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Development & testing of an IoT system to monitor selective physiological parameters to understand different physiological responses of various plant species across different seasons

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1. ABSTRACT

Climate change effects forests as well as individual trees at different levels. There is a necessary need to quantify and monitor the seasonal changes in tree physiology i.e., sap flow, foliar changes and light transmission, radial growth and wood temperature. With the help of a smart and reliable IoT system it is possible to achieve this on continuous bases which can help us understand the instantaneous responses of the individual trees to a certain stress stimulate e.g., abrupt seasonal changes as recently observed in the current decade.

IoT used in the current study is a cloud-based system currently used is composed of “Tree talkers”, a device that can continuously measure sap flow, light transmission through canopy, radial growth, tree oscillation and stem humidity, and record the data on hourly basis. This acquired data is sent to an online server where data can be analysed for studying a physiological profile of an individual tree as well as of a forest. There has been a certain need as well a growth in the new IoT technologies and their application in the ecological sector particularly because of their improved capabilities, consistency and low costs. The developed device system used in the project is designed to measure different plant physiological parameters such as stem humidity, xylem moisture, sap flow density and foliar light transmission, radial growth and angular movements understand climate variability impacts on trees and individual level.

In the present study, the system used in the experiment consisted of a set of devices planted in two field sites to monitor sap flow density, xylem moisture and foliar light transmission. Plant composition included both deciduous plantations and coniferous forest in each study site. Different species showed variability in their physiological changes that showed their response in different seasons which helped us profile each tree species. By connecting each parametric changes, we can assess the condition of a forest or a plantation at a cumulative level.

Key words: Tree talker, Sap flow, Stem humidity, Piegara forest, IoT.

The Ph.D. thesis project aims towards development and testing of an IoT system that is capable of effectively monitor of different physiological parameters such as Sap flow density, foliar light transmission and xylem moisture content and their relationship across different seasonal changes. These changes were deeply correlated with different environmental conditions that arose during the year 2019. The parameters studied such as sap flow can used as an indicator of plant health and an important metabolic process that is essential to the vitality of the tree and is an important component of evapotranspiration (Zaremba and Smoleński, 2000).

2. MAIN FINDINGS

In the current study sap flow measurements were continuously recored in order to better understand the sudden changes that accurs in plant regarding evapotranspiration and how these changes are linked with other parameters such as foliar light transmission and xylem moisture. This acquired data that is recorded hourly is then sent to an online server where we can study it to construct a physiological profile of an individual tree as well as a forest. Two fores ecosystems (coniferous forest, deciduous plantation) were studied in the experiment. To calculate sap flow density, Granier method was used. In which the transpiration rate of whole plants is closely approximated by the sap flow rate in the main stem or trunk. For these reasons there is a need for a relatively simple and affordable device to continuously monitor the sap flow rate in trees of all sizes. In order to measure sap flow density we used Granier method (Granier, 1987, 1988). The device was equipped with moisture sensor that measured the xylem moisture. Moreover, foliar light transmission was recored with device installed under the canopy and that recorded the transmitted light components later used in the analysis to define canopy changes in the both ecosystems.

Later these three parameters were used to depict the long term changes in response to yearly changes in seasons and drought particularly in summer 2019. Overall analysis of sap flow density in site 1 (forest area), *Quercus petraea* L was significantly higher as compared to the coniferous species (*Pseudotsuga menziesii* F and *Pinus sylvestris* L). Furthermore, *Pseudotsuga menziesii* F

had significantly higher rate of sap flow density than *Pinus sylvestris* L in spring and summer with April being the only exception where both had marginally same mean values. Detailed illustrations are shown later in results. Sap flow density during peak hours (11:00 AM – 15:00 PM) showed only slight changes as the peak duration did not vary in different species. We used the probability density functions of peak hours, namely, the hour of the day at which the SFD reaches its maximum value. Overall, species with maximum sap flow at a later time of the day will have a lesser impact of water stress, as stomata continue to be functioning for longer time. Data on peak hours suggest that some trees, mostly belonging to the deciduous species, reach the maximum daily SFD around 11-12 am, while evergreens reach maximum SFD later on, approximately at 3 pmsuggesting a greater capacity to maintain good water conditions preventing stomatal closure. *Prunus avium* L has an intermediate behavior. The radiometer installed on the Tree Talker device has 12 selective narrow bands for light detecting at 450+, 500+, 570+, 600+, 610*, 650+, 680*, 730*, 760*, 810*, 860* nm ((+)± 10nm+; (*) ± 20nm).

Results obtained are consistent with the typical vegetation reflectance curve found in different studies (Bowker et al., 1985) showing the largest incident light intensity in the IR, mainly due to high reflectance and transmittance from leaves, followed by the green waveband, i.e. 500nm (Lillesand et al., 2015). Lower incident light intensity occur at 450 and 660nm, namely in the blue and red band waves, as expected to be due to chlorophylls absorptions. In the present study, two Normalized Difference Vegetation Indices obtained from pairwise combination of IR plus RED (hereinafter NDVI) and IR plus GREEN (hereinafter GNDVI) are presented. Since data collected by the radiometer are raw digital numbers, i.e. without any transformation into absolute units, atmospheric corrections and/or sensor calibration, normalized vegetation indices are generally appreciated as the normalization makes some of these corrections unnecessary. Moreover, the results are also unaffected by the solar zenith allowing the comparison of data from different times of day, season and latitudes (Banari et al., 1995; Ryu et al., 2010). Xylem moisture provides information about the internal water storage to water consumption (Wang et al., 2008). Overall, xylem moisture is broadly synchronous with precipitation events, decreases in very hot days and increases in relative cold-wet days. Moreover, a negative balance between canopy transpiration and basal sap in the afternoon allows for the stem water recharge before night. Xylem moisture has a sudden effect on stem diameter size, with a time lag between stem moisture changes and diameter variation that can be of few minutes (Simonneau et al., 1993). As a consequence, stem

moisture, radial growth, sap flow and meteorological condition are all strongly related and broadly affecting the whole plant water use. Statistics from individual trees showed that the sapwood of deciduous species generally has larger water content than evergreens and are more prone to a wide variability. Looking at the time series, it emerges that with the exception of *Pinus sylvestris* L, all the species have constantly increased the sapwood water content during 2019 until reaching values ranging from 3 times (*Pseudotsuga menziesii* F) to 6 times (*Quercus cerris* L) as much in just 9 months. The ranges are in line with what has been observed in the literature (Sparks et al., 2001). This evidence could be explained by two factors, first, in summer most of the plants control the opening of the stomata and reduce perspiration despite the high VPD (saturation relation shown in the Results) allowing the plant to preserve some water reserves and/or recharge them during the nights. Secondly, a moderate yet constant precipitation in the summer has helped to preserve water reserves during the hottest time of the year.

3. BACKGROUND

Sap flow measurements provide a powerful tool for quantifying plant water use and monitoring qualitative physiological responses of plants to environmental conditions. As such, sap flow methods are widely employed to investigate the agronomic, ecological, and hydrological outcomes of plant growth. The following study provides an overview of thermodynamic sap flow measurement techniques used to quantify volumetric water use in plants. A variety of sap flow techniques have been described in the literature, but here we will focus on the most commonly used methods suitable for measuring sap flow in stems of woody and herbaceous plants (Granier method), (Granier, 1987). Measurement of sap flow provides many benefits for studies of plant–water relations. Sap flow sensors can be easily replicated and automated and installed without disrupting the microclimate around the plant (Smith & Allen 1996). When installed at different positions within the same plant, they can provide information on the dynamics of water flow around the plant. Recent examples include the role of tissue capacitance in buffering transpirational water loss (James *et al.* 2003 ; Burgess & Dawson 2008); documenting reversal in sap flow direction, particularly in large diameter roots growing in drying soil (Burgess *et al.* 1998

; Smith *et al.* 1999); and the coupling of stomatal physiology to plant hydraulic capacity and root functioning (Clearwater *et al.* 2004). Disruptions to a forest ecosystem, both natural and anthropogenic, frequently result in destruction or alteration of the forest's leaf coverage, or canopy. Such disruptions include effects of pollution and biological invaders, but also result from common human forestry practices like logging and intentional thinning of vegetation. Even native deer, if the population becomes large enough, can disrupt the canopy through excessive consumption of small trees (Pedersen and Wallis 2002). A knowledge of the distribution and intensity of light, or light climate, of the forest canopy and floor may inform management practices dealing with disturbances to forest ecosystems.

Piegaro forest and plantation covers an area of more than 150 hectares and is the first time an Italian initiative of this genre has obtained international standards certification in keeping with both the PEFC® and FSC®. It attests to a forest management style that meets the most advanced criteria for environmental, economic and social sustainability. They represent an ecological and socio-economic reality relevant especially for inland areas. Their traditional ecosystem services are wood, carbon dioxide absorption, tourism and recreational activities.

The current research study has been divided into 2 main steps;

- Development, calibration, assembly and installation of an IoT system to continuously measure physiological parameters in both study sites.
- Using that system to viably obtain and analyse the data to profile the different trees species in both sites (in terms of sap flow density, foliar light transmission and xylem moisture and radial growth).

The main objectives of the study were as follows;

1. Are we able to continuously monitor the tree physiological parameters?
2. How sap flow, xylem moisture, spectral responses and vegetation indices respond to seasonal variability?

4. MATERIALS AND METHODS

In autumn (October) 2018, total of 13 Tree Talker devices were installed on two conifer species (*Pseudotsuga menziesii* F and *Pinus Sylvestris* L) and a deciduous species (*Quercus petraea* L) in Piegaro forest, Umbria (Latitude: 42° 58' 4" N, Longitude: 12° 4' 5" E, 352 ASL). The study area was named SITE 1. Furthermore, 17 additional Tree Talker devices were installed in the same region but 4 kilometers away with different deciduous plantation consisting of three dominant species (*Quercus patraea* L, *Quercus cerris* L and *Prunus avium* L) in spring (April) 2019). This was named SITE 2 (Latitude: 42° 58' 8" N, Longitude: 12° 3' 60" E, 399 ASL). Devices were monitored continuously, and data was recorded by the devices at hourly basis. The established monitoring system consists of 30 TreeTalkers (TT⁺) mounted on *Quercus petraea* L, *Quercus cerris* L, *Prunum avium* L, *Pseudotsuga menziesii* F and *Pinus sylvestris* L. (number was later reduced). A general illustration of the setup layout is given below.

