Ambient influences on the results of non-destructive pulling tests

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Abstract

In several field studies, the effect of environmental conditions like air, wood, and soil temperature, soil moisture content and high ground water table, were tested on mature trees in non-destructive pulling tests and winching tests to ultimate failure. Furthermore, the effects of repeated loading with increasing stem base rotation were tested in destructive winching tests on 13 trees of two species. This experiment investigates the effect of fatigue in a tree's anchoring system due to cyclic loading in natural turbulent winds. The uprooting behaviour and the anchoring strength under such conditions were compared to a quasi-static pull to anchorage failure of trees of the same species. All results were evaluated with regard to the estimation of stem strength and anchoring strength of root systems by means of non-destructive pulling tests.

Keywords: environmental effects, soil moisture, temperature, cyclic loading, pulling test

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Introduction

Pulling tests are used in arboriculture to non-destructively assess the strength of open grown trees (Sinn and Wessolly 1989). A tree's strength characteristics can be assessed by applying a moderate non-destructive load with a winch, measuring the tree's reactions with high-precision sensors for fibre strain and stem base inclination, and extrapolating those data to determine the minimum resistance of the stem against fracture (Wessolly 1991, Detter and Rust 2013, Detter et al. 2014) and anchoring strength of the root system (Wessolly 1996, Detter and Rust 2013, Buza and Divós 2016).

The tests are usually performed under moderate climatic conditions, but the fracture resistance in bending and the anchoring strength of the root system of the subject tree may be challenged by natural storms under more extreme temperatures and humidity. On the other hand, for reasons that are not at the discretion of the appraiser, e.g. to identify a potential immediate hazard, the tests must be carried out during periods with extremely high or low temperatures as well as during droughts or after periods of intense rainfall. How the changes in temperature and soil moisture content affect the load response of the trees in the non-destructive range has not been subject to intensive research so far.

For tomographic and drilling methods it has already been shown that the results can be significantly affected by frost (Rust, 1999, 2003). In Finland and North America, it was found that trees subjected to bending were up to 50 percent stiffer during frost (Silins et al. 2000). Freezing also changed the sway behaviour of standing conifers (Granucci et al. 2012). Schmidt and Pomeroy (1990) found a significant increase in the flexural stiffness of frozen conifer branches. In a moderate climate, Roodbaraky et al. (1994) did not find great variations in load vs. deflection curves for the same trees in different seasons. But from material science it may be expected that the MOE of green wood rises with decreasing wood temperature and decreases with rising wood temperature (Kretschmann 2010).

The effect of temperature on soil properties was described earlier for specific soil types (Jefferson 1994). The anchoring strength of trees is the result of the deformability of the root soil matrix. Temperature may affect the load response of the soil and the wooden body of the roots differently, eventually changing their interaction and the contribution of these components to the uprooting strength of the tree. As soon as the soil is frozen, the increased soil stiffness alters the failure patterns of trees (Peltola et al. 2000).

Material tests on specimen of green wood indicate that above the fibre saturation point changes of moisture content do not affect strength properties (Kretschmann 2010; Niklas and Spatz 2012). Since pulling tests in arboriculture are exclusively performed to assess the strength of living trees, we did not expect an effect on the measured strain values in the stem under bending (Spatz and Pfisterer 2013).

Yet, a strong increase in soil moisture content sometimes significantly affected the stability estimated from non-destructive pulling test during investigations at the Nürtingen University of Applied Sciences (Wohn 2003). Experiments in Japan with a massive irrigation of the root zone showed initially a higher, later reduced stability of forest trees (Kamimura et al. 2011). But in another experiment on soils that are typically not water saturated, soil moisture had very little discernible effect on tree stability until very high levels of soil moisture were reached (Peterson and Classen 2013). In the Netherlands, practitioners of the pulling test method reported that trees growing on sites with high ground water table showed high inclinations at low load levels (Mol and Goederen 2017). Therefore, the standard extrapolation from non-destructive levels of tilt to the anchoring strength of the root system of such trees was questioned.

In addition, the test procedure of a pulling test does not mimic the behaviour of trees during uprooting. In field experiments it was shown that during the failure process, the stem base inclination of the trees increased with each load cycle until the tree finally tipped over (James 2014). For forest trees, it was presumed that the resistance to this cyclic loading was lower than to a single static pull (Jonsson et al. 2006; Leigh 2014; O'Sullivan and Ritchie 1993; Rodgers et al. 1995). But preliminary experiments by Coutts (1983) indicated that uprooting trees by a series of pulls and relaxations rendered similar results to continuous pulling.

We presume that temperature and soil moisture content may affect the load response of trees in the non-destructive range. It is not subject to this paper how the ultimate strength may be altered by those influences. We also investigated how high ground water tables may affect the estimations of stability based on pulling tests and tested if a static pulling test can be adequate to estimate anchorage strength of trees gradually failing in a sequence of increasing cyclic root plate tilt.

