Monitoring the water status of trees by electrical pulse resistance measurements.

Summary

Trees are increasingly suffering from drought stress. In order to maintain tree function in urban environments or performance in horticultural production, it is important to understand and respond to tree responses to drought stress. This is only possible if, on the one hand, basic knowledge of tree water balance is available and, on the other hand, robust measurements are available for decision making. In addition to the basics of the water balance, this white paper therefore presents various measurement methods that are suitable for such tasks. Treesense pulse sensors, which work with measurements of electrical resistance, are used as an example to show the possible applications for monitoring systems based on tree physiology.

1 Introduction

Water is often the most important limiting factor for tree growth (Allen et al. 2015). Climate change, bringing higher temperatures and altered precipitation distribution, will increasingly lead to periods of drought stress in the future (IPCC 2014). This may result in disturbances in tree physiology, including death (Clark and Kjelgren 1990; Kreuzwieser and Gessler 2010; Sevanto et al. 2014). In particular, services that are important in urban environments, such as cooling, air quality improvement, and aesthetic quality, are greatly diminished, and there is a tremendous loss of ecological and economic value (Bowler et al. 2010; Escobedo et al. 2011; Soares et al. 2011; Roeland et al. 2019). Restricted growth performance in nurseries or losses in fruit quality and fruit quantity in orchards can also be expected in the horticultural sector (García-Tejero et al. 2010; Vera et al. 2013). This also applies to excessive water applications, which additionally lead to a massive waste of resources (Chappell et al. 2013).

To avoid or minimize such effects, trees can be monitored using physiological measurements (Jones 2004). Suitable monitoring systems must be able to provide a reliable and up-to-date picture of the water status of the trees, be scalable to large stands, require little maintenance, and be cost-effective. With such systems, it is possible to detect drought stress at an early stage and to use available resources such as water, personnel, and vehicles in a targeted and efficient manner.

In the following, we will describe how the water balance of trees works, what options are available to monitor the water status of trees, and how such monitoring systems can be used, using pulse resistance measurements as an example.

2 Water balance of trees

2.1 Water transport and water storage in trees

Within a tree, water is used as a means of transport, to maintain turgor, and to cool leaves (Hirons and Thomas 2018). However, while trees are photosynthesizing, they are necessarily losing water by opening stomata (Jensen et al. 2016). Therefore, constant water uptake and subsequent water transport is necessary.

In the root, water is taken up into the conducting xylem (Steudle 2000). There it is further transported according to the hydrodynamic laws of e.g. Hagen-Poiseuille (Tyree and Zimmermann 2002). In coniferous tracheids with a diameter of 5 - 80 µm, flow velocities of 1 - 2 m per hour are achieved. In contrast, hardwood tracheids are 15 - 500 µm in diameter and allow water transport of 6 - 40 m per hour (Choat et al. 2008). Annular-pored tree species conduct water only in the outer growth rings, while dispersed-pored tree species have wider conducting sapwood (Phillips et al. 1996).

At least 95% of the absorbed water is released back into the atmosphere via transpiration (McElrone et al. 2013). Diffusion resistance depends on the degree of stomatal opening, the thickness of the water-saturated boundary layer above the stomata, and the VPD (vapor pressure deficit) (Hirons and Thomas 2018). Transpiration is controlled by the stomata. An isohydric behavior is when there is an adjusted transpiration rate through gradual closure of the stomata in the correlation of soil moisture and VPD. Anisohydric behavior occurs when there are sustained high transpiration rates independent of soil moisture and transpiration only follows VPD (Klein 2014). Transpiration can be several hundred liters per tree per day (Wullschleger 2000; Martin et al. 2001).

Within the tree, water is stored in the wood and bark primarily of the coarse roots, trunk, and branch axes. The amount stored is approximately 10-22% of the daily water consumption (Köcher et al. 2013). The stored water is used for transpiration and as a buffer during drought stress (Schepper et al. 2012; Köcher et al. 2013).

