerns mittels "Elektrischer Widerstandstomographie". AFZ/Der Wald 20:1093–1096

101. Wessoly, L. 1991. Verfahren zur Bestimmung der Stand- und Bruchsicherheit von Baumen. HolzalsRoh- und Werkstoff 49: 99–104.

102. Wessolly, L. and Erb, M. 2016. Tree Static and Tree Inspection. ISBN 978-3-87617-143-2

103. Wang, X. and Allison, R. B. 2008. Decay detection in red oak trees using a combination of visual inspection, acoustic test- ing, and resistance microdrilling. Arboriculture & Urban Forestry. 34(1): 1–4.

104. Wang, X.; Wiedenbeck, J.; Liang, S. 2009. Acoustic tomog- raphy for decay detection in black cherry trees. Wood and Fiber Science. 41(2): 127–137.

105. Wang, X., Carter, P., Ross, R. J., and Brashaw, B. K. 2007. Acoustic assessment of wood quality of raw forest materials – a path to increased profitability. Forest Prod. J. 57(5):614.

106. Wessolly, L. 1991. Verfahren zur Bestimmung der Stand- und Bruchsicherheit von Bäumen [Methods for determining the safety against uprooting and stem fracture]. Holz als Roh- und Werkstoff 49:99–104.

107. Wessolly, L.; Sinn,G. 1989, A Contribution to the Proper Assessment of the Strength and Stability of Trees. Arboricultural Journal, 13:45-65

108. Yang, C. H., Lin, H. L. and Han, C. C. 2010. Analysis of international touristarrivals in China: The role of World Heritage sites.Tourism Management,31(6), 827–837.R. Cellini / Tourism Management 32 452– 454454

109. Zenone, T., Morelli, G., Teobaldelli, M., Fischanger, F., Matteucci, M., Sordini, M., Armani, A., Ferre, C., Chiti, T. and Seufert, G. 2008. Preliminary use of ground-penetrating radar and electrical resistivity tomography to study tree roots in pine forests and poplar plantations. Functional Plant Biology 35: 1047–1058.

`

Appendix A: The photographs and analysis of crown surface area of the trees at the time of measurement
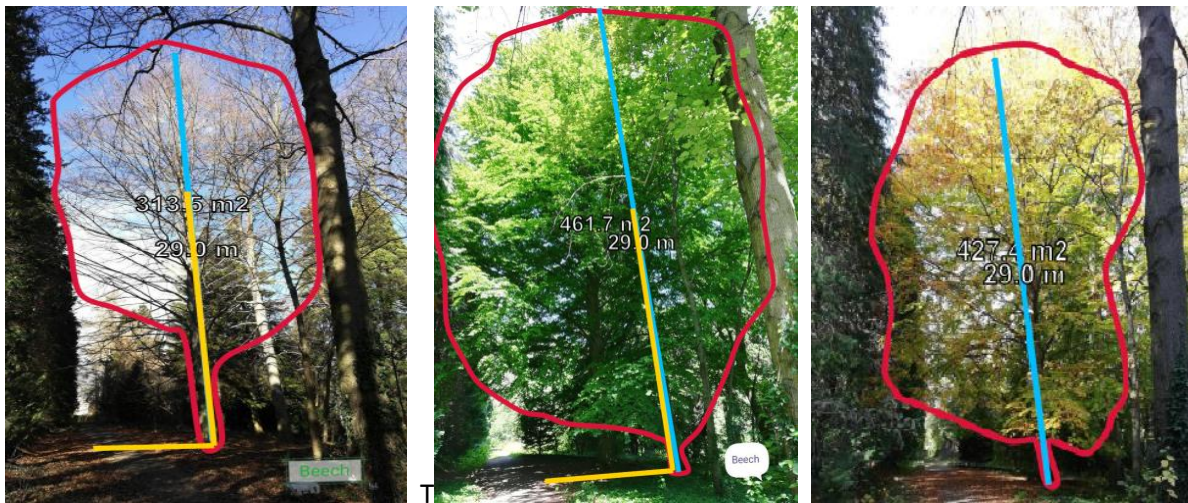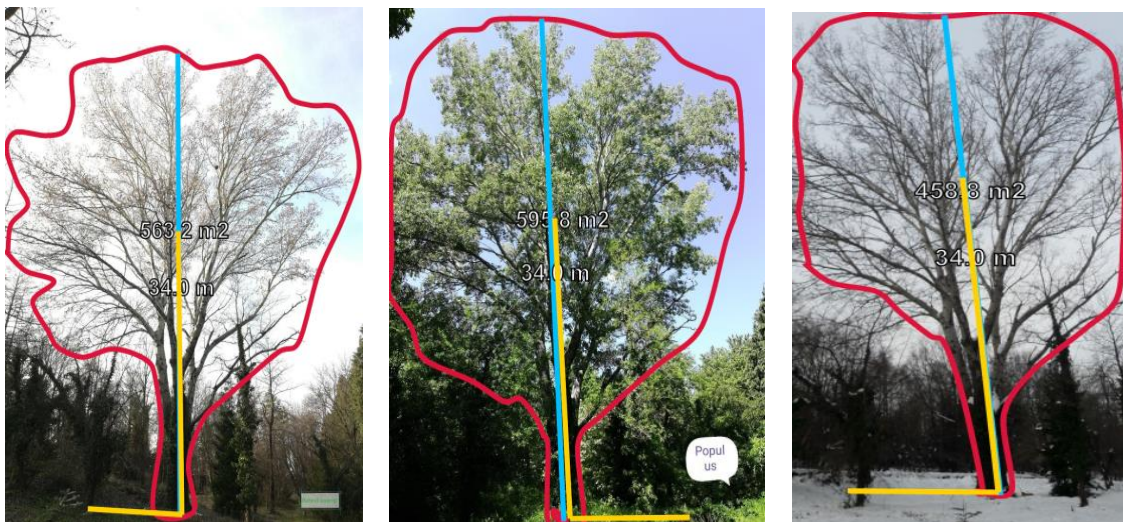