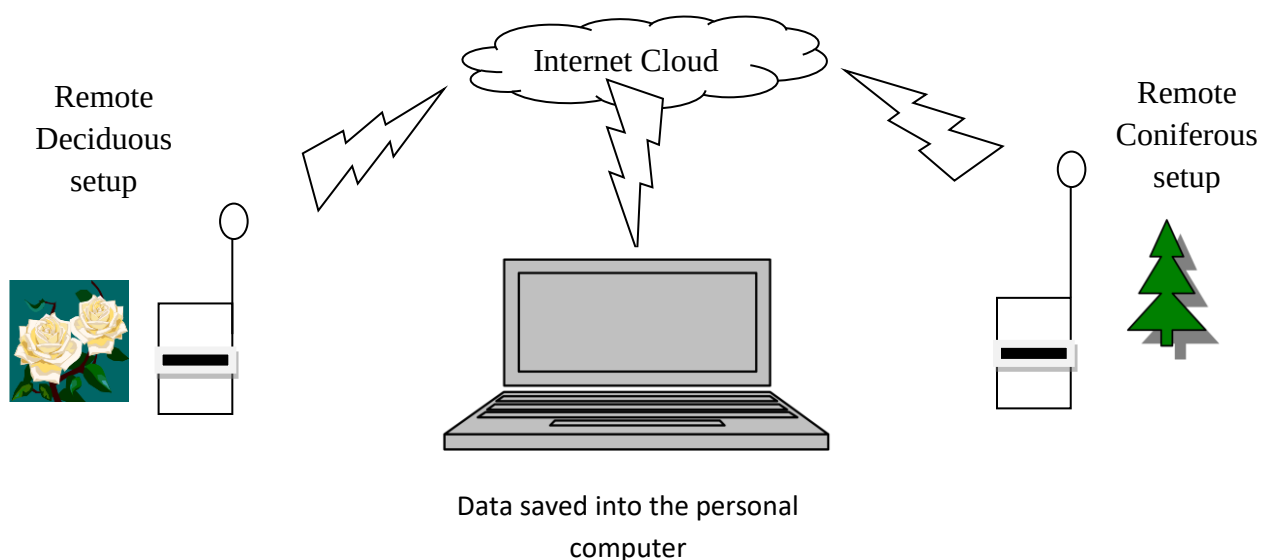


Fig. 1a: IoT set up and the functioning structure

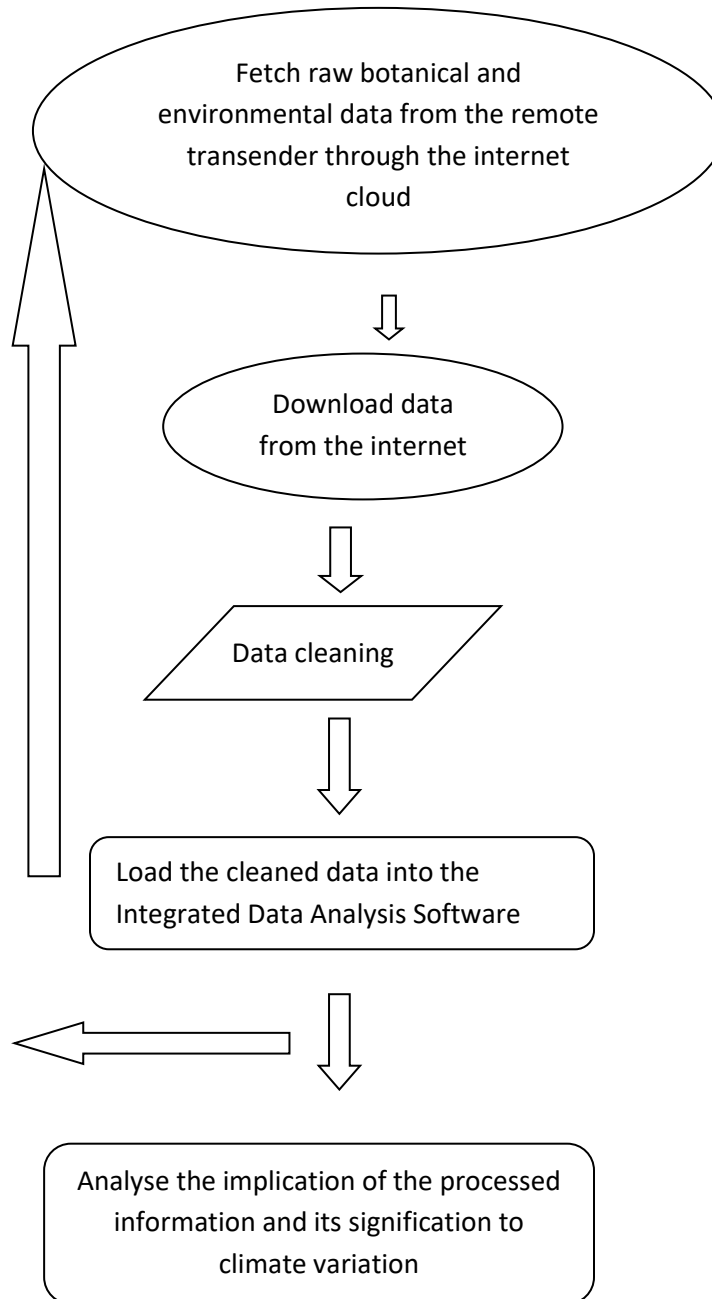


Fig. 1b: Schematic layout of IoT data processing

Overall, the analyzed data covers the period 31/10/2018 - 31/12/2019 at hourly time scale, embracing a time frame of 10903 hours, corresponding to 455 days (hereinafter *timeline*). However, due to the above-mentioned shortcomings there exist some shortage of data during the

first months which was meant to be compensated for 2020 but because of COVID-19 pandemic and regional restrictions, it was not possible. For this reason, the results here reported are mostly highlighted from March 2019. The parameters include sap flow density, foliar transmitted light components, xylem moisture and radial growth.

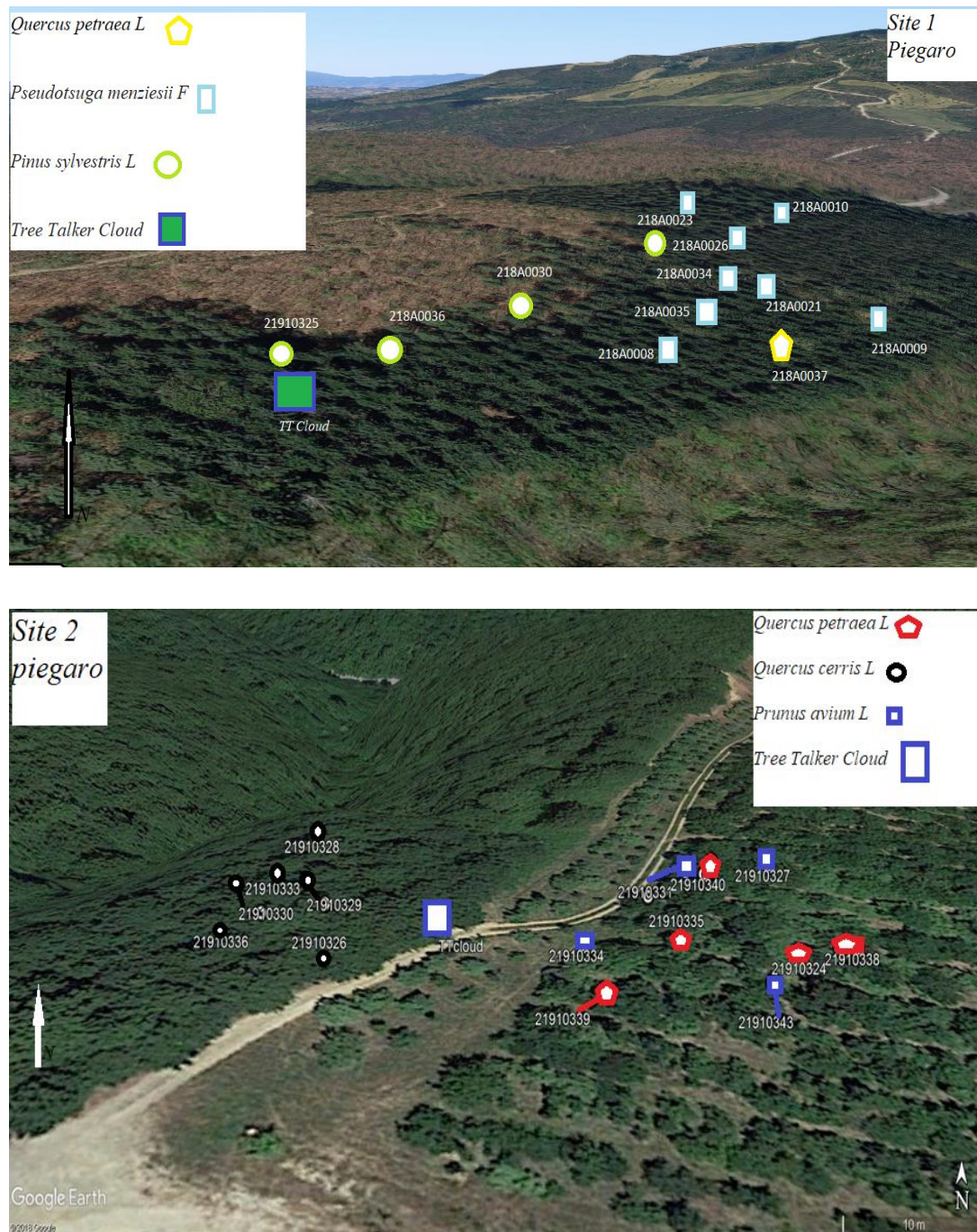


Fig. 2: Study area with installed devices

The analysis that is detailed in the latter chapters was carried out after a pre-processing of the raw measurements to align the timestamps and correct some data inconsistency. The explored variables are the sap flow density (SFD), two vegetation indices, (NDVI and GNDVI), radial growth and xylem moisture. In terms of study structure, the whole study program was divided into 2 main steps;

- **A1) Assembling the Devices, Calibration and Installation.** Initially the devices were calibrated in the lab for some time to check the data and then the devices were assembled, and an inventory was made to maintain the record of the devices in use. Two sites were selected, and the devices were installed on different species of trees.
- **A2) Data acquisition, Monitoring, Processing & Analysis.** Devices were continuously monitored on weekly basis and data was recorded by the devices on hourly basis for different seasons from both sites.

