FACT SHEET Diagnostic tools – version August 2019

1) Introduction

Many arboricultural diagnostic tools and equipment have been developed during recent decades, mainly in order to evaluate mechanical stability of trees and the risk of branch or stem failure. Other diagnostic tools focus on soil or on tree health. Each of these techniques has pros and cons. Because of the specific characteristics of veteran trees (dysfunctional wood and decay present, secondary crown formation, complex mechanical structure, …), these pros and cons may well be different (or amplified) compared to 'standard' trees. This fact sheet aims at offering a general overview of existing diagnostic tools and equipment and evaluating their use for veteran tree management.

In general, many of the following tools can deliver valuable information to feed into management decisions for veteran trees. But given the complex mechanical and physiological structure of veteran trees, please do not rely on the result of one tool to take management decisions. Always take into account the whole tree, above and below ground, and be aware of how difficult it is to extrapolate a localised measurement to the whole structure of a veteran tree.

2) Diagnostic tools primarily used for evaluating mechanical stability

These diagnostic tools are focused on distinguishing (mechanically) dysfunctional or decayed wood from (mechanically) functional wood. On the basis of the proportion of decayed wood and hollowing, an evaluation of the tree's mechanical stability and/or a prognosis about the probability of the tree failing are expressed.

a) Sounding mallet

The simplest diagnostic 'tool' used in arboriculture is a sounding mallet: a wooden or plastic hammer is used to tap the trunk and stem base in search of hollowing, loose bark, etc. It is very low tech, but it demands a lot of experience in order to be somewhat reliable. Observations can be hard to interpret, especially for veteran trees with a complex biomechanical structure.

b) Increment borer

An increment borer is a tool used to extract a core of wood from a living tree. The diameter of the extracted wood core is generally around 4 - 5 mm, the hole is slightly bigger. The length varies depending on the length of the increment borer. For detailed (microscopic) analysis the wood core can be glued on a carrier and sanded down.

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Fig. 1 Increment borer near the stem base

Fig. 2 Extracting core from borer

The wood core can be used to evaluate residual wall thickness, ring width/growth speed, ring count and wood quality at the sampling position. Using low tech tools like the pocket size Fractometer, one can also evaluate bending and compression strength in the radial direction of the wood core and detect early stages of wood decay. Be aware that the bending or compression properties of wood are dependent on the direction (longitudinal/radial/tangential), the place where one has taken the sample and on the positioning of the sample in the device. On top of that, it is very hard to extrapolate the findings to the whole tree, especially when trying to evaluate mechanical stability or risk of failure in complex (mechanical) structures like most veteran trees.

There is an ongoing discussion in the arboricultural world about the impact of coring on the introduction or spread of decay in living trees, especially when coring veteran trees, which already have dysfunctional wood and decay present and developed barrier zones. Arborists may adhere to the prudence principle of not coring living (veteran) trees if this is avoidable, turning to less invasive tools.

Fig. 1 Fractometer while measuring the samples: in the middle is measured the bending and compression strength and force; in the upper part the bending angle is measured. The bending angle can be used for calculation of bending stiffness.

Advantages
Compact and easy to carry
Visual evaluation of a real wood sample
Microscopic evaluation of wood possible
Low tech and low cost
Disadvantages
Invasive
Damages living cells causing dysfunction and possible decay
Can potentially break down barriers between functional and dysfunctional wood
Very localised sampling, hard to scale up to a whole tree, let alone a complex veteran tree

c) Needle resistance drilling equipment

These tools are electronic devices that drive a rotating, thin, long needle in the wood and measure the resistance of the wood to drilling. The diameter of the drill tip is typically around 2-3 mm.

Fig. 4 Use of resistograph near the tree base.

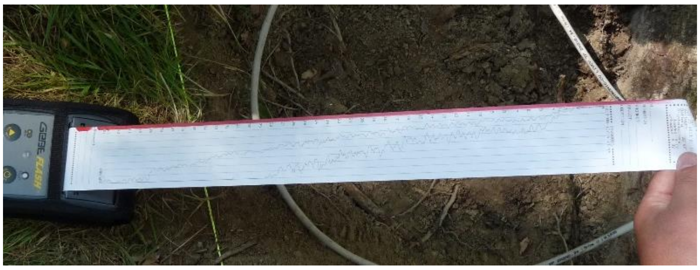

Fig. 5 Resistance to drilling across the cross section in the place of taking samples printed out.