The water potential gradient from the soil to the atmosphere serves as the driving force for water transport. The resulting "suction force" is called transpiration suction. The water is held together by cohesive and adhesive forces, forming a continuous water column (Tyree 1997). The water is absorbed at the roots in a compensatory manner (Jarvis 2011).

2.2 Diurnal cycle of the water balance

Before dawn, the water balance of a tree is in the maximum saturated state under the given conditions, because at night the stomata are closed, no transpiration takes place, and at the same time water can be absorbed from the soil (Jensen et al. 2016). Sap flow is very low (Forster 2014) and water content in sapwood peaks (Kumagai et al. 2009). This water is distributed throughout the tree and, in some cases, to other areas of the soil (Hafner et al. 2017). With the onset of radiation from the rising sun, the tree begins to photosynthesize and loses water through the open stomata (Jensen et al. 2016). This water initially comes from stored water supplies to ensure a continuous water supply at the times of highest photosynthetic rates in the morning (Köcher et al. 2013). In parallel, sap flow begins at the base of the trunk to meet water demands. If reservoirs are exhausted by midday, water is provided only from long-distance transport. The risk of cavitation increases and the stomata close. Towards afternoon, therefore, photosynthesis and transpiration rates decrease (Willert et al. 1995). Water stores are then replenished, especially in the evening and at night (Scholz et al. 2011).

2.3 Annual cycle of the water balance

The water balance of temperate trees is strongly linked to the seasons and associated tree phenology (Waring and Running 1978; Kravka et al. 1999; Wullschleger et al. 1996). Both sap flow and stem moisture vary greatly from year to year depending on weather patterns (Bovard et al. 2005; Wullschleger et al. 1996). The weather-dependent dependence of water balance is also species-dependent (Bovard et al. 2005). In deciduous trees, sap flow begins with budbreak and reaches its maximum in early summer to summer (Cermak and Nadezhdina 1998). Thereafter, sap flow decreases due to lower transpiration rates toward the end of the growing season until foliage shedding in autumn (Tognetti et al. 2004; Gebauer et al. 2012; Nalevanková et al. 2020). Stem water content behaves similarly. It is high in spring and early summer (Hernández-Santana et al. 2008) and declines as water availability decreases later in the summer (Hernández-Santana et al. 2008; Hao et al. 2013; Matheny et al. 2015; Beedlow et al. 2017). In winter, frost-induced cavitations may occur, further decreasing water content. In the spring, these cavitations may partially re-flood and the water content increases again (Hao et al. 2013; Hacke and Sauter 1996).

2.4 Effects of drought stress

Trees can die from drought stress due to hydraulic failure or lack of photosynthetic products (Sevanto et al. 2014). Extreme drought causes loss of sapwood conductivity due to air infiltration (cavitation) (Choat et al. 2018; Adams et al. 2017). Trees generally do not survive an 88- to 90-percent loss of conductivity (Barigah et al. 2013; Urli et al. 2013). For hardwoods, a 50% loss of hydraulic conductivity is thought to cause severe damage (Barigah et al. 2013), but some of this damage is still reversible depending on tree species, vigor, and location (Ogasa et al. 2013). Prolonged but less extreme droughts can lead to carbohydrate deficiency as stomata fail to open to protect against damage to the conducting xylem, preventing photosynthesis from occurring (Mitchell et al. 2013). The two processes often influence each other. In addition, stressed trees are more susceptible to pests or other abiotic factors (Anderegg et al. 2015).

3 Measuring parameters of the water balance

3.1 Soil Water Potential and Soil Moisture

Measurements in soil are divided into volumetric moisture measurements and water potential measurements (Campbell 1988; Carter and Gregorich 2008). Capacitive sensors or time domain reflectometry (TDR) sensors measure volumetric or gravimetric soil moisture (Lekshmi et al. 2014). However, because plant-available water varies greatly by soil type at the same soil moisture content, soil moisture has little value without more information about the soil (Hirons and Thomas 2018). Tensiometers, on the other hand, measure soil water potential and therefore allow us to say whether or not the water present in the soil is plant-available. Plant-available water is only present in the soil in the field capacity range up to the permanent wilting point. The permanent wilting point marks the soil water potential at which irreversible loss of turgor occurs (Kirkham 2004). In trees, this point ranges from -2.0 to -4.0 Mpa (Hirons and Thomas 2018). However, the measurement technique is costly and requires high maintenance.