4.1 IoT SYSTEM COMPOSITION

Tree talker IoT system has 3 basic components

1. Tree talker cloud
2. Tree talker + device
3. Battery unit



Fig. 3a: IoT system components

Device composition information

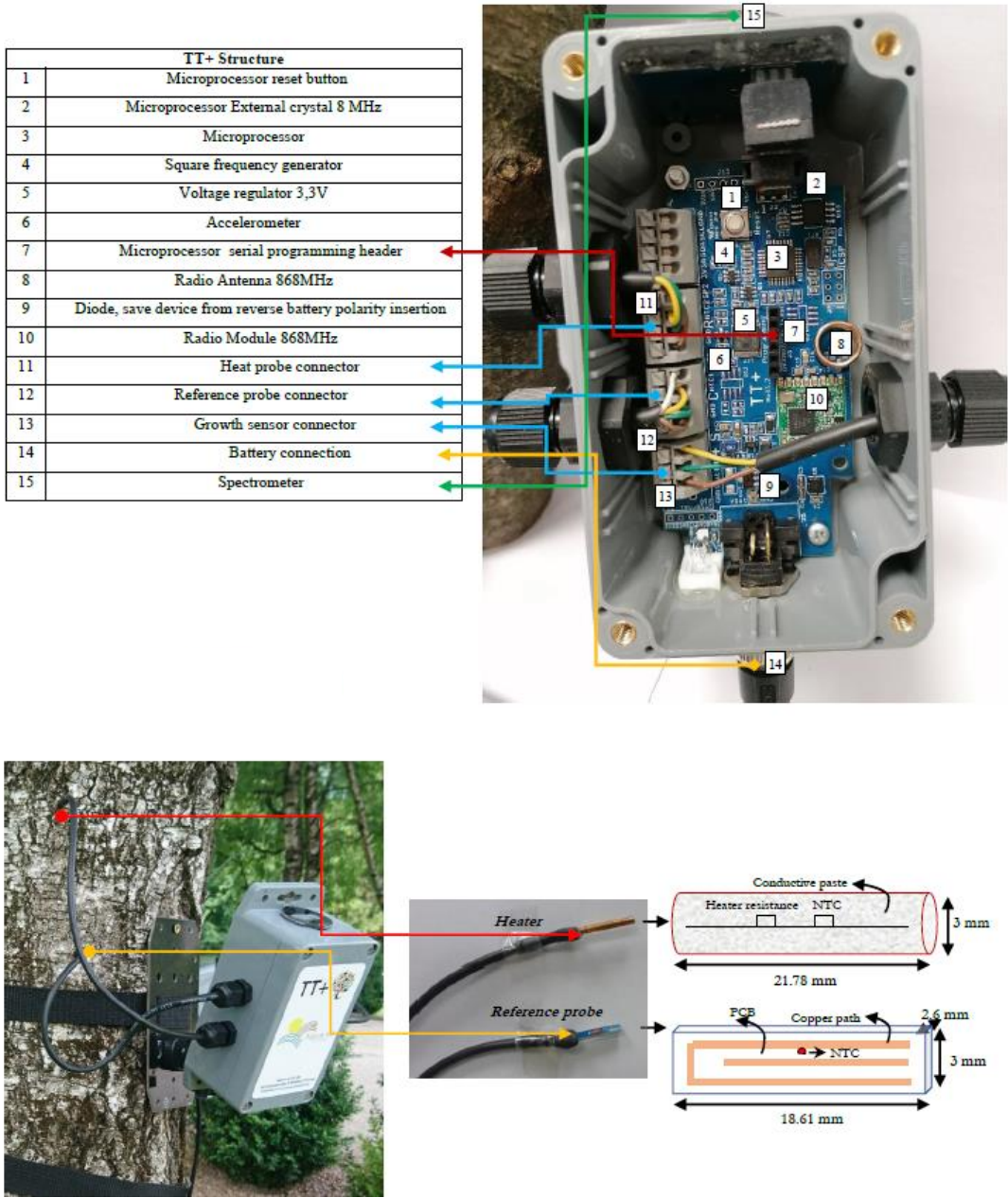


Fig. 3b: internal components/sensors of Tree Talker device

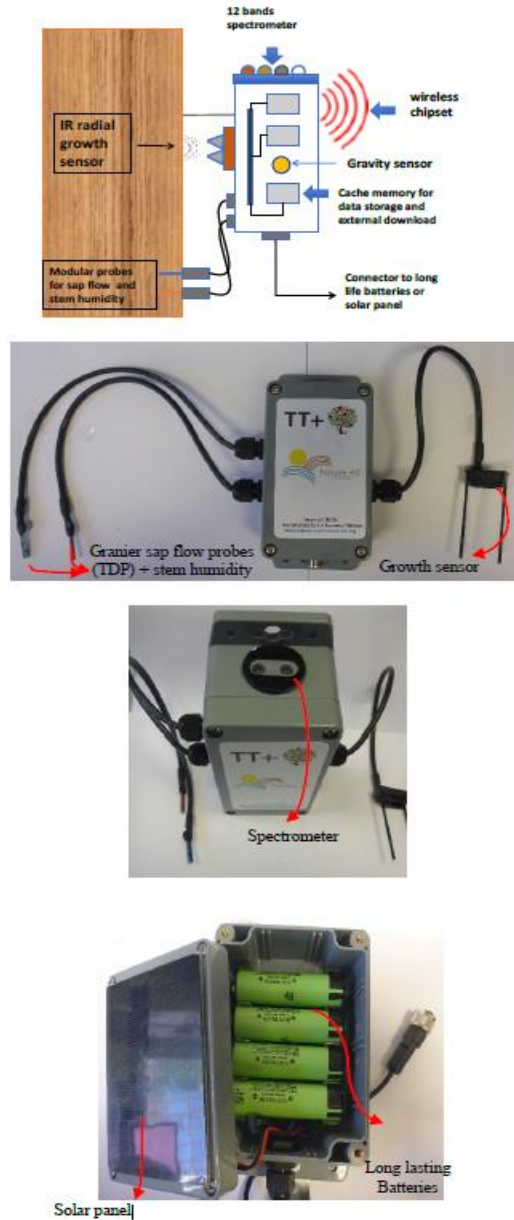


Fig. 3c. Sensor information

Tree talkers installed in the study area were equipped with the power source (batteries) which were replaced routinely and later after installation, planned biweekly visits were organised to inspect the devices, batteries performance and sensor condition. After the data is recorded by each individual device, it is saved within that device and is also sent to the TT cloud by radio signal which saves it again and then transmits to the online server via GPRS signal through sim cards installed within. This elaborate data transmission and data saving mechanism was used in order to

have multiple back ups of the recorded data in case device is broken, damaged or stolen. Furthermore, solar panels (as seen in the figures 3a and 3c) were used in the battery boxes in order to increase battery reserves for longer period of time which was proven very helpful during summer period because of longer sunlight exposure to the solar panels. Different parameters that are mentioned below were studied and analysed in order to have a better profile of each species groups present in both sites in piegaro.

4.2 SAP FLOW DENSITY

The transpiration rate of whole plants is closely approximated by the sap flow rate in the main stem or trunk. A method for that purpose was proposed by Granier (Granier, 1987), who inserted a needle, containing an electric heater, in the sapwood of a trunk and measured the difference between the temperature of the heated needle and that of the sapwood some distance below the needle. The method is relatively simple and it is called the Thermal Dissipation Probe (TDP) method. TDP heated needle is an improved heat dissipation sensor, as proposed by Granier, which measures the temperature of a line heat source implanted in the sapwood of a tree, referenced to the sapwood temperature at a location well below the heated needle. The probe measures the sapwood heat dissipation, which increases with sap flow and cools the heat source. When the sap flow velocity is zero or minimal, the temperature difference (ΔT) between the two sensors is maximal. When the flow increases, this temperature difference decreases. (Fig. 4)

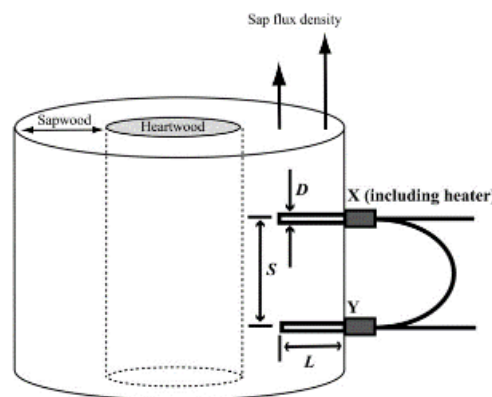


Fig. 4: Sap flux density in greenwood stem based on Granier method

Moreover, many factors are involved to decide about the number of inserted probes in the trunk to measure sap flow, such as tree's diameter and stem uniformity... It should be noted that the sap flow velocity varies within the sapwood, so other parameters like sapwood thickness introduces some uncertainty in the calculation of the sap flow. For this reason cyclic heating/cooling system (Do and Rocheteau, 2002; Do et al., 2018, 2011) was followed. The default of TT⁺ is designed to measure sap flow according to the thermal dissipation method (TDP) with cyclic heating system (10 minutes of heating/ 50 minutes of cooling). A probe pairs is inserted in the main trunk with a vertical separation of 10 cm, facing north to avoid direct solar heating. One of the probe is heated while the other is used to measure the reference temperature and includes a capacitive sensor of wood humidity. Granier equation is used to determine sap flux density in TDP devices.

$$Fd = 118.99 \left[\frac{\Delta T_{\max} - \Delta T}{\Delta T} \Delta T \right]^{1.231}$$

Where Fd is the sap flux density (gm⁻²s⁻¹), ΔT is the actual temperature gradient between the two probes after heating and ΔT_{max} the maximum temperature gradient measured between the probes after heating in a given time period.

Since in high natural temperature gradient, Granier method underestimates the amount of sap flow. To avoid this issue different method known as Do's method (Do et al., 2018) was applied to estimate sap flux density with considering both temperature measurements at the end of cooling (Tref_0 & Theat_0) and heating (Tref_1 & Theat_1) periods.

$$Fd = 12.95 \left[\frac{\Delta T_{\max}}{\Delta T_{\text{on}} - \Delta T_{\text{off}}} - 1 \right]$$

$$\Delta T_{\text{on}} = \text{Theat}_1 - \text{Tref}_1$$

and

$$\Delta T_{\text{off}} = \text{Theat}_0 - \text{Tref}_0$$

Where Fd is sap flux density expressed in 1gcm⁻²h⁻¹.

4.3 FOLIAR TRANSMITTED LIGHT COMPONENTS

The radiometer installed on the TT+ has 12 selective-narrow bands for light detecting at 450+, 500+, 570+, 600+, 610*, 650+, 680*, 730*, 760*, 810*, 860* nm ((+)± 10nm+; (*) ± 20nm), in order to better differentiate between different wavelengths. Devices were installed at about 1.4-1.5 meters above ground in order to capture better light transmission. However due the fact that devices had only 40° field of capture which could have the tree stem hindering the direct transmitted light if installed without any gap between device and tree stem. For this reason, devices were tilted away 20° from the stem in order to avoid indirection of light due to bouncing off from stem/bark of the trees (Fig. 5).