Beech tree Left to Right respectively: Winter, Spring, Autumn
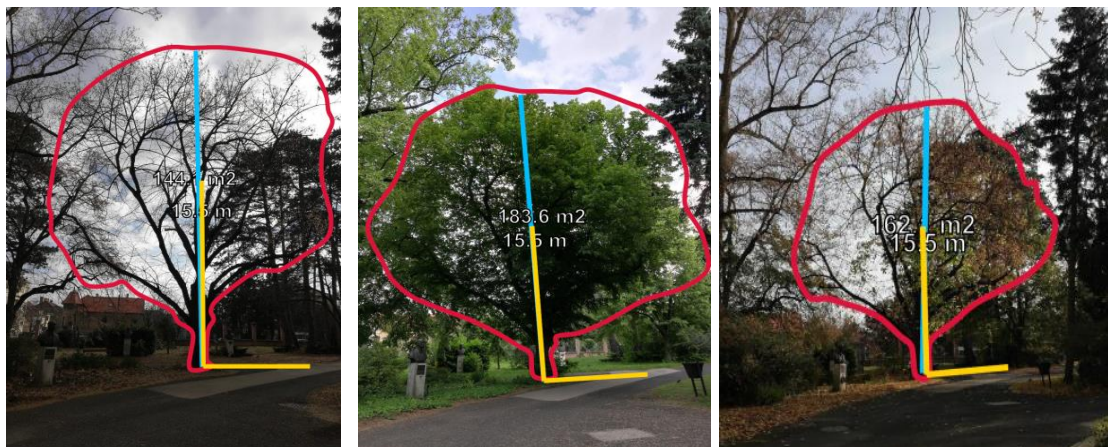
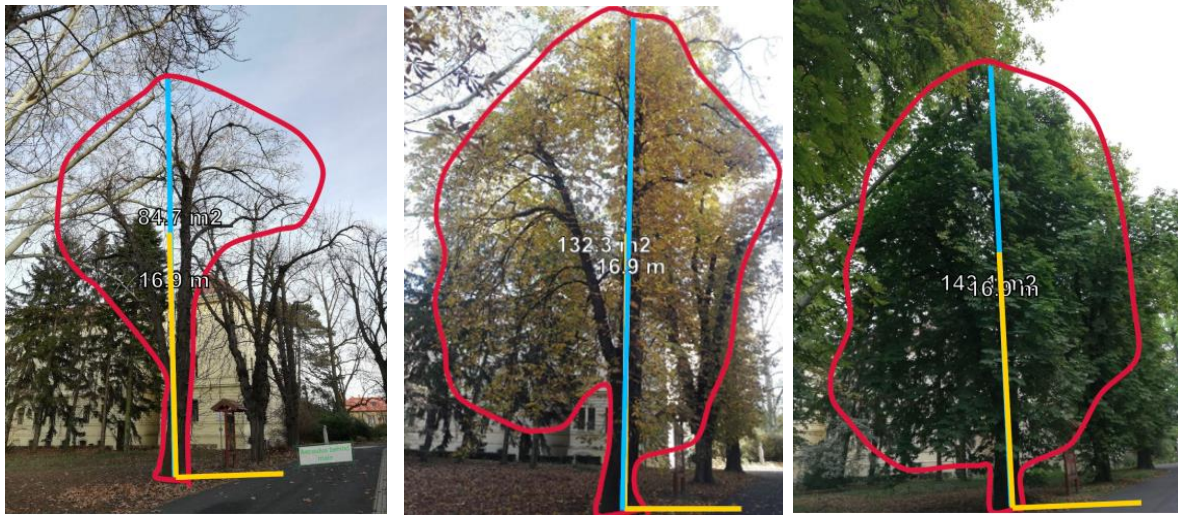Lime tree Left to Right respectively: Winter, Spring, Autumn