Different manufacturers measure drill resistance in different ways, but they all correlate the measured values with wood density and thus mechanical functionality. Note that not all manufacturers obtain the same degree of accurateness and precision. In this way a cross section of the wood quality can be obtained. The data can be used to analyse residual wall thickness, wood quality and ring width/growth speed, ring count (for species with distinctive annual rings) at the sampling position. It is however very hard to extrapolate these findings to the whole tree, especially when trying to evaluate mechanical stability or risk of failure in complex (mechanical) structures like most veteran trees.

Although the drill diameter is less than the diameter of an increment borer, the drill may be long enough to drill all the way to the centre of large diameter trees. There is an ongoing discussion about the impact of needle drilling on the introduction and spread of decay in living trees, especially when drilling veteran trees, which already have columns of dysfunctional wood and decay present. Arborists may adhere to the prudence principle of not drilling living (veteran) trees if this is avoidable, turning to less invasive tools.

Advantages
Detailed analysis of wood density along the drilling profile
Quick setup
Disadvantages
Invasive
Damages living cells causing dysfunction and possible decay
Can potentially break down barriers between functional and dysfunctional wood
Very localised sampling, hard to scale up to a whole tree, let alone a complex veteran tree
Investment cost

d) Sonic tomography

Tools using sonic tomography use sound waves generated by tapping with a hammer and travelling between sensors to analyse wood quality. The sensors (similar to nails) are driven through the bark and a couple of mm in the sapwood to make contact with the wood column. The general principle is that sound will travel fastest between two sensors (one emitting and one receiving) if the wood in between them is sound. Decayed wood or hollows will slow down or redirect the sound wave and thus extend the time needed for the sound to travel from one sensor to the other. By using multiple sensors and software analysis, a complete cross section of a tree can be analysed at once. Typically 8 to 12 sensors are used for one measurement, but this can go up to 36 sensors (the more sensors, the higher the resolution). Complex stem geometry (as with most veteran trees) also demands higher numbers of sensors and demands a precise measurement of the sensors' geometric position in order to get a correct measurement.

Sonic tomography can be used to analyse residual wall thickness and geometry of wood quality (stages of decay, hollowing) in a given cross section (2D). The results are generally presented in a colour coded cross section image of the stem. By measuring more sections one above another, it is possible to obtain a 3D image. Be aware of the fact that this image only reflects extrapolated values from measured 2D cross sections.

Fig. 3 Set up of sonic tomography.

Fig. 2 Set up of sonic tomography in detail: in the case of complicated geometry is better to use more sensors. It is recommended to have one on each bulge and one in each depression.

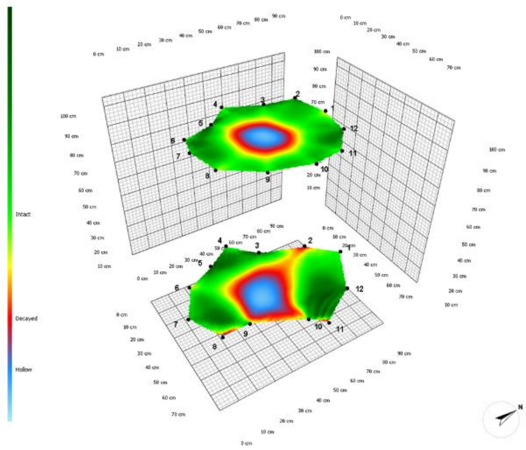

Fig. 4 Based on the measured values of sound velocity, the software also delivers a colour coded image, making a distinction between sound and decayed wood. This is an extrapolation , so it is better to evaluate the actual measurement values between sensors..