3.2 Stem moisture

Drought leads to empty water reservoirs in the wood and bark (Betsch et al. 2011), as the trees evaporate water but no water can be absorbed due to insufficient soil moisture. This can also lead to cavitation, i.e., air infiltration in the xylem and consequent hydraulic failure of the affected areas (Nardini et al. 2013). Overall, this reduces the water content in the xylem. It can therefore be used as a measure of the hydraulic status of a tree (Gao et al. 2020; Matheny et al. 2017). Like the following methods, stem moisture is measured directly on the tree and therefore integrates all environmental influences. Depending on the weather pattern, for example, there may be a different curve shape compared to soil moisture (Hernández-Santana et al. 2008). In other cases, the curves run parallel (Matheny et al. 2015).

There are several measurement techniques for how stem moisture measurements can be made. Popular techniques include capacitive measurement (Matheny et al. 2017; Riccardo Valentini et al. 2019), time domain reflectometry (TDR) probe measurement (Wullschleger et al. 1996; Nadler et al. 2006), and electrical resistance measurement (Borchert 1994). These techniques are minimally invasive, have low power consumption, and can be integrated into IoT networks (Matasov et al. 2020). Electrotomographs can also be used to obtain information about the areal moisture distribution in the stem cross-section (Ganthaler et al. 2019; Bär et al. 2019).

3.3 Radius measurements

Point dendrometers can be used to determine the fluctuations in the radius of a tree. On the one hand, these fluctuations are reversible and are caused by the filling and emptying of the phloem and xylem cells during the course of the day (Zweifel et al. 2001; Sevanto et al. 2002; Steppe et al. 2006; Zweifel et al. 2014; Pfautsch et al. 2015; Swaef et al. 2015). The diurnal pattern follows a sinusoidal curve with a maximum in the early morning and a minimum in the afternoon. During dry periods, the xylem is not completely refilled and the stem shrinks (Zweifel et al. 2001). Radius measurements are directly related to water potential in the crown (Dietrich et al. 2018). Dendrometers are sensitive and expensive, but their low power consumption and relatively low maintenance make them suitable for use within IoT networks. They are sometimes used for irrigation control in nurseries, orchards, and vineyards (Ortuño et al. 2009; Kišš et al. 2019).

3.4 Sap flow

Sap flow measurements are commonly used in the scientific field to describe the water balance of trees (Eller et al. 2018; Mencuccini et al. 2019). If stomata are closed during a dry period to limit transpiration (Mencuccini et al. 2019), sap flow is also reduced (Brinkmann et al. 2016; Sitková et al. 2014; Hölscher et al. 2005; Zapater et al. 2013). It has also been shown that during a drought, sap flow on dying trees was reduced several months in advance compared to surviving trees (Preisler et al. 2020).

To make sap flow measurements, at least two holes are drilled into the sapwood with a vertical spacing of, say, 10 cm. A temperature sensor is inserted into the lower hole and a temperature sensor with heater is inserted into the upper hole. The heater is operated continuously or at intervals, depending on the system. The temperature difference between the two sensors is used to determine how quickly the generated heat is dissipated. The smaller the difference between the sensing elements, the more sap flow takes place (Granier 1985). There are very many variations of this technique (Burgess et al. 2001; Trcala and Čermák 2012; Vandegehuchte and Steppe 2012; Rabbel et al. 2016). What they all have in common, however, is the high power consumption that results from heating and the high maintenance requirements.