Material and Methods

In order to study the effect of such ambient conditions on the result of pulling tests, we conducted a number of experiments on road side trees, urban trees and plantation trees. The experiments reported in the present paper are:

1. Seasonal effects on the results of arboricultural pulling tests
2. Effects of wood temperature on apparent flexural stiffness in stem bending
3. Rotational stiffness at soil temperatures above and around freezing point
4. Differences in rotational stiffness at increased soil moisture content
5. Rotational stiffness and anchoring strength of trees growing on water saturated soils
6. Uprooting behaviour under cyclic loading with rising inclinations

Each experiment will be briefly described in the following. All sensors used in the experiments are part of the *TreeQinetic* set (*Argus electronics GmbH,* Rostock, Germany) which consists of a forcemeter (accuracy 25 N), sensors for fibre strain (Elastometers, accuracy 1 µm) and sensors for root plate tilt (Inclinometers, accuracy 0.002°) as well as a communication unit for wireless data transfer and the measurement software for logging data (*Treeqinetic Measure*). All pulling tests were carried out according to the Elasto-Inclino-Method or SIM (Wessolly and Erb 2016) following the standard setup (Brudi and Wassenaer 2002, Detter and Rust 2013).

Seasonal effects within 12 months

Pulling tests were carried out with identical setup on a row of 9 mature urban Linden trees (*T. x europea*) at 5 dates within 12 months from 2011 to 2012 under changing climatic conditions, including summer drought and deep winter frost. The trees had stem diameters at 1 m height between 38 and 56 cm (mean

48.4 cm, sd 5.8 cm) and heights between 14 and 20 m (mean 16.9 m, sd 1.6 m). The climatic conditions during each pulling test are listed in Table 1.

Table 1 climatic conditions at pulling tests investigating seasonal effects within 12 months

Property	Feb '11	June '11	Aug '11	Nov '11	Feb '12
mean ambient temperature in °C	13	26	26	10	-10
mean air humidity in %	30	43	47	72	61
mean soil temperature in °C	2.3	22.5	22.1	13.9	-3.3
Mean soil moisture content in %	-	5.0	4.7	6.2	-
Mean stem surface temperature	15.9	23.2	26.9	14.9	-14.0

The site has a deep rooting space and the soil consists of a gravel-sand mixture with less than 10% fine grain content. Therefore, the soil has a very low field capacity and was very dry at all times, even though heavy rain occurred prior to the tests in June and November 2011. The pulling tests in February 2012 were preceded by a period of severe frost during which ambient temperature did not exceed -10°C for more than two weeks. Therefore, stems and soil were frozen.

The anchoring strength of the root system and the resistance of the stem against fracture were estimated from the non-destructive pulling test and compared to a wind load estimation as described by Detter & Rust (2013). Safety factors were deducted using *Arbostat* evaluation software (*Arbosafe GmbH*, Gauting, Germany) by using the same wind load estimation but evaluating different data from one force meter, 4 Elastometers and 2 Inclinometers for each test date.

Wood temperature

In a nursery near Dachau, Germany, 8 Birch trees (*B. pendula*) standing in one line were exposed to non-destructive pulling tests on four days between January and July 2012. Diameters at 1 m height ranged from 18 cm to 29 cm and heights from 16.4 to 17.4 m. Air temperature and wood temperature in the stem at a depth of 2 cm below the stem surface were recorded. The wood temperatures in this test series ranged from -21 to 23° C. Two measurements were carried out with frozen wood, one above freezing point with wood temperatures between 2 and 4°C and one with wood temperatures between 17 and 23°C.

Soil temperature

The effect of sinking soil temperature until the freezing point was investigated at of 10 semi-mature Linden trees (*T. x europea*) growing along a road-side in an urban setting. The mean stem diameters at 1 m height ranged from 34 to 51 cm (mean 39.5 cm, sd 4.2 cm) and tree height from 10 to 13 m (mean 11.6 m, sd 0.8 m). Soil temperature was measured at 4 depths (2, 10, 20 and 30 cm) at the stem base of 3 trees at each test day. Soil moisture content was also measured as a control and ranged from 0.20 in October 2014 to 0.33 in February 2014.

Non-destructive pulling tests were carried out at 7 different dates from October 2014 to February 2015 on all 10 trees. From the load vs. tilt data, the rotational stiffness was derived and the anchorage strength (in kNm) was estimated based on the extrapolation methods described in literature (Detter and Rust 2013, Rust and Detter 2019) using *Arbostat* evaluation software.