Correlating sound velocity to wood quality or strength loss is not straight forward and is subject to the software models and parameters used. So the results should be interpreted by an consultant experienced in this matter, especially when dealing with valuable veteran trees. Be aware of the fact that decay that does not slow down sound speed (e.g. some types of soft rot) or features that block sound waves (e.g. cracks) can blur the sonic tomography measurement and might lead to misinterpretations. Some manufacturers try to tackle this with additional software, but its effectiveness has not been unambiguously established. Combining sonic tomography with electrical impedance tomography (see below) might overcome this problem. When working with old and large trees it is very important to have precise measurements of the distance between sensors (not all manufactures offer this possibility) and to use enough sensors, to obtain a realistic cross section of the trunk and an acceptable resolution of the final tomogram.

The complexity of veteran trees (both mechanically and physiologically), urges for restraint when taking management decisions for the whole tree on the basis of 2D (or even 3D) tomographic cross sections. Always take into account the whole tree, above and below ground.

Advantages
Not invasive into central wood column, only small, localised damage to functional sapwood (nails driven a couple of mm into functional sapwood).
Complete 2D cross section analysis possible
Disadvantages
No direct measurement, deduction of wood quality through software modelling based on sound velocity
Not all types of decay or cracks are (easily) distinguishable (but can be combined with electrical impedance tomography)
High investment cost

e) Electrical impedance tomography

Electrical impedance tomography is identical in setup as sonic tomography, but instead of sound waves, an electric current is used. This technique visualises the electrical resistance properties of the cross section of a tree, rather than the biomechanical properties visualised by sonic tomography. The local electrical resistance in the wood is influenced by water content, chemical makeup of the wood (ions, …) and cell structure. This allows for a detailed and high resolution image of the analysed stem or branch, but often makes interpretation rather hard.

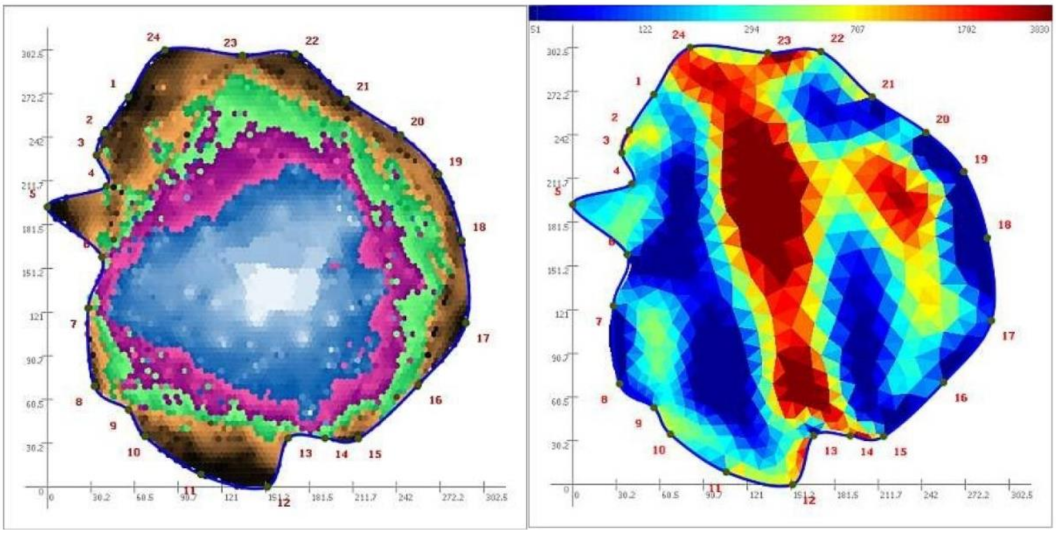

Fig. 5 The difference between sound tomography and electrical impedance tomography – picture of results for V fork: left – sound tomography, right – electric impedance tomography (Praus et al., 2013).

Electrical impedance tomography can be used to analyse residual wall thickness and geometry of wood properties (water content, decay, hollowing) in a given cross section (2D). It also allows to distinguish physiologically separate functional units. The results are generally presented in a colour coded cross section image of the stem. For a correct interpretation of the results however, it is necessary to know the distribution of cross section conductibility for a healthy tree of the same species, because there is high variability between species and it is impossible to rely on general rules for interpretation. By measuring more sections one above another, it is possible to obtain a 3D image. Be aware of the fact that this image only reflects extrapolated values from measured 2D cross sections.