3.5 Leaf water potential

The leaf water potential is measured using a Scholander bomb (Scholander et al. 1965) and is a very precise way of recording the current water status. A leaf is separated and clamped in a pressure chamber. The pressure at which a water drop appears at the interface is measured. The amount of the chamber pressure corresponds to the amount of the water potential. The measurement is usually made before dawn because at this time the regeneration of water stores in the trunk is complete and the tree is at its highest water potential (Ritchie and Hinckley 1975). During drought stress, leaf water potential decreases (Breshears et al. 2009). Because both the equipment is expensive and the measurements are very laborious, this technique is not used to monitor tree stands in a city, for example. With limitations, it can be used in horticulture. There, measurements are mainly made during the day (Lampinen et al. 2001; Moriana et al. 2012; Mirás-Avalos et al. 2016).

4 Electrical pulse resistance measurements using Treesense Pulse sensors as an example

Since 2020, sensors for monitoring the hydrological status of trees have been manufactured by the company Treesense GmbH. The sensors measure the electrical resistance between two electrodes in the sapwood at 15 min intervals, which depends significantly on the moisture content of the wood. The compact sensor box (dimensions 8.5 x 5.5 x 3.5 cm, weight 150g) contains a LoRa antenna, which allows the data to be sent via a gateway to a cloud and thus in real time to the user. The power supply is initially ensured by a battery/accumulator (1200 mAh). This allows the sensor to operate for 6 months without additional sunlight. In addition, a solar panel is mounted on the surface of the housing. The panel makes it possible to operate the sensor permanently without changing the battery if the orientation is suitable.

For mounting, two holes (1.5 mm diameter) must be drilled approx. 9 mm deep into the sapwood at a distance of 2 cm. Brass screws are screwed into the wood as electrodes. At the same time, a silicone carrier for mounting the sensor box is attached to the screws. Pre-drilling and screwing in causes small wounds. However, these wounds are located in the outer sapwood and thus in very reactive tissue (Shigo 1984), so that no relevant damage is caused to the woody material. Due to the shallow depth of the bolts and annual growth, exacerbated by wound reaction, the sensors must be relocated and maintained every half year. The rest of the time there is no maintenance.

Due to the thickness of the bark in conjunction with the short electrode screws, the sensors are not mounted at chest level but inside the crown. In conjunction with the small device size, this is particularly attractive in the city, as the sensors can thus be operated inconspicuously. Vandalism of the devices is almost impossible. Since the sensor is very cost-effective compared to other sensor technology, measured values can be collected over a large area.

The sensors output the electrical resistance in kΩ as measured values. These values are initially dependent on the ambient temperature of the sensors. For this reason, calibration series were performed to establish a compensation function. In the software, both the compensated values and the raw data can be retrieved. Furthermore, the measured values depend on the tree species for wood anatomical and chemical reasons. Since the electrical conductivity can differ significantly even within a tree species, it is recommended to analyze especially the extent of the resistivity variations and less the absolute values. In general, an increase in electrical resistance, i.e. a decrease in conductivity, should be interpreted as decreasing sapwood moisture content.

In order to check whether the measurement series of the Treesense sensors within a tree are consistent and their measurements agree with other measurement methods, three Treesense sensors were mounted in the field on a beech (forest tree, approx. 30 m high) in the crown at 14 to 20 m height. In addition, sap flow (Ekomatik SF-L) and diameter were measured on the tree at a height of 1.3 m using a dendrometer (Ekomatik DR). As an example, the values from 5/20/21 to 5/23/21 are shown here (Fig. 1-2). Sap flow density reaches high values from 10:00 to 16:00 as a result of transpiration (Fig. 1). Water consumption causes the diameter of the tree to decrease during this time (Fig. 1). This is in line with expectations (see chapter 2.2). As the tree grows in spring, the curve increases from day to day. The temperature compensated values of the Treesense sensors show an increase in resistance, i.e. a decrease in moisture, until the afternoon due to water consumption by transpiration (Fig.2). As the water reservoirs regenerate overnight, the moisture increases and the resistance decreases again by early morning. The curves of the raw data run inversely to this. The curves of the three sensors run parallel, but differ in the absolute values. For this reason, it is recommended to primarily evaluate the changes in the resistance values.