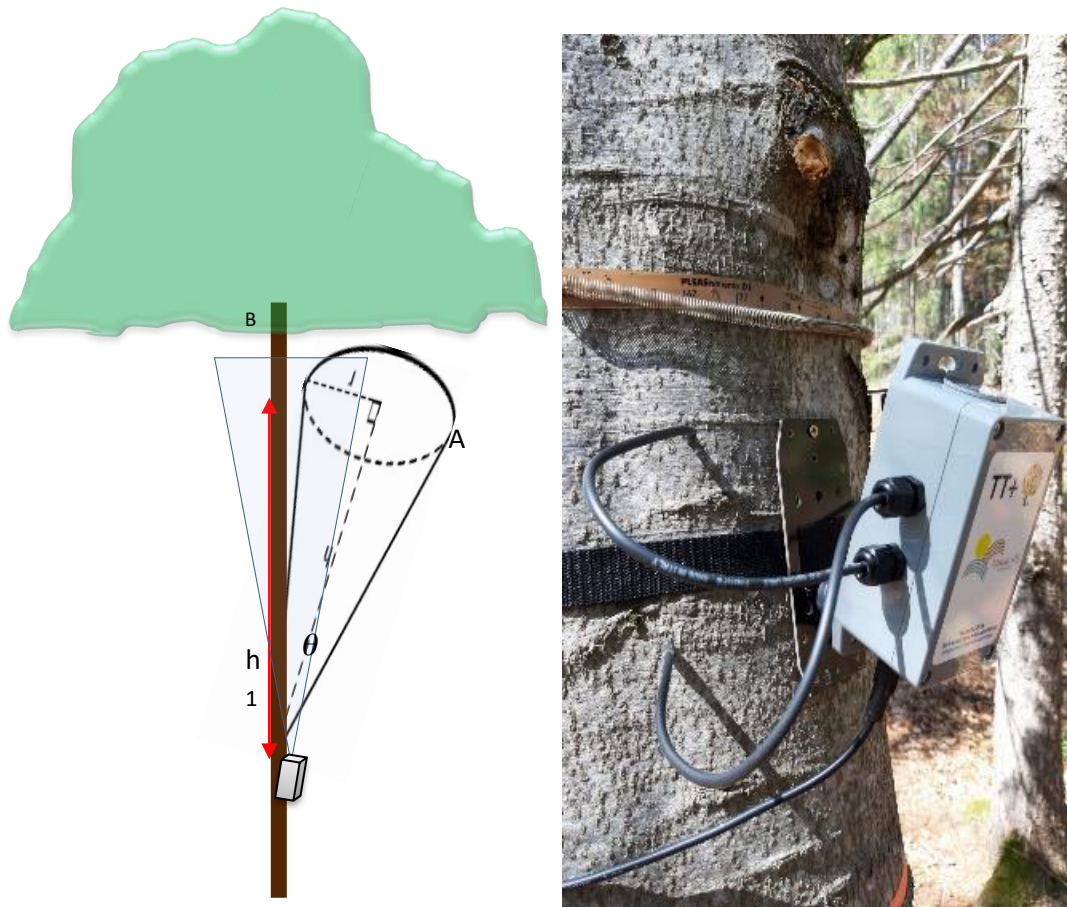


Fig. 5. Angel correction during installation where A is the corrected field of capture, B is the actual field of capture, h is the distance from device to the crown level.

Since this practice was done to obtain transmitted light through tree canopy but in order to avoid any errors due to heating of the glass protection a separate Tree Talker device was installed away from the primary IoT area. The purpose for that is capture direct sunlight spectral profile or total radiation profile (Fig. 6). This helped us in calculating different vegetation indices based on light transmission.



Fig. 6. Tree Talker with solar panel attached to the battery pack, without tree to obtain direct light transmission.

4.4 XYLEM MOISTURE

Devices used in the experiment were equipped with the moisture sensor that was inserted into the stem of the tree to measure hourly moisture rate. Stem humidity measurement is alternative capability of Tree Talker devices which is expressed as frequency signal with the range of 7000 to

14000 Hz in green wood. The range of frequencies is significantly influenced by environmental factors. High frequency occurs in very hot days and shows less stem water content. Considering the effect of wood density on frequency data, calibration was done on 2 different harvested stem samples (*Fagus sylvatica* L. & *Pinus sylvestris* L.) as representatives of broad-leaved and narrow-leaved families to convert the sensor-reported values to xylem moisture in percentage.

4.5 RADIAL GROWTH

Stem radial growth is measured by an infrared pulsed distance sensor also known as sharp sensor which is positioned at few centimeters away from the tree trunk's surface and kept in place by a carbon fiber stick anchored in the xylem (Fig. 7).

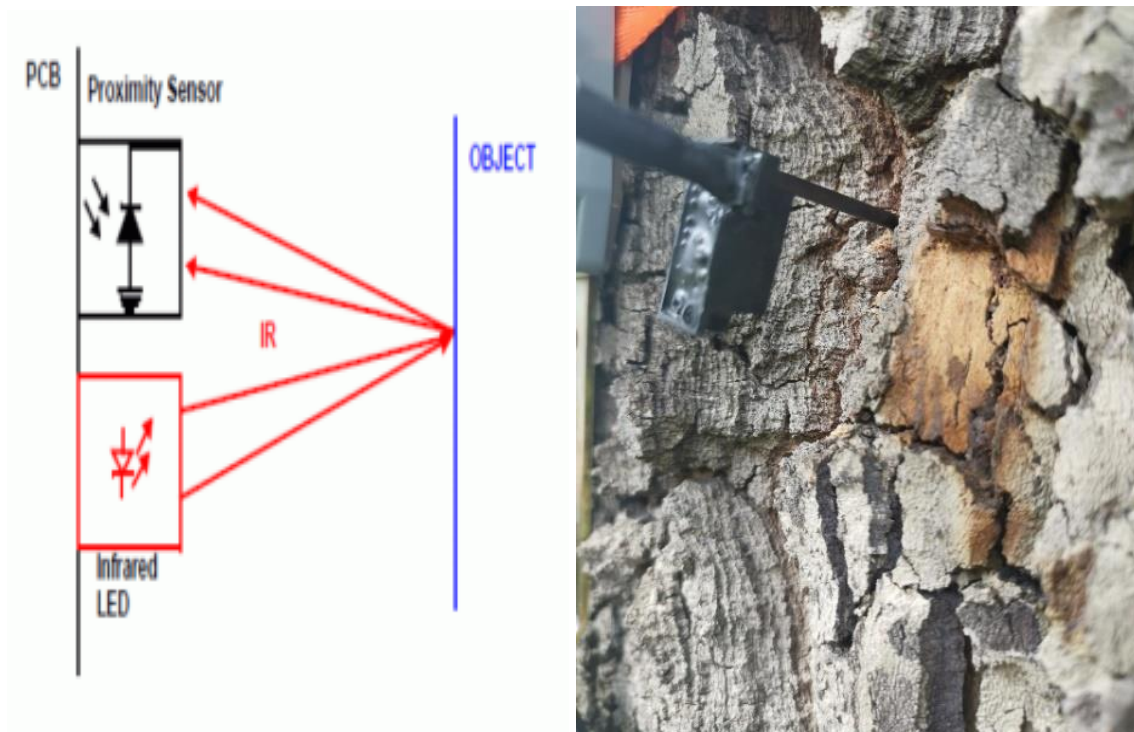


Fig. 7. Sharp sensor working mechanism.

At the time of installation the length of the carbon needle was inserted in a way that the total distance between the sharp sensor and the tree back was 2.5 centimeters. Due to radial growth, when the distance was reduced to 1 centimeter, the needle was replaced.

4.6 DATA HANDLING & STATISTICAL ANALYSIS

Data obtained through devices was stored in the device itself as well as sent to the cloud which would save it there again and then by using GPRS signal, send it to the online web server. By using a 6 pin cable (to connect with tree talker or cloud) with the other end having USB type A opening (to connect with portable computer), it was possible to extract the data from both device and cloud in case due to disruption of signal, some data was not sent. By using Arduino 1.8.5, data was copied into Microsoft Excel file sheets. Each file was updated following the same procedure when the data extraction was done. Each file corresponding to the tree talker ID number which was attached to different tree species in both study sites was then loaded into two main softwares (R-Studio 3.0.1 & Python anaconda 3.7) which were used to process, clean, group and analyse the data.

5. RESULTS AND DISCUSSION

During the PHD program, the low cost IoT system in use (Tree Talkers) collected different sets of data that was used to construct a profile of each species that was monitored by the above said system. These parameters include sap flow density, foliar light transmission, xylem moisture and radial growth. The system used for the experiment was found reliable to use in a remote area such as the selected study sites in piegaro. Factors such as strong wind, high temperatures in summer, heavy rainfall and casual encounter with the local wildlife had no affect over the system and devices showed consistent data without any external influence of above mentioned biotic and abiotic factors. Parameters under investigation are discussed in details below.

5.1 SAP FLOW DENSITY

Sap flow within a tree is strongly affected by environmental variables such as solar radiation, vapor-pressure deficit (VPD) and soil moisture, because these variables affect the difference of the water potential between the atmosphere and the leaf airspace. The scientific relevance of Sap Flow Density (SPD) mostly relies on its daily maximum value, the hour of the day at which the SFD reaches its maximum (hereinafter peak hour) and on its relationship with meteorological conditions (Doronila and Forster 2015). For these reasons, sap flow measurements are here analyzed together with the climatic conditions, in particular the Vapour-Pressure Deficit (VPD), derived from the near reference meteorological station of Piegara.

The SFD can be estimated from the temperatures measured by the (two) probes radially inserted in the sapwood. From the probe temperatures, it is possible to estimate the SFD according to the Granier method (Lu et al., 2004; Do and Rocheteau, 2002). This method compares the temperature difference between probes to the maximum temperature difference obtained under zero flow conditions (i.e. when the heat in the sapwood is supposed to be solely transported by the mass conduction) and estimates a relative sap flow velocity). The sap flow velocity is then scaled to the actual SFD. The maximum temperature difference is commonly estimated over the 24 hours, supposing zero flow conditions at night. Hence, the second requirement to rely on a correct estimate of SFD is the availability of probes temperatures during the 24 hours. The SFD is

here estimated only in the days where at least 18 hours (75%) of probes' daily measurements are available. This approach is precautionary but does not exclude some underestimations of SFDs. Descriptive statistics for SFD (daily peak score) for single TT are shown in **Figure 8** (grouped per species). Data reveal a very high variability across trees, even across the same species. The median from single tree ranges from roughly 2 to 15 $\text{g cm}^{-2} \text{ hr}^{-1}$, maximum values from 0.5 to 132 $\text{g cm}^{-2} \text{ hr}^{-1}$.