Tulip tree Left to Right respectively:, Spring, Winter and Autumn

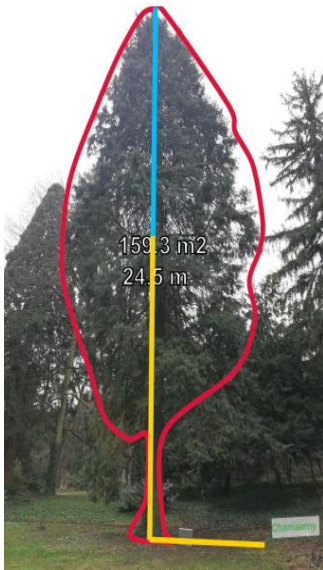White poplar Left to Right respectively: Autumn, Spring, Winter
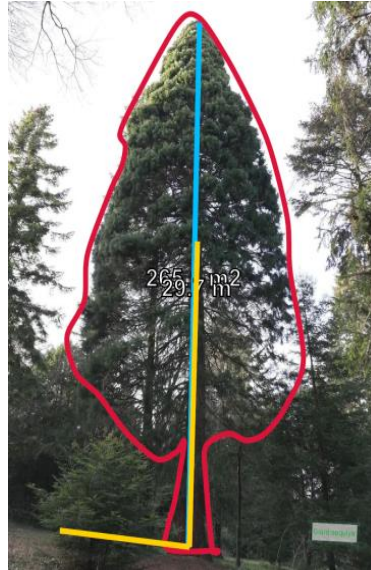

Oak tree Left to Right respectively: Spring, Winter
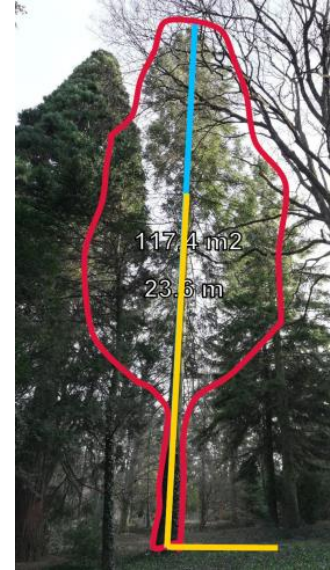
Horse chestnut tree Left to Right respectively: Winter, Autumn, Spring

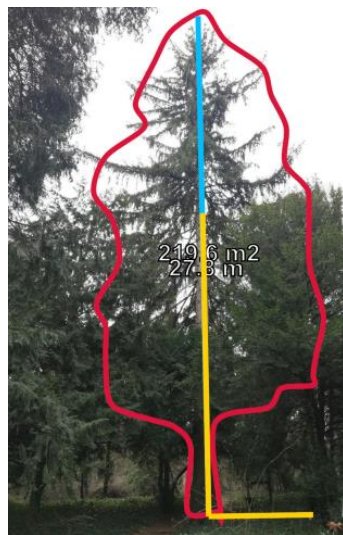Japanese zelkova chestnut tree Left to Right respectively: Autumn, spring, Winter

Port-orford-Cedar   Giant sequoia   Grand Fir

English Yew   Black Pine

Acknowledgment

Foremost, I take pleasure to express sincere gratitude to my advisors Prof. Dr. László Bejó and Prof. Dr Ferenc Divós for the continuous support of my Ph.D. study and research, for their patience, motivation, enthusiasm and immense knowledge. As well as stipendium Hungaricum scholarship where gave me the golden opportunity to study Ph.D. and led me to discover great extent of new knowledge.

`

I   am   extremely   thankful   and   pay   my   gratitude   to
 Ms Vera Tolvaj for her valuable guidance and support on completion during my study.

Last but not the least; I would like to thank my brother "Ashkan Fathi" and his wife for supporting me financially and spiritually through my life. Also thanks to my maternal family for all their support. Finally all my respect to my parents who are looking me over sky but are main motive to study as this is what I promised them; therefore, I would like to dedicate this thesis to their pure souls.

Thanks to all who helped me!

`