In contrast to sonic tomography, electrical impedance tomography is able to distinguish cracks, early decay stages, reaction wood, etc. Since both sonic and electrical impedance tomography can be conducted with the same sensor setup, these can be combined to analyse the same tree, which can raise the accuracy of the analysis. However, due to the difficulty of interpreting electrical impedance tomography (variability in the conductivity of trees), it is advised to use the latter only as a supportive measurement to sound tomography.

The complexity of veteran trees (both mechanically and physiologically), urges for restraint when taking management decisions for the whole tree on the basis of 2D (or even 3D) tomographic cross sections. Always take into account the whole tree, above and below ground.

Advantages
Not invasive into central wood column, only small, localised damage to functional sapwood (nails driven a couple of mm into functional sapwood).
Complete 2D cross section analysis possible
High resolution

Disadvantages
Deduction of wood properties and functionality through interpretation of local electrical resistance
Because of many influential factors, the results are not easy to interpret (high variability)
High investment cost

3) Diagnostic tools primarily used for evaluating roots

The above tools allow for a diagnosis of the above ground parts of a tree and in some cases also the root collar. But they are generally unsuitable to evaluate underground root structures or root plate stability as a whole. Below are some tools that allow the evaluation of the below ground parts of trees.

a) Static pulling test

During a static pulling test a tree is pulled with an increasing force (with a rope and a winch) while simultaneously the strain of stem and inclination of the root-plate system is measured with very sensitive mechanical devices. The stem strain is measured by extensometers along the stem (on the tension or compression side). The root-plate inclination is measured by inclinometers usually placed near the tree base. Generally, the maximum inclination during a pulling test is in the range of 0.1- 0,25° from its original state, to avoid root damage.

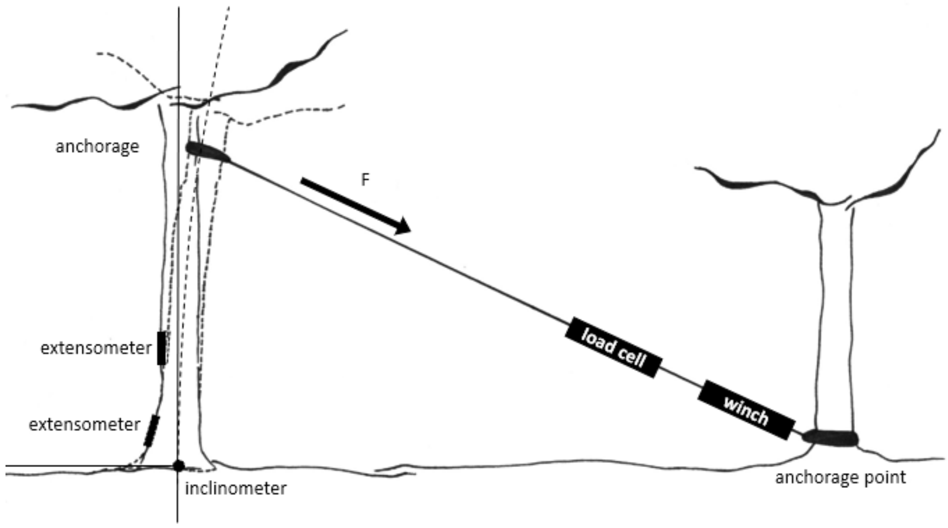

Fig. 6 One of the possible set up for pulling test.

Fig. 82 Extensometer on the tension side of stem and inclinometers near the tree base.