Soil moisture content

Seven experimental trees of similar age, size and morphology were selected in a lime tree avenue (*T. cordata*) along a village road. The trees had diameters ranging from 47 to 67 cm (mean 58.1 cm, sd 6.4 cm) and heights from 13 to 18 m (mean 16.4 m, sd 1.7 m).The natural soil was a loamy brown earth from Pleistocene river sediments, but during the construction of the road, the subsoil was partly replaced by mineral material. In the rooting space between the stem base of the trees and an adjacent meadow, the topsoil (0-20 cm) contained only little organic matter and about 20 percent clay. From 20 cm downwards, the proportion of organic matter even decreased and the clay content increased to roughly 30 percent. Since the ground has been changed by road construction, high variability in the soil properties occurred.

One series of tests was carried out in September 2011. On every tree non-destructive pulling tests were performed prior and after irrigating the trees. Root plate tilt and applied force were measured continuously. After the irrigation, the same load was exerted as prior to the test and inclination was measured with inclinometers at the same positions as prior to the irrigation. After two weeks, at the beginning of October 2011, the same procedure of pulling tests and irrigation was repeated on every tree.

Since all tested trees had a similar trunk diameter, the trees were uniformly irrigated on an area of 2.5 m x 2.5 m around the stem base. The soil was sufficiently porous to accommodate for 500 l per tree during each watering cycle. The soil was just able to absorb this quantity without water running beyond the irrigated surface. The soil moisture was measured at different depths in a hole (depth 45 cm and diameter 30 cm) drilled with an earth boring device. An electronic moisture meter was pricked into the sides of the borehole at depths of 5, 10, 20, 30, 40 cm, thus determining the volume fraction of water in the soil at the respective depth.

Water saturated soils

In order to assess the stability of trees under water saturated soil conditions, we selected two sets of Hybrid Poplars (*P. x canadensis*) growing on sites in Northern Germany and The Netherlands. At site 1, the water table was usually 50 cm below surface, but at the time of testing it had fallen to 90 cm due to a sequence of droughts. At site 2, the water table usually reached 30 to 50 cm below ground level and even the top soil was water saturated. In the sandy soil at site 1, roots reached depths of 70 to 120 cm below the surface. On site 2, the clay soil showed a colouration layer at 45 cm depth indicating anaerobic conditions. No roots were growing below this layer. The test trees had diameters ranging from 34 to 84 cm (mean 56.4 cm, sd 12.5 cm) and heights from 25 to 36 m (mean 30.5 m, sd2.8 m). Prior to winching the trees to failure, non-destructive pulling tests were carried out.

Cyclic loading

13 plantation trees were pulled in a sequence of winching tests to rising inclinations in each load cycle. The increments in stem base tilt were roughly 0.25° until the peak tilt either exceeded 2.5° or the maximum load was decreasing in subsequent load cycles. Then, the trees were pulled to primary anchorage failure, i.e. until either the stem base tilt exceeded 5° or the applied load decreased during the load cycle. All trees were growing on Ravenna Silt loam in Shalerville, Ohio, USA, and were roughly 40 years old. Tests were carried out under dry summer conditions within 4 days in 2013.

The data set consists of 6 London Plane Trees (*P. x hispanica*), mean height 18.9 m and mean stem diameter 30.3 cm, and 7 Silver Maples (*A. saccharinum*), mean height 17.5 m and mean stem diameter 28.8 cm. We recorded the tipping behaviour of those trees under cyclic loading with a forcemeter and two inclinometers at the stem base in standard pulling test setup. From this data we calculated the correlation between the rotational stiffness of each tree in the non-destructive range (bending moment applied at 0.25° stem base tilt) and its anchoring strength (maximum recorded bending moment). This correlation and the recorded load vs tilt graphs were compared to results from winching tests on similar trees in other test series and to the typical uprooting process described in literature (Wessolly 1996, Detter and Rust 2013, Wessolly and Erb 2016).

Results and discussion

Seasonal effects within 12 months

Except for the test under severe frost, we recorded only moderate seasonal changes in the calculated safety factors against uprooting and stem fracture (Figure 1). There was an average increase from March to June testing of 7 and 10% respectively in calculated factors for fracture and uprooting safety. This may be attributed at least to some part to the increment growth of stem and roots during this period. The variability between June and November was greater for the tipping safety than for the fracture safety, were safety factors lay on average 7% above the minimum value, but at max only 15%. The mean difference to the lowest value was 10% for the tipping safety, with extreme deviations of almost 30% under wet and cold conditions in November. Because the deviations reached 25% in dry and warm summer conditions as well, there is no obvious correlation to soil conditions alone.

Freezing changed the predictions of anchoring strength from the non-destructive test dramatically. In February 2012, the rotational stiffness increased so much that the calculated uprooting safety reached in average 1.9 times the lowest value in March 2011, the highest increase was almost 140%. Because this effect is much more distinct than for the calculated fracture safety, we argue that the strong increase in soil stiffness is mainly responsible for these results, whereas the flexural stiffness of the roots has a lesser effect. The stem stiffness was increased in the frozen condition as well, but it accounted on average for an increase of 30% from the lowest value in March. As an extreme, the flexural stiffness had increased by 50% which is consistent with the findings on other experiments (Silins et al. 2000).