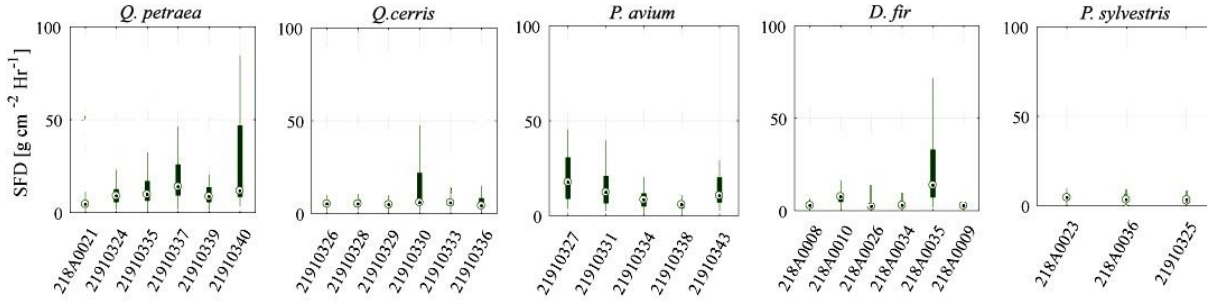


Fig. 8: Daily peak score for sap flow density for each device/tree (Synthetic boxplot of daily SFD for single group. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles)

The intra-variability of SFD could be explained by the different time of the year at which data are collected, while the inter-variability should be explained by other factors than climate. Indeed, the monitored trees belong to the same experimental field, thus the environmental/climate and edaphic conditions to which the plants are subjected can be roughly considered homogeneous. Examples of factors potentially affecting SFD could be the tree age, the depth of the sapwood, the fraction of the sensor surface actually surrounded by the active sapwood (i.e. water-conducting wood), the health of the tree and other tree-specific differences.

As described in Table.1, mean values of conifer species (*Pseudotsuga menziesii* and *Pinus sylvestris*) were found relatively lower than deciduous species (*Quercus petraea*, *Quercus cerris* and *Prunus avium*) except for last group of months where *Pseudotsuga menziesii* had slightly higher mean values of sap flow density than deciduous species and almost 3 times than *P. sylvestris* which showed the lowest in total duration. In the previous studies, it is evident that for both seasonal and diurnal periods, variations in water content within the tree can cause differences between inflow (change in soil water reserve) and sap flow in the bole (Schulze et al. 1985, Granier 1987).

	AMJ				JAS				OND			
TT+ id	Mean	std	min	max	Mean	std	min	max	Mean	std	min	max
<i>Q. petraea</i>	17	13.2	2.5	95.6	13.5	6.8	3.7	49.6	16.1	10.4	7.3	60.3
<i>Q. cerris</i>	13.5	6.7	2.2	61.7	6.8	3	2	18.3	8.3	5.1	2.2	34.8
<i>P. avium</i>	13.8	5.9	3	42.6	20	5	4.8	43.9	8.5	5.1	1.9	31.9
<i>P. menziesii</i>	8.4	4.7	2.5	30.1	8.2	3.3	2	20.8	9	7.8	2.4	40.5
<i>P. sylvestris</i>	4	0.9	2.5	6.6	3.1	0.9	0.9	7.7	3.4	1.5	1.2	9.7

Table. 1: Descriptive statistics of sap flow density ($\text{gcm}^{-2}\text{h}^{-1}$) for each tree species in a 3 months group in 2019 (AMJ=April, May, June) (JAS=June, July, August) (OND= October, November, December).

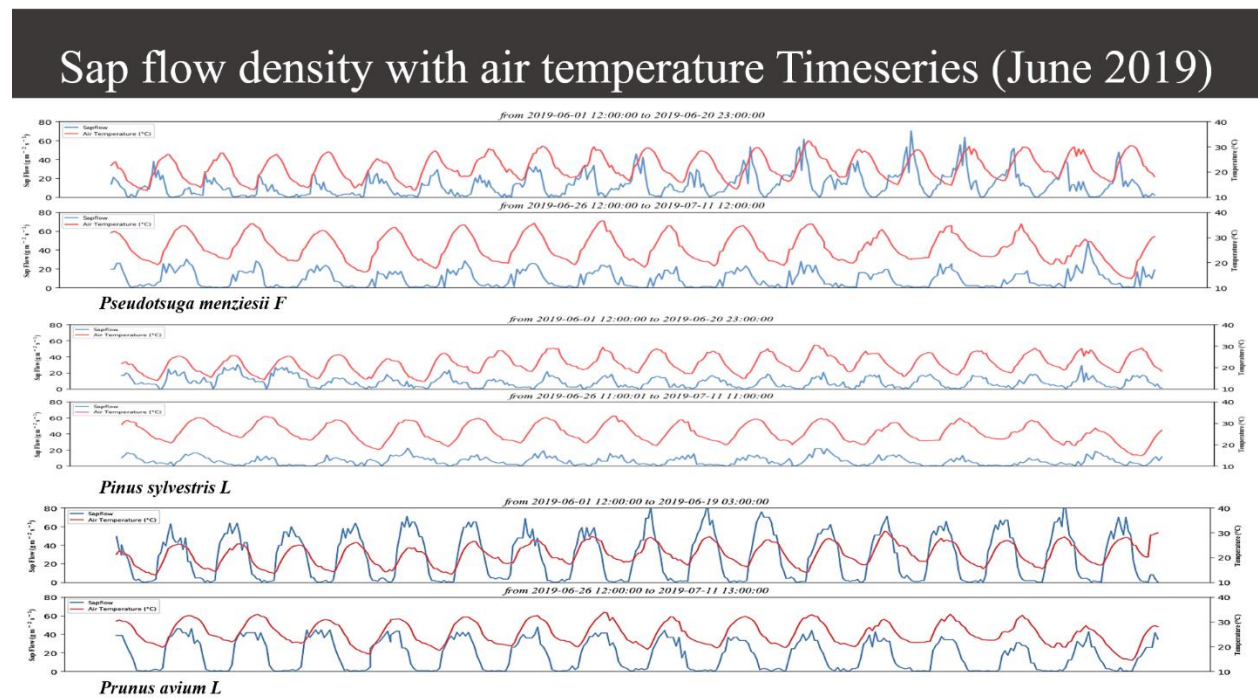


Fig. 9: Sap flow density (Blue line) with air temperature (Red line) timeline during June 2019.

The available water volume in the bole is also species specific. Which can lead to this difference of sap flow density.). The time series (Fig. 9) during June 2019 showed some hourly sap flow density values that were prominent in both evergreen species. Furthermore, another aspect that has direct impact on sap flow density is the diameter and height of the species. Diameter growth is the parameter that was under investigation during this study so it will

explained with details in the later chapters. In simple terms, mean diameter values of douglas fir was 0.42 meters whereas scot pine had the mean diameter of 0.36 meters. This is not a very significant difference but coupled with height difference which was 19 meters in douglas fir and 15.6 meters in scot pine. Taking into consideration both factors, which also reflect the canopy volume (that was measured with drip line method) which was also showing the same trend it is plausible that these factors are the reason for the slight increase in sap flow density not to mention the fact that position of scot pine was more congested and TxT distance was very low as compared to douglas fir. Which means there is more competition going on in terms of nutrient, water and sunlight availability (Barbour and Whitehead 2003, Fernandez and Gyenge 2009, Mitchell et al., 2012, Kallarackal et al. 2013). Site-wise distribution of sap flow density during summer period is shown in Fig. 10. Describing the site specific relative difference for each month starting from March-April to July 2019.

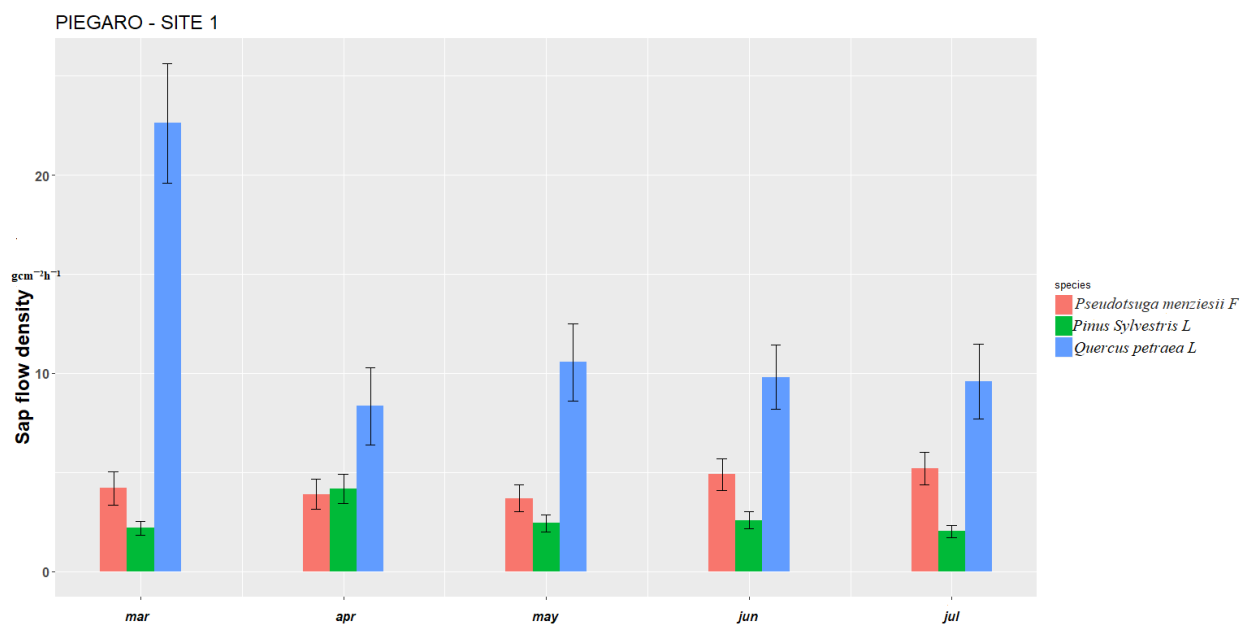


Fig. 10: Bar graph showing sap flow density (with S.E) for single month of each species located in site 1.

During start of March, due to high precipitation, *Quercus petraea* being a large oak species with capability to store water and accumulate high nutrient intake has the ability to start growing rapidly which was also evident in radial growth monitoring data that was collected. Sap flow density in Dendroclimatic studies show the relationships between climatic data and standardised

tree-ring width indices (Fritts, 1976). They highlight the growth sensitivity of each species to monthly temperatures and precipitation. Additional physiological indices, such as related to soil water deficits (Zahner and Stage, 1966), are used rather than climatic data to allow biological interpretations of the growth response to climate. These indices could be better correlated with radial growth than monthly climatic variables (Foster and Leblanc, 1993) because soil water availability is a major limiting factor for tree growth.

Trees growing on sites with a low available water capacity could be more sensitive to climatic variations compared to trees growing on other sites (Lebourgeois *et al.*, 2005). It should be noted in the bar chart below that the plantation site 2 where installation was done in April (hence missing March) was completely dominated by the deciduous species and not conifer trees or canopy shading was observed. The ground was much balanced and shrubs were much in number as compared to site 1 where light barely passed through the dense canopy of conifer trees such as douglas fir and scot pine. Number of trees per 100 m² in site 1 was 13 where as in site 2 it was 8. Another factor for very high value is number of trees. In site 1 only 1 deciduous tree (*Quercus petraea*) was present whereas in site 2, number of oak trees was 5. In other words high fluctuation in different samples can lead to lower stable measurements as compared to one high value.