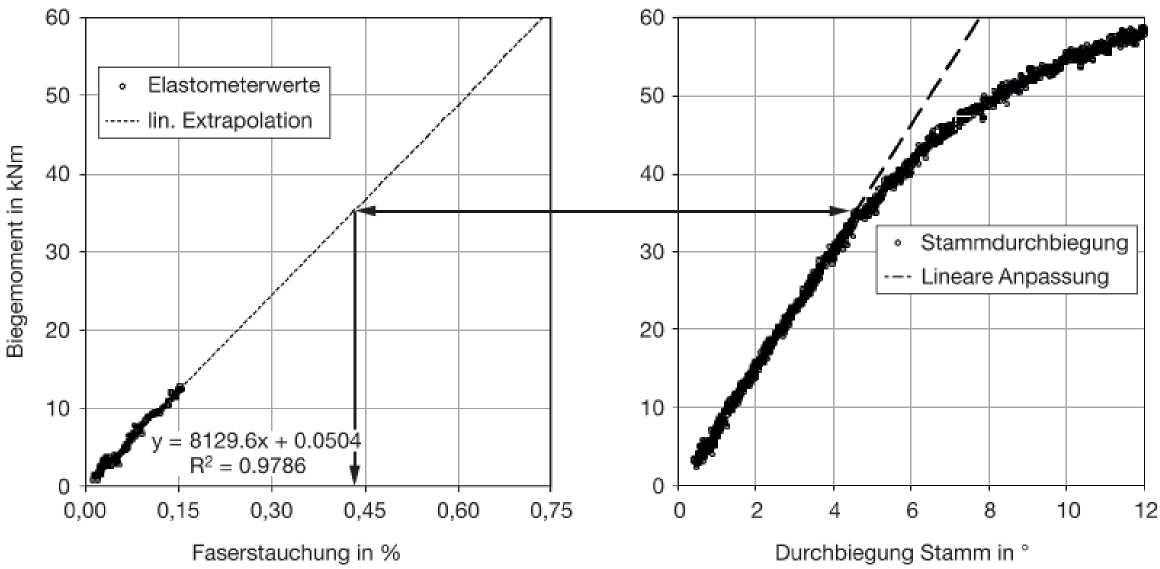

Fig. 73 Example of measured values of strain in stem (left) and inclination of root-plate (right) (Detter and Rust, 2013).

The measurements result in the correlation between strain, inclination and the applied force. These values can be extrapolated to the calculated wind force potentially acting on the tree, generating a tipping curve for the tree. Generally the models used are part of the software.

This will indicate if the tree is able to withstand storm winds and if so, with which safety factor. In case of insufficient stability, it is possible to use this model to estimate how much of the tree's 'sail area' needs to be reduced in order to sufficiently raise its safety factor for root plate stability.

There are two major discussion point about static pulling tests: firstly it is an analysis based on extrapolation and modelling of a tree's reaction to wind, based on multiple factors. Each of those factors influence the final evaluation. But even then there may be many more factors influencing the stability of a tree that are not being taken into account. And secondly it is a static approach to something that has a dynamic nature: trees are not just sails that get loaded by a static wind load. Instead both the tree and its branches swing back and forth during gusts of wind. Aspects like mass damping by the swinging branches (which reduces the impact of wind load) have to be theoretically modelised.

When applying static pulling tests to veteran trees, one must also take into account the complex mechanical structure of many veteran trees. Especially veteran trees that consist of multiple functional/mechanical units are hard to analyse, since these trees do not mechanically react as a whole. Due to their complex shape (stem geometry), veteran trees are more demanding in terms of number and positioning of the measuring devices. It is often better to place more measuring devices along the stem (extensometers) and around the circumference (inclinometers) during the measurement. Also consider pulling in more than one direction. The sheer size of the tree has to be considered as well: if the veteran tree has a significant diameter it is possible that it will not follow the generalised tipping curve in the modelling software.

Advantages
Very low invasiveness (small nails in sapwood)
Allows for evaluation of the total root plate stability
Disadvantages
Root plate stability is analysed through extrapolation and modelling of static wind load
Static approach to a dynamic phenomenon
The more complex the mechanical structure of the veteran tree, the higher the probability of inaccuracy
High investment cost

b) Dynamic wind load analysis

Dynamic wind load analysis consists of inclinometers/strain meters or accelerometers that are attached to a tree and left for hours, days or even weeks. These sensors log the movement of the tree’s root plate and/or trunk in a natural wind situation together with the direction. These data are used to generate an extrapolated tipping curve, or can be used for further analysis of oscillating frequency and damping. Dynamic wind load analysis can be combined with a static pulling test to evaluate root plate stability.