Our findings show that pulling tests will overestimate both stem and anchorage strength under moderate climatic conditions if they are carried out during severe frost. Even though the extrapolations may be valid for frozen stem and frozen soil, those results are not suitable to assess the stability of urban trees. The deviations resulting from moderate seasonal changes indicate that sufficient safety factors are generally required to accommodate for variability in the non-destructive tests. A desired safety factor of 1.5 would be sufficient to cover the variability found in this test series.

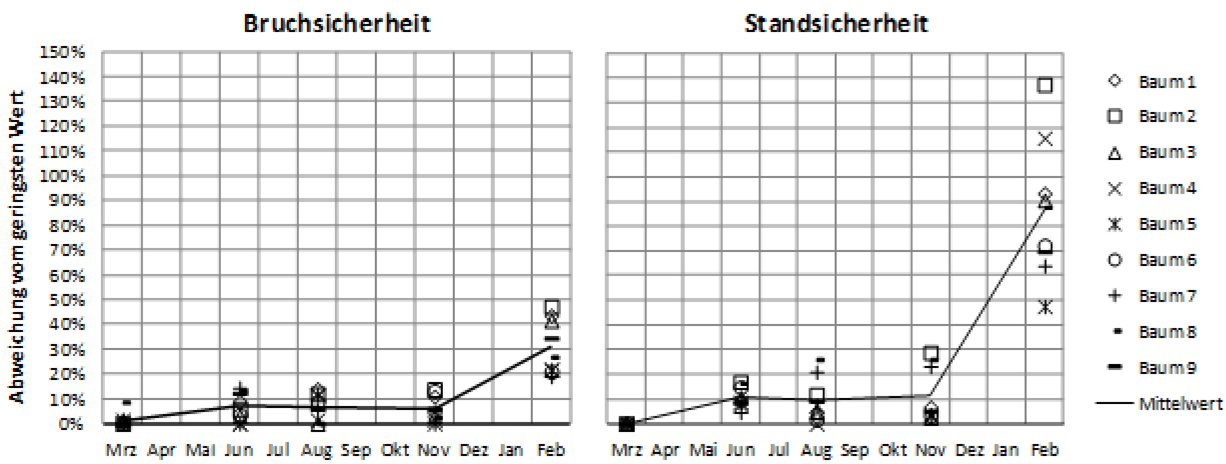

Figure 1-Seasonal changes in the results of pulling tests for estimated fracture safety ("*Bruchsicherheit*" left) and estimated safety against uprooting ("*Standsicherheit*" right) on 9 Linden trees (tree numbers on the very left). Displayed is the deviation from the minimum values ("*Abweichung vom geringsten Wert*". Reprinted from Detter and Rust 2013.

Wood temperature

The results of this test series confirm that significant changes in MOE of stem wood occur as the wood freezes. The Young's modulus in bending increased from 6,779 MPa ± 329 MPa at 20 °C to 7,882 MPa ± 329 MPa as the wood temperature fell to -20 °C, accounting for an increase of roughly 16% in MOE (Figure 2). Differences in wood temperature from 20 to 4°C or from -12 to -20°C did not have a significant effect on the MOE in bending for the tested Birches.

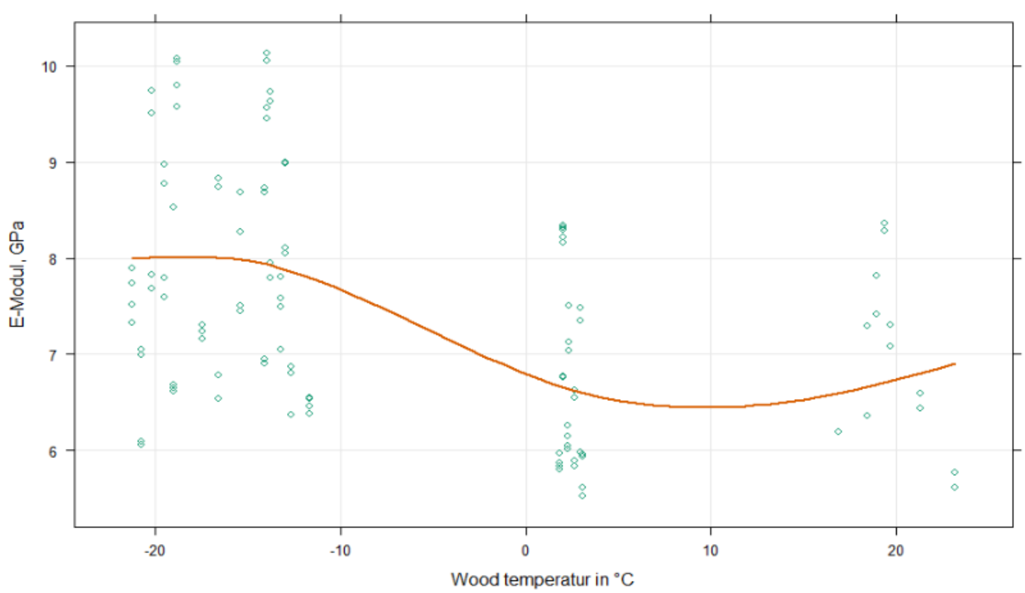

Figure 2-Changes in MOE of 8 birches at different wood temperatures.