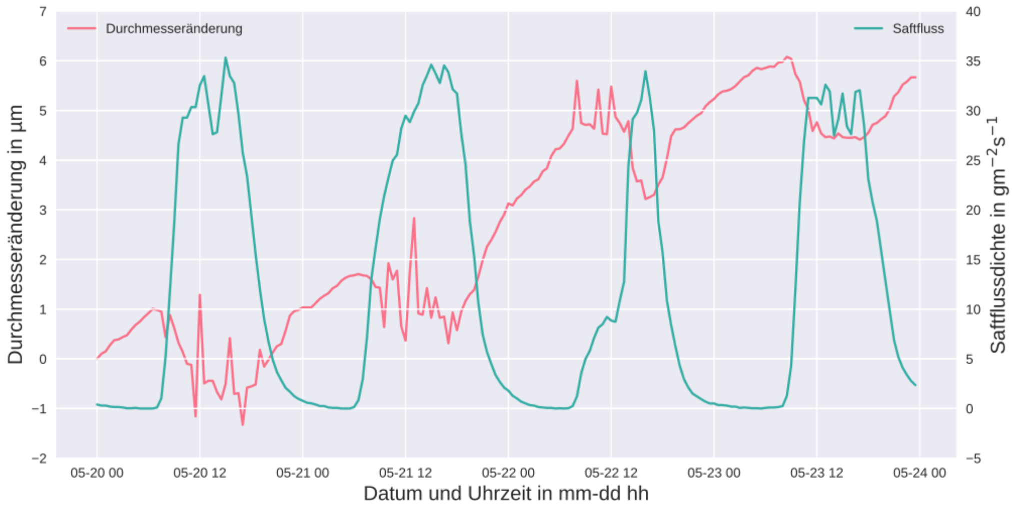

Fig. 1: Sap flow density and diameter changes of a beech tree about 30 m high.

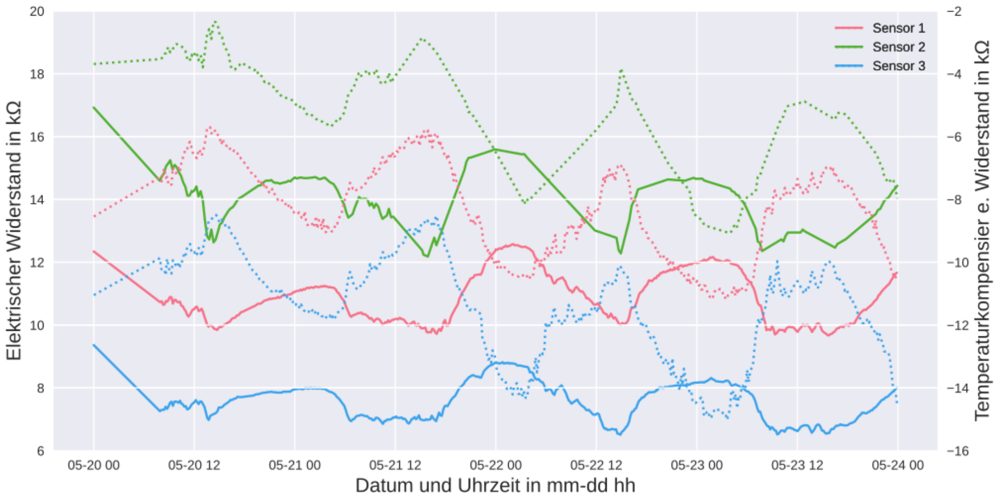

Fig. 2: Electrical resistance of 3 sensors within the crown (raw data (solid line) and compensated values (dotted line)) of beech from Fig. 1.