Fig. 14 Comparison of mechanical devices: left – inclinometer, middle – accelerometer (older type), right – accelerometer with high frequency (not in commercial use).

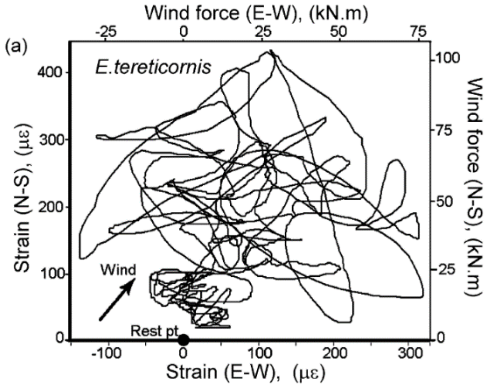

Fig. 95 Time domain plot of two strain meters showing complex sway (James and Kane, 2008).

This type of analysis generates lots of raw data, which have to be analysed using advanced modelling software. The model has to take into account dynamic movement of trees in wind, including phenomena like mass damping by branches. Evaluation of the raw data is very complicated (many variables to consider) and often insufficiently underpinned by scientific research. When analysing complex veteran trees, which can consist of multiple functional/mechanical units, the amount of raw data will be even bigger and a correct interpretation of the results increasingly complex.

Advantages
Very low invasiveness (small nails in sapwood)
Takes into account dynamic movement of trees in wind
Disadvantages
Generates lots of raw data, which are not easy to analyse
Relies on advanced modelling of tree movement in wind
Long-term measurement (during wind seasons) necessary
No easy way of interpreting data in terms of tree stability
High investment cost

c) Ground penetrating radar

Ground penetrating radar technology can be used for detection of living roots in soil. The radar antenna emits microwave electromagnetic radiation and detects the reflected waves from underground structures. Living roots reflect the waves because they have a significantly higher water content than the surrounding soil. Software and filters are used to distinguish between roots and other underground structures like stones, pipes, cables, soil layering, … The wavelength of the radar unit used depends on a trade-off between resolution (how fine a root can be detected) and penetration depth. Usually a unit is used which can detect roots (or fine root bundles) above 2 cm in diameter to a depth of about 2,5 m. The technology cannot determine the diameter of a detected root, just that it is a living root above the detection threshold. It will also not allow a qualitative evaluation of the roots.

Fig. 16 Ground penetrating radar

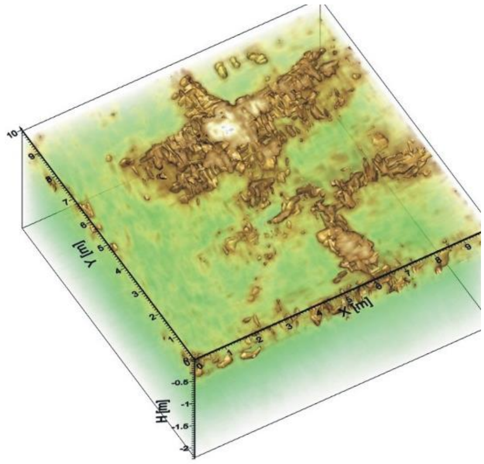

Fig. 107 One of the possible results of ground penetrating radar – 3D picture of signal distribution. (heat map)

Ground penetrating radar can be used to establish rooting area and depth. It is especially effective to produce so called heat maps of where the major living root activity is located. This can be used to evaluate root plate stability or design effective root protection areas at construction or event sites.

Radar technology can also be used to evaluate wood quality in stems. It can detect hollows, decay and cracks.