These results alone cannot explain the observed increase in the calculated fracture safety observed in the experiment above. Since apparent flexural stiffness serves as a proxy for stem strength in the evaluation of pulling tests (Detter & Rust 2014), we expected a greater difference in Young's modulus for frozen wood. It is unclear if this could be attributed to different wood properties in the two tested tree species, to different tree age or to the difference in stem diameter of the two groups of trees.

Soil temperature

During the period of the first 6 tests, the soil temperature averaged over different depths sank from roughly 11 to 2.5°C. It fell slightly below zero only at the seventh test date.

The differences in calculated anchoring strength were rather small in the temperature range from 2 to 11°C. We only observed a small increase of 5 to 12% (mean 7.1%, sd 1.9%) with soil temperature sinking by almost 10°C. As the soil temperature fell below the freezing point, the estimated anchoring strength rose on average by 16.4% (sd 7.5%) against the mean value in former tests, with individual increases ranging from 5% to almost 30% (Figure 3). Compared to the increases in calculated safety observed when the soil was deeply frozen in the investigation described above, this is still a minor effect and would be covered by the usually required safety factor of 1.5 as recommended in literature (Wessolly & Erb 2016).

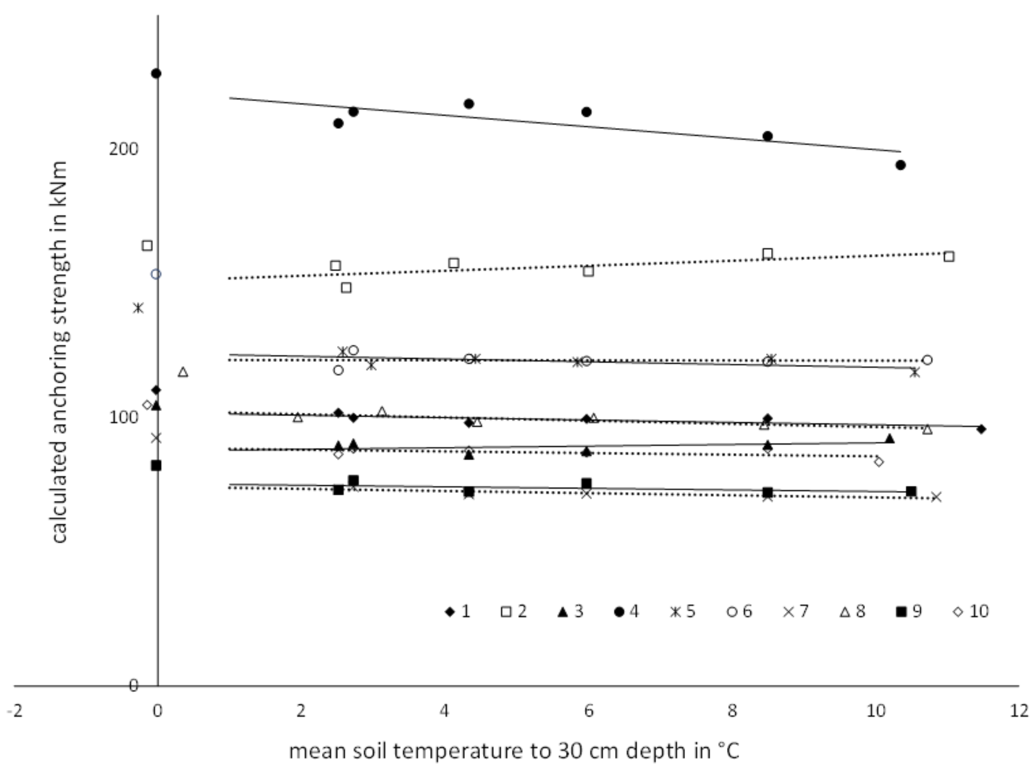

Figure 3-Changes in calculated anchoring strength of 10 Linden trees at sinking soil temperature. Lines serve only as an orientation for the trend at soil temperatures above 2°C and do not include data below 2°C for clarity.