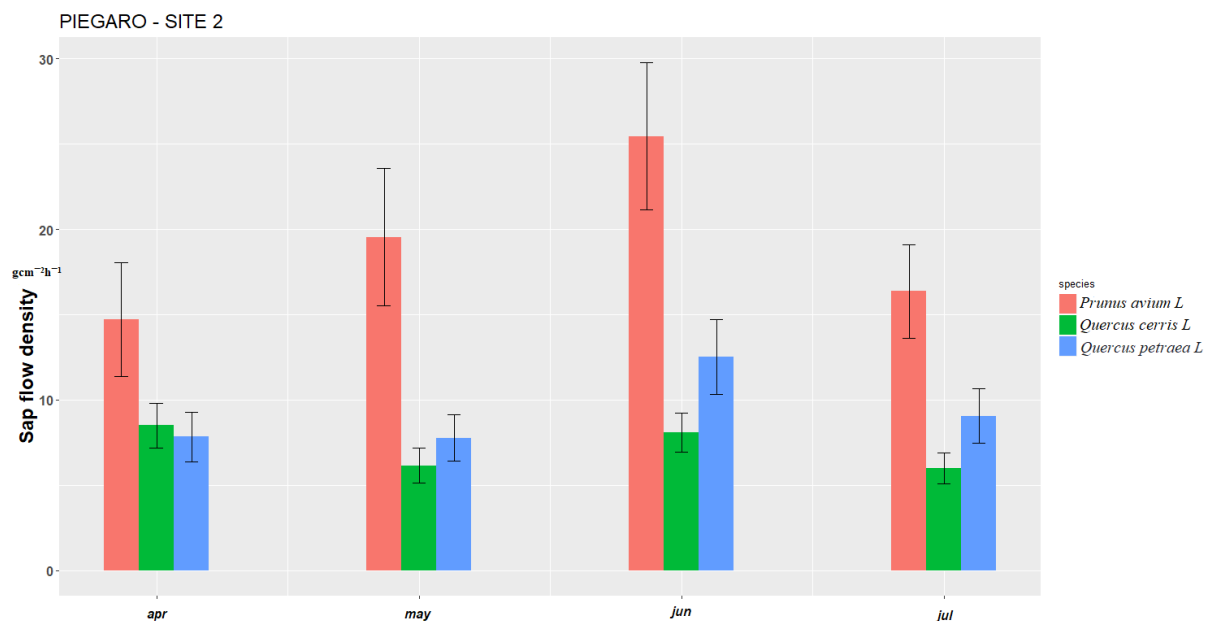


Fig. 11: Bar graph showing sap flow density (with S.E) for single month of each species located in site 2.

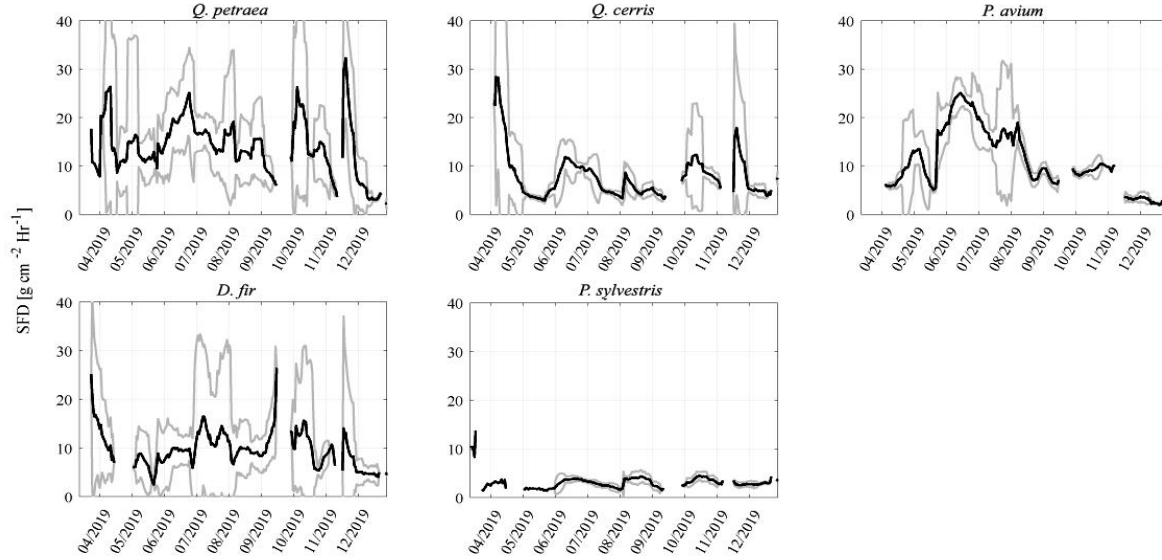


Fig. 12: Sap flow density fluctuation in each month (grey line showing standard deviation).

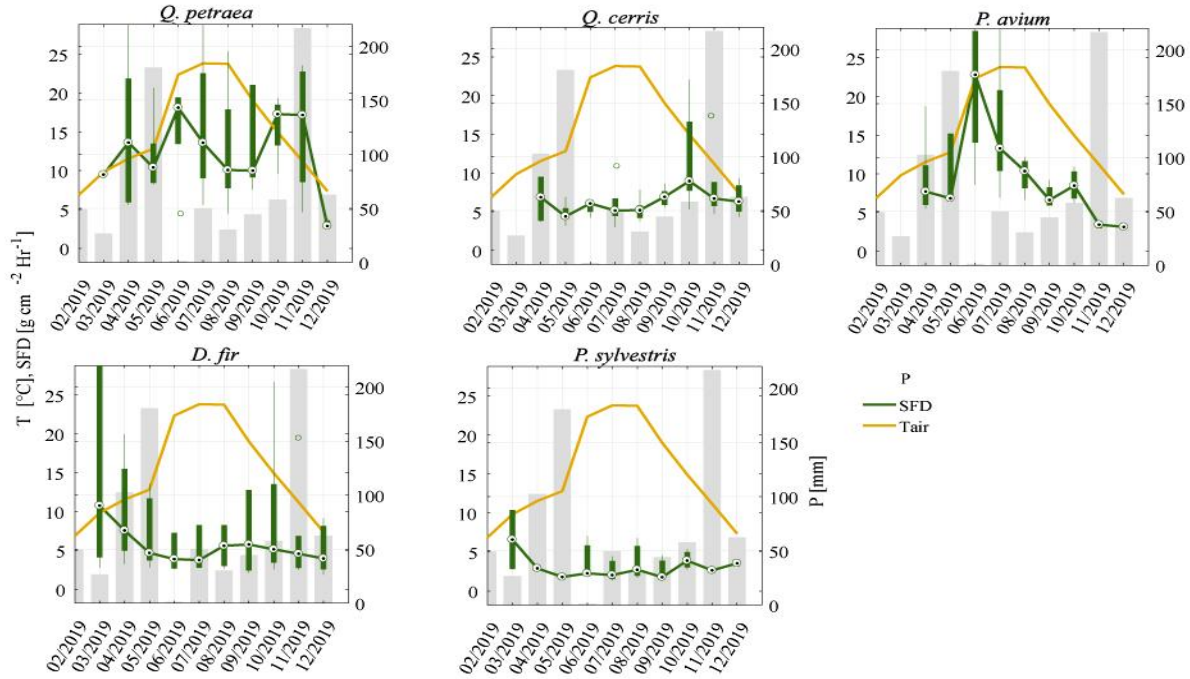


Fig. 13: Monthly statistics for SFD for single group. In each box, the dotted circle is the SFD median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{IQR}$). The yellow line represents the monthly average air temperature, the grey bars represent the total monthly precipitation.

In Fig.13, it is shown clearly the precipitation and temperature had clear impact on sap flow density of both deciduous species as well as evergreen species. Overall in both deciduous and evergreen species, it was observed that sap flow density was increased when rain fall was moderate of even low but monthly mean temperature was increasing however increase in rain fall and decrease in monthly mean temperature did not have any affect. Notably *Quercus petraea* responded well with precipitation prevalence as described previously. As a major driving element of the structure and function of arid and semiarid ecosystems, rainfall is the essential factor limiting plant biological processes (Cao, Jiang, Zhang, Zhang, & Han, 2011; Moran et al., 2009). Furthermore, global climate change appears to increase the variability of rainfall patterns in these regions. As a result, plants may endure recurring cycles of water scarcity followed by rainfall events (Jackson et al., 2001; Smith & Nowak, 1990). Understanding the mechanisms that underlie plant responses to rainfall is a key to understand how global climate change will affect arid and semiarid ecosystems (Jiang, 2001; Yuan & Deng, 2004).

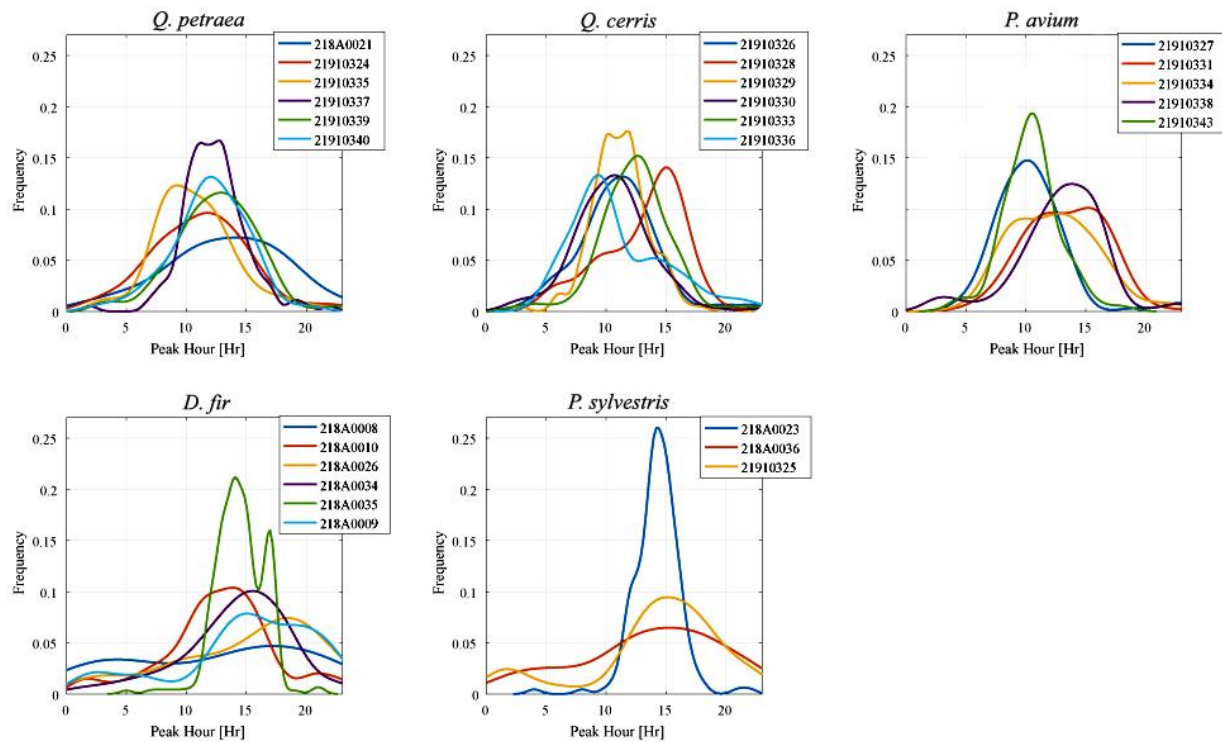


Fig. 14: Probability density functions of peak hours for single group. The peak hour represent the hour over the 24h where the SFD reached its maximum daily value.