Advantages
Non-invasive
Can be used on any surface (bare ground, hard surface, …)
Faster, more comprehensive and less invasive than digging

Disadvantages
Data are hard to analyse, relies heavily on analysis software
Only allows to establish the presence of a living root (no diameter of qualitative evaluation)
High investment cost

d) Air excavation tools

Air excavation tools use compressed air to generate a focused beam of air which can dislodge soil without damage to underground objects. Air excavation tools are used for working around pipes and cables, but can also be used to uncover roots without damaging them. Often air excavation tools are used in combination with vacuum excavators, to suck up and evacuate the loose soil. Trademarks and patents mainly depend on nozzle design (influencing the focus of the air beam).

Fig. 128 Use of air excavation tool.

Fig. 11 Exposed roots after excavation by air tool.

A discussion point about air excavation tools is the amount of damage that is done to finer roots and mycorrhizas, especially because of drying them out. On the other hand, the finest roots of a tree are generally replaced with a rapid turnover, limiting the impact of some finer root loss. The localised nature of most interventions for root quality assessment will also limit the overall amount of root damage.

Advantages
Moves soil without damage to underground objects and woody roots
Allows a qualitative evaluation of roots
Low tech

Can also be used to alleviate compaction and anaerobic conditions and for soil replacement and mulching
Disadvantages
Scatters soil over a large area
Potentially damaging to fine roots and mycorrhizas
Given the extent of root systems, air excavation tools generally only allows to evaluate a (small) section of the root system
Requires a compressor to be brought onto site, and possibly onto the root protection area
High investment cost.

4) Diagnostic tools for evaluating soil quality

a) Penetrometer/penetrologger

A penetrometer (and its digital cousin the penetrologger) is a tool that is used to evaluate soil compaction. This is done by measuring the soil's resistance against penetration of a metal pin. The tool consists of a long rod and a conic tip with a known surface area, combined with a manometer in the handle. The tool only allows for a spot measurement, but given its fast use, it is easy to do multiple measurements which allow for an average overview.

Fig. 20. Penetrometer

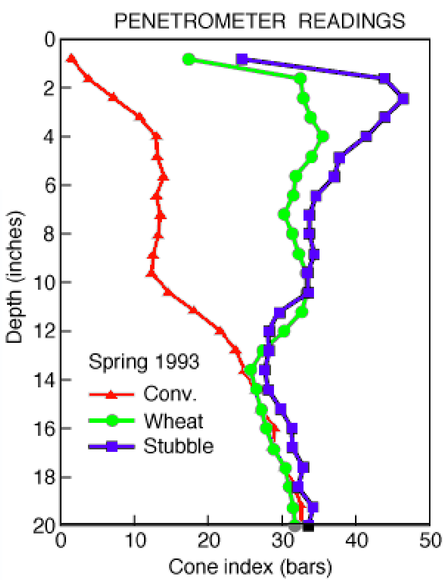

Fig. 21. Example of penetrometer readings

A major disadvantage is that the measurement is influenced by soil characteristics, mainly soil moisture: a wet soil will give a lower reading and a dry soil will give a higher reading. In order to really have an objective measurement, which is replicable and comparable, the measurement needs to be done at field capacity (the state after excess water has drained away and the rate of downward water movement has strongly decreased).

Advantages
Allows for an objective evaluation of soil compaction
Fast measurement, immediate result
Low cost, low tech
Can be used before and after soil treatment to evaluate effects
Disadvantages
Influenced by soil characteristics (mainly soil moisture) and underground objects
Spot measurement

b) Oxygen meter

Root growth is strongly influenced by the aeration of the soil. Low oxygen or anaerobic conditions will limit root growth or lead to roots dying off, often related to soil compaction or degradation of soil structure. In order to have an objective measurement of the aeration of the soil, a direct measurement of soil oxygen content can be taken to be compared to known threshold values.

Users need to take into account that soil oxygen content will fluctuate during the year, depending on oxygen consumption of roots and the soil food web (higher in summer, lower in winter; higher in warmer soil; …).

Because of the CO_2 production associated to underground oxygen consumption, the oxygen content and the CO_2 content have a strong negative correlation. So also a CO_2 measurement will allow for an evaluation of soil aeration.