The sensors were further tested under standardized conditions in the greenhouse on 8 young lemon trees in 5.6 L pots to show the behavior of the trees and the response of the resistance values to increasing drought stress (Fig. 3-4). For this purpose, the lemons were irrigated with 500 ml of water at the beginning of each week. In between, no more water was given. The soil moisture in the pot then decreased by about 10 to 15 % (Fig. 4). Diameter variation was also recorded dendrometrically on two trees (Fig. 3). The dendrometer measurements confirm that the plants lose diameter after 3 to 4 days without watering due to transpiration losses. The raw data of the resistance values of the 8 trees basically show a parallel trend. The drier the soil and the higher the drought stress level becomes, the higher the electrical resistance values become. However, as in the case of beech, the absolute level of the measurements differs significantly. The diurnal variations are clearly visible. During the day, electrical resistivity in the raw data decreases somewhat, while it increases again at night.

Nevertheless, a trend caused by drought is clearly visible. Water deficiency in the trees can thus be detected with the help of Treesense Pulse sensors.

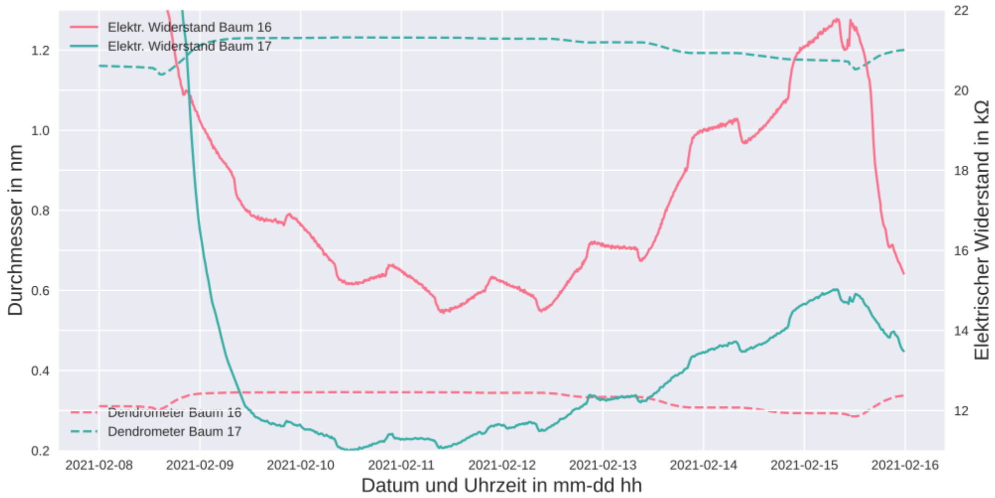

Fig. 3: Electrical resistance (in kΩ, raw data) and diameter (in nm) of 2 lemon trees.

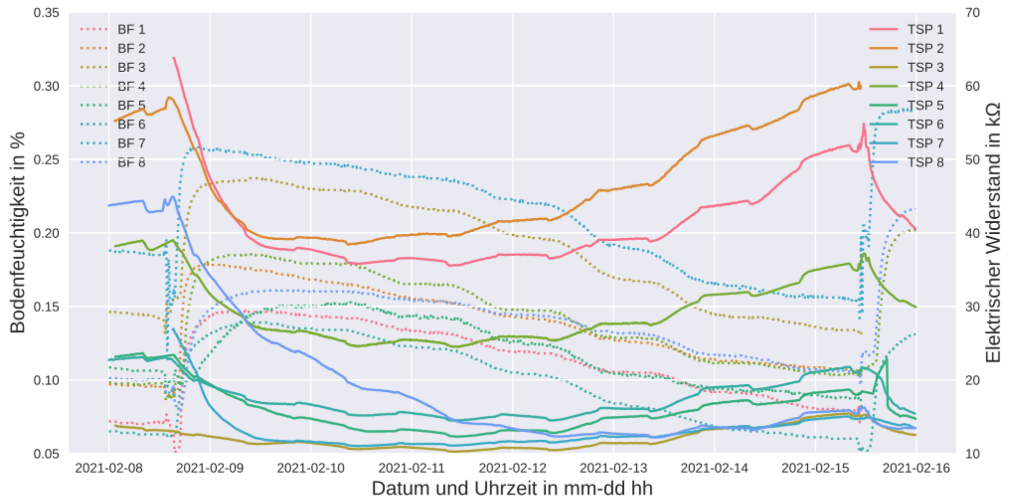

Fig. 4: Electrical resistance (in kΩ, raw data) and soil moisture (in %) of 8 lemon trees.