Figure 14 shows the probability density functions (PDF) of sap flow density peak hours, namely the hour of the day at which the sap flow density reaches its maximum value. Overall, species with maximum sap flow at a later time of the day have a higher growth rate, as the stomatal openings occurs for longer period of time hence increase the amount of carbon uptake by the plant per day. This also support the results illustrated in previous figures stating that species such as *Prunus avium* L and *Quercus petraea* had prolonged duration of sap flow density in terms of hours. The curves belonging to above mentioned species of deciduous trees had gradual decrease in hours whereas *Quercus cerris* had relatively rapid decrease. In conifer species. Douglas fir showed the same behaviour as compared to scot pine having longer duration of high values where sap flow was maximum. In general perspective, analysed data on peak hours suggested that some trees, mostly belonging to the deciduous species, reached the maximum daily SFD around 11-12 am, while evergreens reach maximum SFD later on approximately at 3 pm suggesting a higher carbon uptake and, thus, a higher photosynthetic rate. *Prunus avium* showed an intermediate behavior. Nocturnal sap flow density is the night-time movement of fluid within the sapwood of a plant's root, stem or branch. Nocturnal sap flow density has largely been regarded as insignificant and most sap flow research has not unreasonably focused on day-time patterns. Moreover, in earlier research experiments conducted in different regions it was believed that nocturnal sap flow density should be equal to zero.

Thus, all sap flow density values were 'corrected' for zero sap flow density, which led to the underestimation of total flow (Daley and Phillips 2006). Increasingly, there has been a greater awareness that nocturnal sap flow can in fact have a significant contribution to total daily sap flow (Dawson et al. 2007, Pfautsch et al. 2011). To date, most research has been on demonstrating that Qn does indeed occur, yet it is still not widely understood how significant nocturnal sap flow density is as a proportion of total daily sap flow density. Looking at the analysed values for peak hours it was noted that evergreen species such as douglas fir and prunus avium showed consistent nocturnal sap flow as compared to deciduous species which is found in similar studies conducted (Forster, 2014).

Sap flow is a direct indicator of tree transpiration, and it can reflect the physiological characteristics and water use response of individual trees to environmental factors (Wang & Wang, 2012). Some studies have shown that sap flow significantly accelerates after trees absorb

water provided by rainfall events (Schwinning & Sala, 2004), but this influence may be related to multiple factors, such as tree species (Cheng et al., 2006) and rainfall amount (Ivans, Hipps, Leffler, & Ivans, 2006). For example, some shallow-rooted species rapidly increased transpiration up to fivefold after a 34 mm rain event, whereas deep-rooted species such as *Eucalyptus* species are sufficiently reliant on antecedent soil water and do not respond to summer rainfall (Burgess, 2006). Zeppel, Macinnis-Ng, Ford, and Eamus (2008) found that rainfall pulses of <20 mm did not significantly increase water use of *Eucalyptus callitris*.

In contrast, a rainfall threshold of 10 mm induced a significant response in mesquite shrubs (Fravolini et al., 2005). Pataki, Oren, and Smith (2000) indicated that broad-leaf species showed the greatest increases in sap flow density with increasing atmospheric water demand, while the coniferous species *Pinus contorta* showed the lowest density which was also the case in the data shown above. The stomatal regulation of transpiration and the hydraulic structure of plants may account for their different behavior in response to changes in water conditions (Franks, Drake, & Froend, 2007; Hölscher, Koch, Korn, & Leuschner, 2005).

5.2 FOLIAR LIGHT TRANSMISSION

The radiometer installed on the Tree Talkers has 12 selective-narrow bands for light detecting at 450+, 500+, 570+, 600+, 610*, 650+, 680*, 730*, 760*, 810*, 860* nm ((+) $\pm$ 10nm+; (*) $\pm$ 20nm),

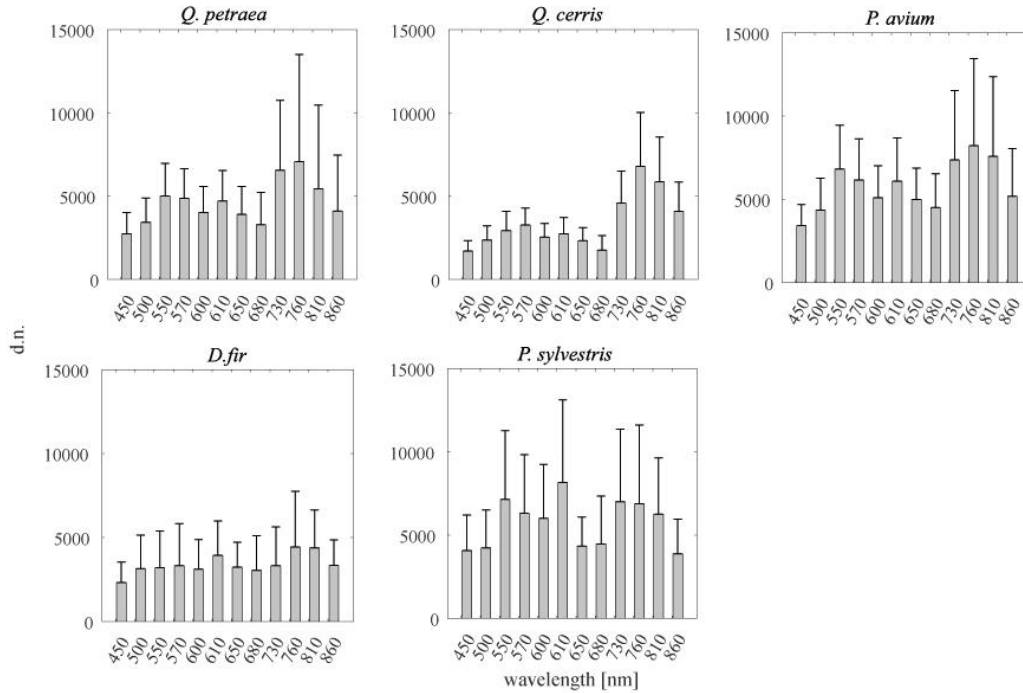


Fig. 15: Spectral profile for single groups obtained from the average score of raw data, ensemble median. Error bars = interquartile range (IQR).

Figure 15 shows the average score of raw data from single spectral wavebands (ensemble median, error bars as interquartile) for single groups.

Data are consistent with the typical vegetation reflectance curve (Bowker et al., 1985) showing the largest incident light intensity in the IR, mainly due to high reflectance and transmittance from leaves, followed by the green waveband, i.e. 500nm (Lillesand et al., 2015).

Lower incident light intensity occur at 450 and 660nm, namely in the blue and red band waves, as expected to be due to chlorophylls absorptions. In the current study, two Transmitted Normalized Difference Vegetation Indices obtained from pairwise combination of

$$\left(\frac{\text{NIR}-\text{RED}}{\text{NIR}+\text{RED}} \right)$$

The conventional method (hereinafter NDVI),

$$\left(\frac{\text{NIR}-\text{GREEN}}{\text{NIR}+\text{GREEN}} \right)$$

green NDVI (hereinafter GNDVI)

are presented. Since data collected by the radiometer are raw digital numbers, i.e. without any transformation into absolute units, atmospheric corrections and/or sensor calibration, normalized vegetation indices are generally appreciated as the normalization makes some of these corrections unnecessary. Moreover, the results are also unaffected by the solar zenith allowing the comparison of data from different times of day, season and latitudes (Banari et al., 1995; Ryu et al., 2010). The most widely investigated NDVI uses the couple of NIR (841-876nm) and RED (620-670nm) spectral bands collected from satellite (Huete et al., 2002).

The NDVI so far obtained allows discerning vegetation with low density (0.1 to 0.3), vegetation with relatively high density (0.6 to 0.8) and bare soils (-0.1 and below) (source: <https://earthobservatory.nasa.gov/features/MeasuringVegetation>). In the experiment new concept that is still under review consisting of transmitted NDVI method is used which is not done before. In this method the transmittance and total radiation data was used from the IoT system where as reflectance data was obtained through area land cover mapping technique. Since there exist some overestimation because of using two different datasets obtained from two very different systems but main aim was to find out if this shows at least cross seasonal increase and decrease observed through conventional method (remote sensing through satellite).

The GNDVI estimated with NIR (730-830nm) and GREEN(~550nm) wavebands proved to be correlated with Leaf Area Index (LAI) and canopy photosynthesis rate (Ryu et al., 2010). In the following, NDVI and GNDVI are estimated on daily time scale averaging the daily scores at the peak hours (i.e. from 11am to 3pm). Figure 9 and 10 show the descriptive statistics for NDVI and GNDVI for single TT+, respectively, grouped per species. The average NDVI (ensemble medians) ranges between 0.30 and 0.42 in deciduous species and between 0.26 to 0.3 for evergreens. Average GNDVI (ensemble medians) ranges between 0.18 and 0.21 in deciduous species and from 0.15 to 0.32 for evergreens, with large variability among TT+.

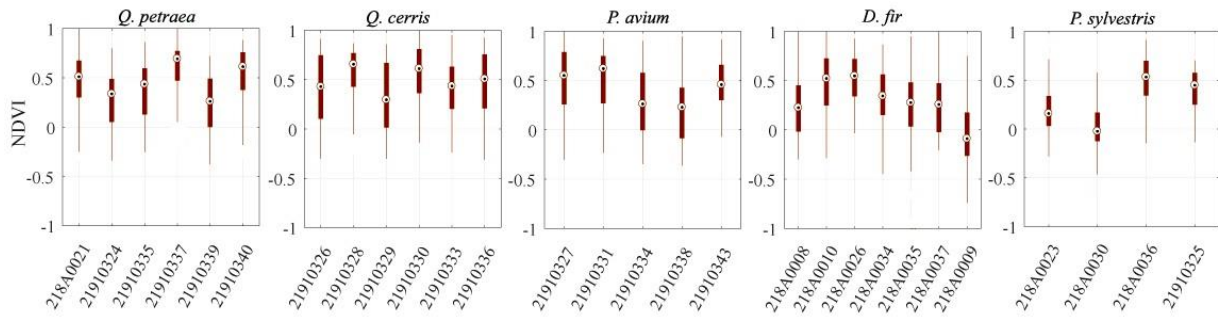


Fig. 16: Synthetic boxplot of daily NDVI for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles.