Advantages
Allows for an objective evaluation of soil compaction
Fast measurement, immediate result
Disadvantages

Influenced by time of year (soil temperature, season, …)
Spot measurement

5) Diagnostic tools and equipment for evaluating tree health and condition

The above diagnostic tools are used for evaluating failure risk or for measuring or evaluating factors that influence tree health, like soil compaction or soil aeration. The diagnostic tools below allow to directly evaluate tree health and condition.

a) Chlorophyl fluorescence

Chlorophyl fluorescence can be used as an indicator of how efficiently a plant uses sunlight and this an indicator of a tree's condition and/or stress. This technology can detect stress in a tree well before this is visually identifiable. The measurement is done by attaching a clip onto a leaf, which shades out an area of the leaf. After 15 minutes, the chlorophyll in that area is in a kind of resting state. It is then activated with a high intensity light source and within the first seconds, the chlorophyll's reaction is measured.

Can be used as an objective measurement of the effect of management interventions (e.g. soil decompaction, mulching, …). On the other hand the measurement can be variable even within a healthy crown. This might be even more significant in the case of physiologically complex veteran trees.

Advantages
Offers an objective measurement of tree condition
Can detect stress well before this can be established visually
Can be used as an objective measurement of the effect of management interventions
Relatively fast (20 minutes/measurement)
Disadvantages
It is a snapshot of a tree's condition, which can vary even in healthy trees
The technology does not allow to identify the origin of the physiological stress

b) Sap flow measurement

Sap flow measurement is the generic name for methods measuring the quantity of water transported in the xylem. They can be used as an indicator of a tree´s condition and stress. The method allows long term observation (which is the preferred way to use this method) and can detect a reduction in transpiration before direct symptoms of water shortage are visible in the foliage. The devices usually heat the xylem to quantify the flow rate or speed of water transport. Most common approaches are based on how much the artificially heated part of the stem is cooled down by the flow of water (heat balance or heat dissipation methods), how quickly the heat pulse moves along the xylem or how the heat field deforms due to the axial flow of water. Small sensors (needles, plates) are usually inserted into the sapwood of trunk (roots) to heat the xylem and to measure the temperature.

Fig. 132 Installation of sensors for Trunk Heat Balance method.

Sap flow measurement can be used as an objective measurement of tree condition or stress, especially in the long-term. Although to date software for easy data interpretation is not available commercially, this method can provide reliable information about tree transpiration. The change in transpiration can for example be observed in case of management interventions (e.g. severe pruning, soil decompaction, …). In comparison to chlorophyll fluorescence, the advantage of this method is its smaller variability (measurement on the trunk, so related to the physiological state of a large part of the crown), the disadvantage is it is more time consuming.

Advantages
Offers an objective measurement of tree condition
Can detect stress well before this can be established visually
Can be used as an objective measurement of the effect of management interventions
Provides information about a large part of the crown (low variability)
Disadvantages
Long term measurement (at least 24 hours – longer is better)
The technology does not allow to identify the origin of physiological stress

c) Remote sensing - infrared screening

As vegetation reflects much more energy in the infrared spectrum of light than in the visible light spectrum, infrared screening can offer an enhanced capacity to evaluate the physiological status of a tree. Remote sensing (airborne or satellite) can be a good tool to perform an infrared screening of a population of trees, as stressed trees can be detected well before this could be established visually. This will allow for a fast identification of the trees that need further investigation using other methods.

Fig. 143 example of an airborne near-IR image (the lighter red the tree, the lower its physiological condition).

(© Eurosense).

This technology will not allow to have a qualitative evaluation of a tree's physiological state or to identify the cause of physiological stress. But it works well for screening purposes.

Advantages
Suitable for screening the physiological condition of large populations of trees
Early-warning for tree stress (before this can be established visually)
Disadvantages
Cost
It is a snapshot of a tree's condition, which can vary even in healthy trees
The technology does not allow to identify the origin of the physiological stress

References:

Brudi, Erk, and Philip Van Wassenaer. 2001. Trees and Statics : Non-Destructive Failure Analysis. p. 1–17.

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James, K., Kane, B. 2008. Precision digital instruments to measure dynamic wind loads on trees during storms. Agricultural and forest meteorology. 148:1055-1061.