Soil moisture content

Irrigation raised soil moisture from about 20 percent to 30 to 40 percent. The higher soil moisture after irrigation caused the inclination during the non-destructive pulling tests to increase by almost 6 percent when the same load was applied (Figure 4). There were great differences between the two dates and the individual trees. As a result, the calculated anchoring strength decreased between 0 and 16.4 %, but for one single tree the estimated stability even dropped by almost 40 %. This is consistent with observations during earlier experiments (Wohn 2003).

If soils are very dry at the time a pulling test is performed, the stability assessment may overestimate the anchoring strength in heavy storms following or accompanied by heavy rain. In such cases, the root zone should be irrigated prior to the test or the threshold for sufficient safety margins should be increased beyond the usually required value of 1.5 in order to accommodate for such effects.

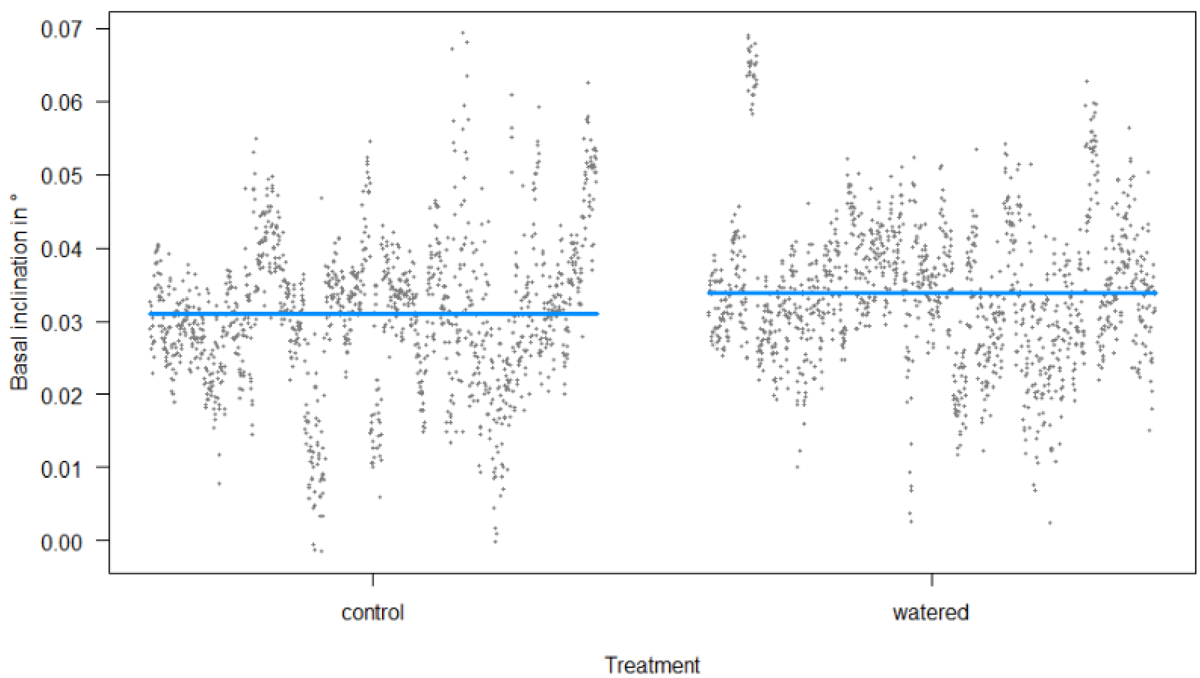

Figure 4-Basal inclination measured at mean force prior and after irrigation.

Water saturated soils

On site 2, where the soil was water saturated and trees had developed a rather shallow root flare, the correlation between the rotational stiffness in the non-destructive level of stem base tilt and the anchoring strength was not different from trees on other sites (Detter and Rust 2013, Rust and Detter 2019). The average correlation factor was roughly 3 and the coefficient of determination was very high (R^2=0.85, Figure 5).

For the trees on site 1, where the usually high water table had dropped at the time of testing, the correlation was different from the findings on other sites. While rotational stiffness still was an excellent indicator for anchoring strength (R^2=0.98), the correlation factor fell below 2.5. As a consequence, standard extrapolations of anchoring strengths would have slightly overestimated the stability of the tested trees. On average, the anchoring strength fell below the expected value by roughly 10%.

This indicates that changes in the height of the ground water table may affect the predictions from non-destructive pulling tests, but deviations were covered by the regularly required safety margin of 1.5. From practical arboriculture it is understood, that flooding can have a more severe effect on the stability of trees. Especially as the flood level sinks again, trees frequently fall over, presumably as a result of increased deformability of the subsoil serving as a foundation for the anchoring root system.