5 Possible applications of electrical pulse resistance measurement

5.1 Urban tree population

Particularly in the urban environment, high expectations are placed on a tree stand. Trees are expected to provide a variety of ecosystem services such as carbon sequestration, reduction of heat, dust, and pollutants, in addition to bringing an aesthetic appearance and being safe for traffic (Bowler et al. 2010; Escobedo et al. 2011; Soares et al. 2011; Roeland et al. 2019). These requirements can only be achieved with healthy, vital trees. However, the increasing effects of climate change are expected to increase the proportion of dying and diseased trees in urban areas (Savi et al. 2015). Drought stress, in particular, is a driver of tree mortality and makes trees susceptible to disease and pests (Choat et al. 2018). Ecosystem services such as urban cooling can also only be achieved if sufficient water is available for transpiration (Konarska et al. 2016). Irrigation of trees is one way to mitigate the effects of climate change on trees and thus maintain their functions. Drought stress should be identified before visible signs are evident, if possible. This allows ecosystem services to be maintained and resources to be used efficiently (Gimpel et al. 2021). To date, however, it has been difficult or very costly to make decisions about the use of irrigation measures based on metrics. This is possible with low-cost, and therefore area-wide, real-time systems such as Treesense Pulse. With such a system, only those trees that actually need water are irrigated. In addition to monitoring existing trees, the system can also be used well for monitoring new plantings or in the context of construction sites, e.g. with groundwater lowering to monitor affected tree stands.

5.2 Horticulture

Irrigation management has a major impact on the performance of horticultural crops. Excessive levels of drought stress or watering can reduce growth in nursery crops as well as fruit yield and fruit quality in orchards (García-Tejero et al. 2010; Chappell et al. 2013; Vera et al. 2013). A great many methods have been used to implement irrigation management based on tree physiological measurements (Brough et al. 1986; Ben-Gal et al. 2010; Fernández and Cuevas 2010; Cohen et al. 2001) including measurements of stem water content (Nadler et al. 2006; Gao et al. 2020). Electrical impedance measurements offer the possibility of inexpensive, area-wide data on the hydrophysiological condition of trees by radio in real time and to control irrigation according to demand.

5.3 Science

Small, lightweight, current-independent, low-maintenance and low-cost sensors, which allow a statement to be made about the water content in the xylem, offer the possibility of answering a wide range of ecophysiological questions. With respect to the individual tree, the sensors can be mounted anywhere, even in the outer branch area. Thus, three-dimensional measurement networks can be created to display hydrophysiological reactions spatially and in a high temporal resolution. Furthermore, it is possible to monitor large areas, for example in forests, with a finer mesh than before. Due to the favorable price, the number of measuring points can be increased. Provided that a mobile radio signal is available and the gateway is supplied with power via a solar panel, the data can also be processed from remote areas in real time.

6 Conclusion

Due to increasing drought stresses on trees, the need for tree physiology-based tree monitoring for intensively used trees will increase greatly in the future. Previous methods already allow such monitoring, but not to the extent needed because the measurements are labor-intensive, or the measuring devices are expensive and require high maintenance. With the electrical resistance measurements of the sensors from Treesense, a method is now available that significantly increases the applicability in practice. On the one hand, reliable values are produced that are in line with other measurement methods, and on the other hand, the sensors are inexpensive and can therefore be used in large quantities. This enables the user to monitor even larger tree populations. Irrigation decisions can thus be made based on tree physiology and in a targeted manner. This allows considerable savings in the use of resources such as water and personnel.

7 References

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