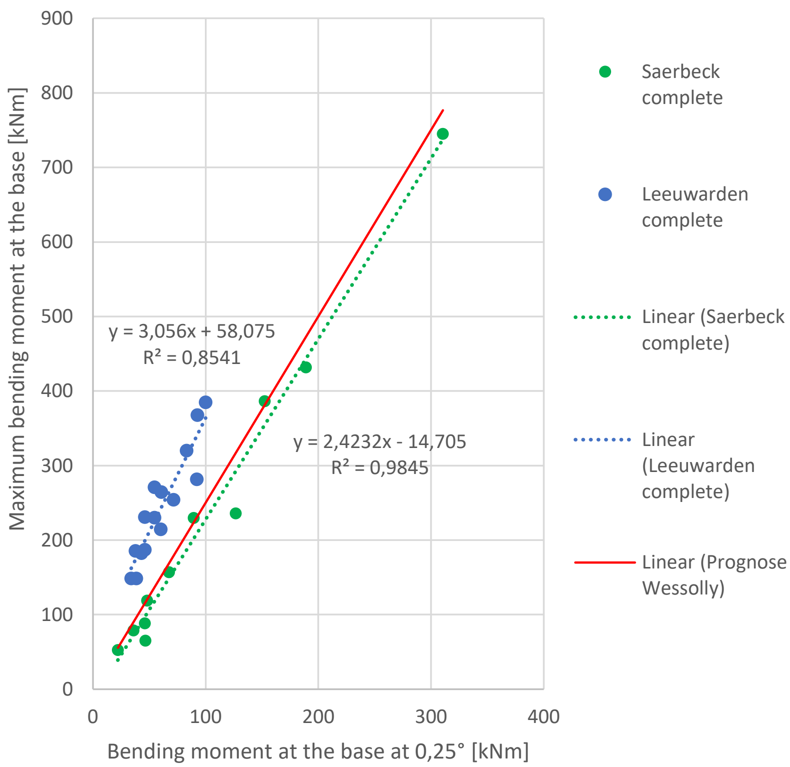

Figure 5-Extrapolation factors from rotational stiffness (bending moment at the stem base at 0.25°) to the anchoring strength of the root system (maximum moment at the base) for site 1 (green, Saerbeck) and site 2 (blue, Leeuwarden). The red line indicates the correlation factor proposed in literature (Detter & Rust 2013, Wessolly & Erb 2016).

Cyclic loading

We observed in all trees that the typical uprooting behaviour was resumed in the next loading cycle as soon as the load was reached where the former loading cycle had been aborted. Until this load was reached, the tangent to the load vs. tilt curves (i.e. the momentary rotational stiffness) had a lesser slope than during the last load cycle if the maximum tilt at the stem base had already once exceeded 0.5° in a former load cycle. This indicates that beyond the non-destructive range, the root system experienced progressive failure as tilt subsequently increased. The successive damage to the root system was also detected by increasing residual inclinations after the load cycle was aborted and the applied force had been fully released.

By removing the data from the current load cycle at loads below the maximum load in the former load cycle, we generated "stitched up" load vs. inclination curve that was not significantly different from curves generate by one single static pull to failure. The curves resembled the so-called "generalized tipping curve" (Wessolly and Erb 2016) with the exception that the maximum load did not occur at 2.5°, but at tilt angles between 2 and 7° (Figure 6).

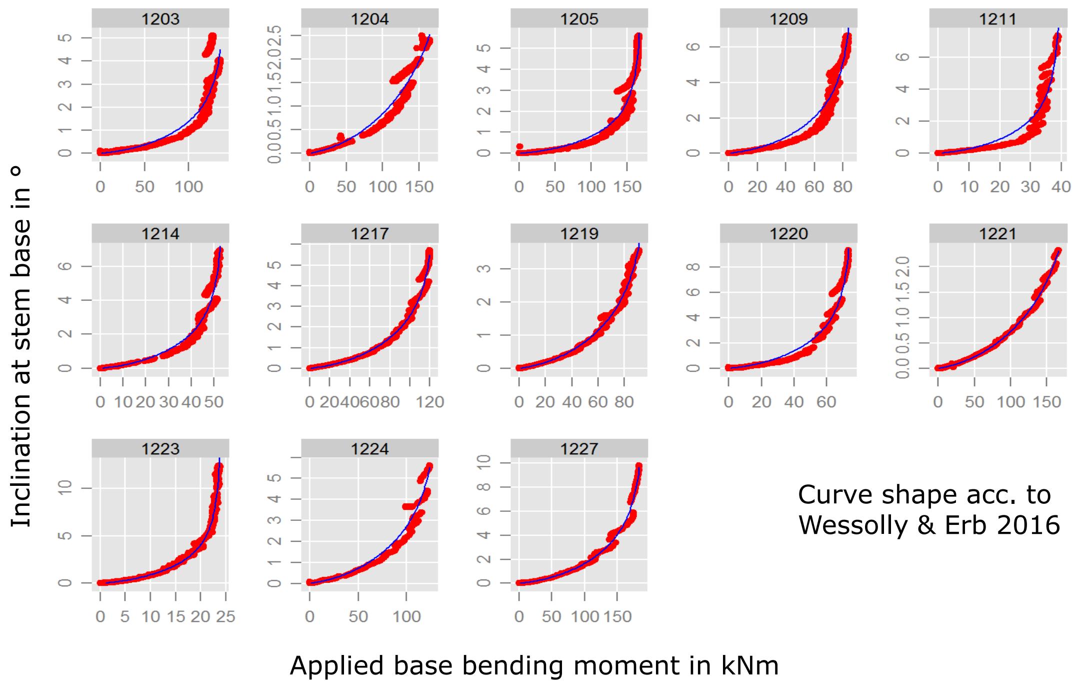

Figure 6*-Load vs. stem base tilt curves for cyclic tests (red dots) compared to the typical uprooting behaviour (blue lines) acc. to Wessolly and Erb (2016).*

The correlation between rotational stiffness (bending moment at 0.25° stem base tilt) and the anchoring strength (maximum bending moment exerted during the uprooting process) was not different from trees pulled to failure in one single static pull. The correlation factors ranged all well above the value 2.5 proposed in literature (Detter & Rust 2013, Wessolly & Erb 2016), so we conclude that predictions of anchorage strength by the pulling test method are also valid for cyclic increasing loads.

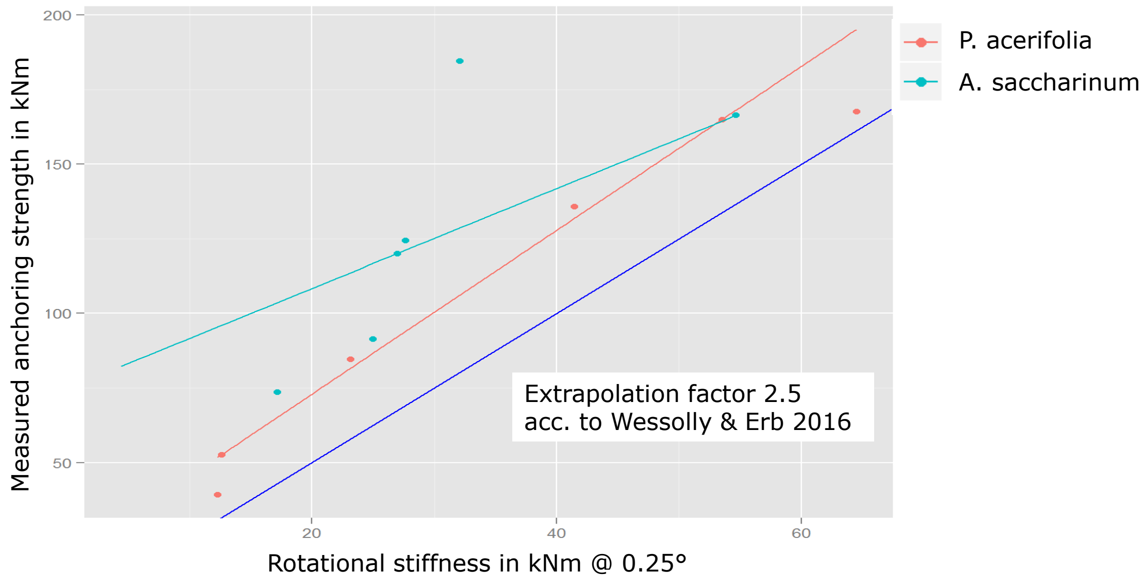

Figure 7*-Extrapolation factors from rotational stiffness to the anchoring strength of the root system for cyclic loaded trees.*

Conclusions

Both an increase in soil moisture content and a longer frost period have significantly changed important output data of the pulling tests, i.e. apparent flexural stiffness of the stem and rotational stiffness of the root system. In the case of irrigation, the calculated stability was reduced, which indicates that measurements in times of drought may overestimate the anchoring strength of the roots. The frost, by contrast, strongly increased the calculated fracture safety and stability factors. The changes were in the same direction and magnitude of the results from other experiments of this type of which there are only a few (Kamimura et al. 2011, Peltola et al. 2000, Silins et al. 2000, Wohn 2003).

Above the freezing point, no influence of the temperature on the calculated fracture safety was detectable. However, the calculated stability was more strongly affected as soon as the soil was frozen even superficially. However, as long as the frost did not extend into deeper areas of the soil, the usual safety factors were sufficient to compensate for the computational errors.

As the effects on the deep-frozen soils and stems are proven and significant, pulling tests during longer frost periods should be avoided as far as possible. If measurements under such adverse conditions cannot be avoided, the influence of soil moisture and temperature on the results of the non-destructive pull tests should be taken into account during the evaluation by appropriate thresholds for desired safety factors.

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