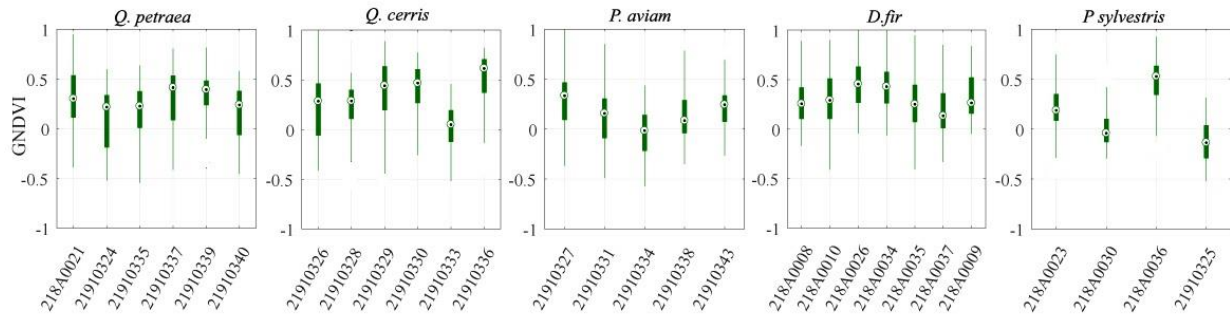


Fig. 17: Synthetic boxplot of daily GNDVI for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles.

There is a large intra-variability among both NDVI and GNDVI that might be explained by the seasonal phenology of the plant. By contrast, the large inter-variability, even across single groups, might be explained by both specific trees difference (e.g. the density of the crown, the health of the plant etc.) and the position of the sensors with respect to the crown.

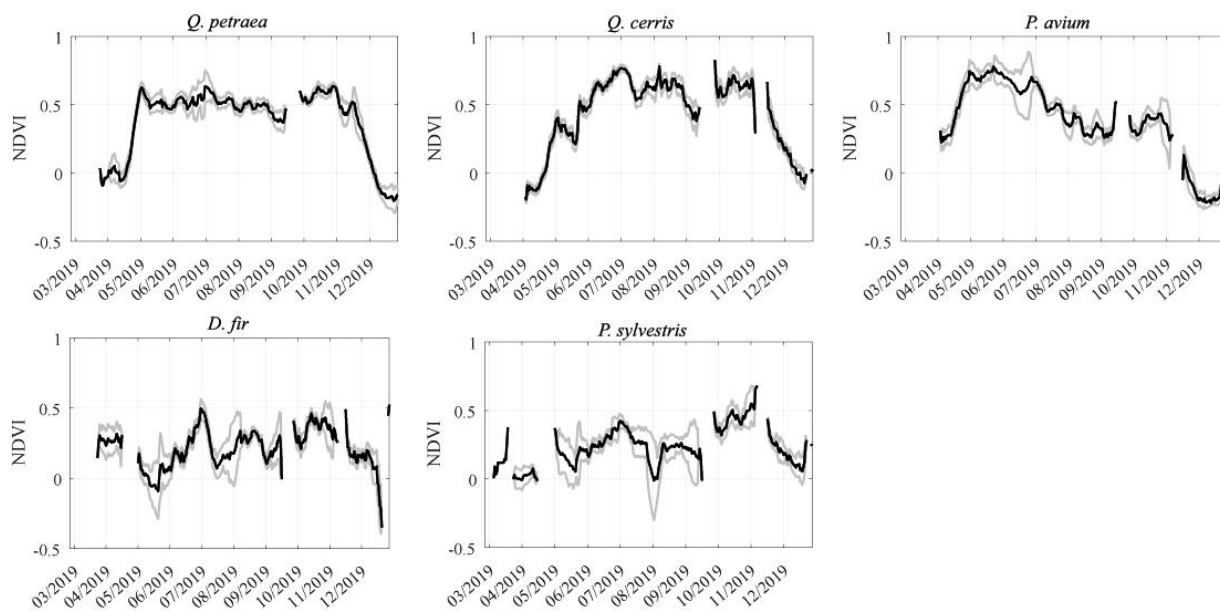


Fig. 18: Daily NDVI time series. Black line: smoothed ensemble median (average on 10 days moving window). grey line: standard deviation.

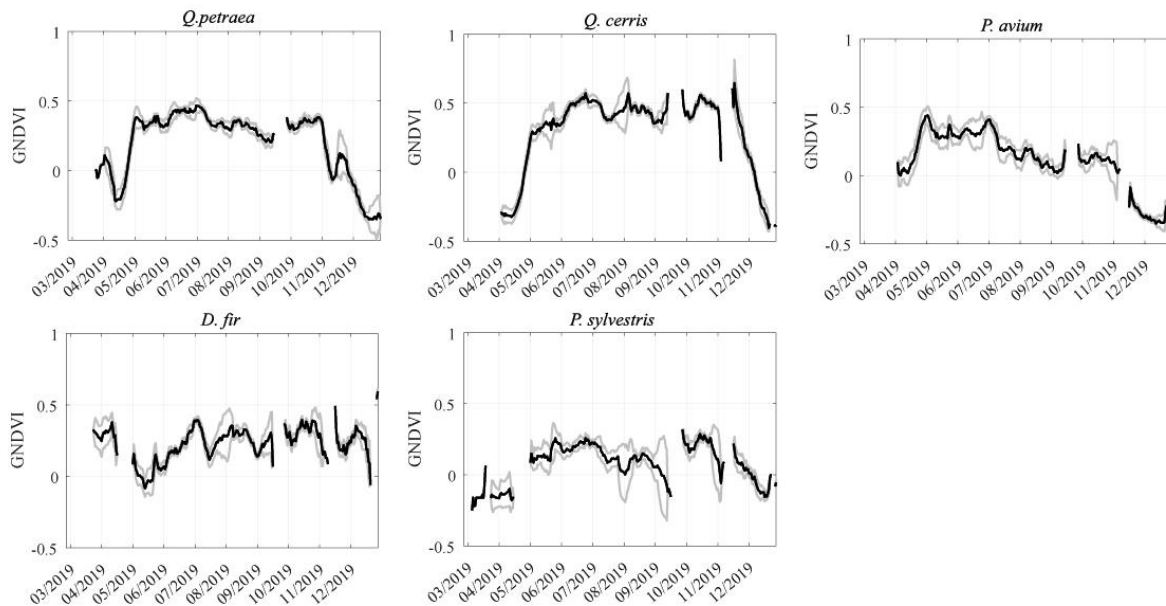


Fig. 19: Daily GNDVI time series. Black line: smoothed ensemble median (average on 10 days moving window). grey line: standard deviation.

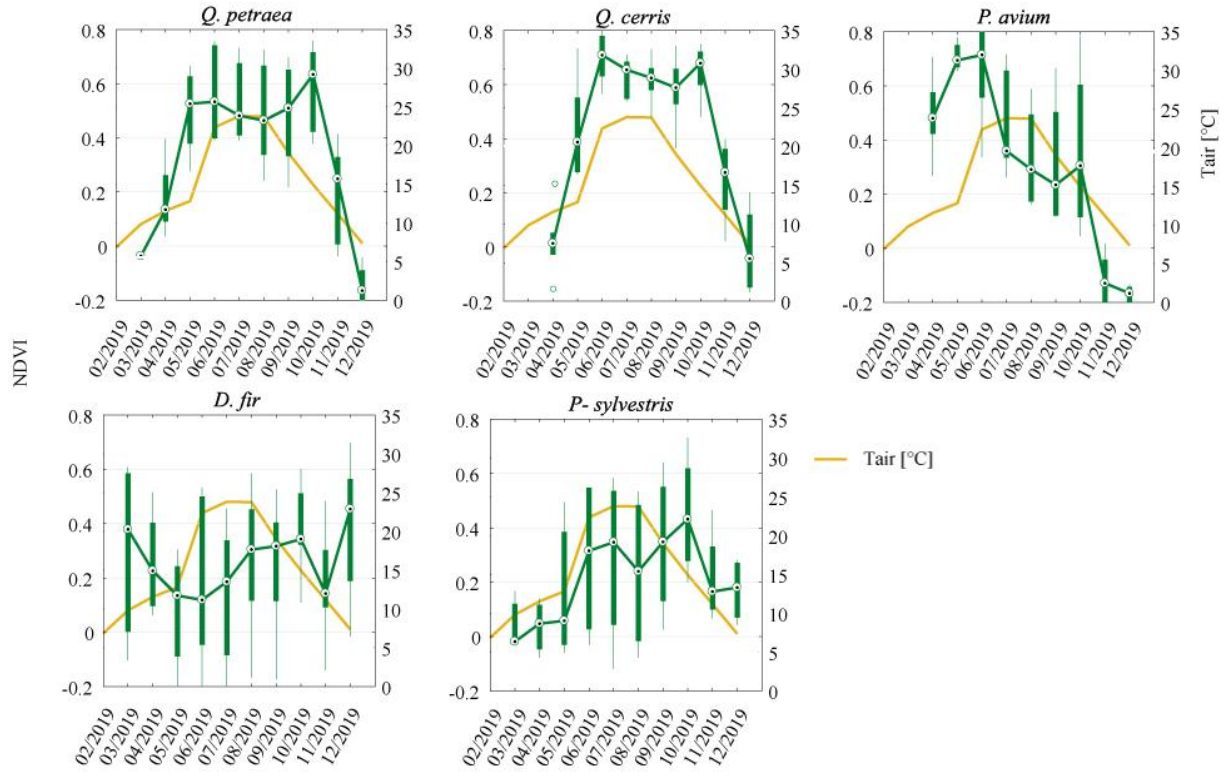


Fig. 20: Monthly NDVI statistics for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{IQR}$).

The yellow line represents the monthly average air temperature (to keep in check if certain degree of temperature has any noising effect on the spectrometer). Figure 18 and 19 shows the NDVI and GNDVI time series, ensemble median for single groups. NDVI in deciduous species allows detecting the onset of the vegetative growth in April, as the index rapidly increases from values close to zero (when leaves are absent) up to the maximum. The NDVI then decreases again in November. By contrast, evergreens show cyclic raises and decrease around the average. The GNDVI shows an overall similar behavior of the NVID. Figure 20 and 21 show the monthly distributions of NDVI and GNDVI, respectively, for single groups along with air temperature collected by the meteorological station of Piegara. Overall, both the indices they seem to warn of the incoming spring rising temperatures and drop as temperature drops in autumn. Tables 3-6 summarizes the averages seasonal NDVI and GNDVI statistics for single TT+ and for species, respectively.

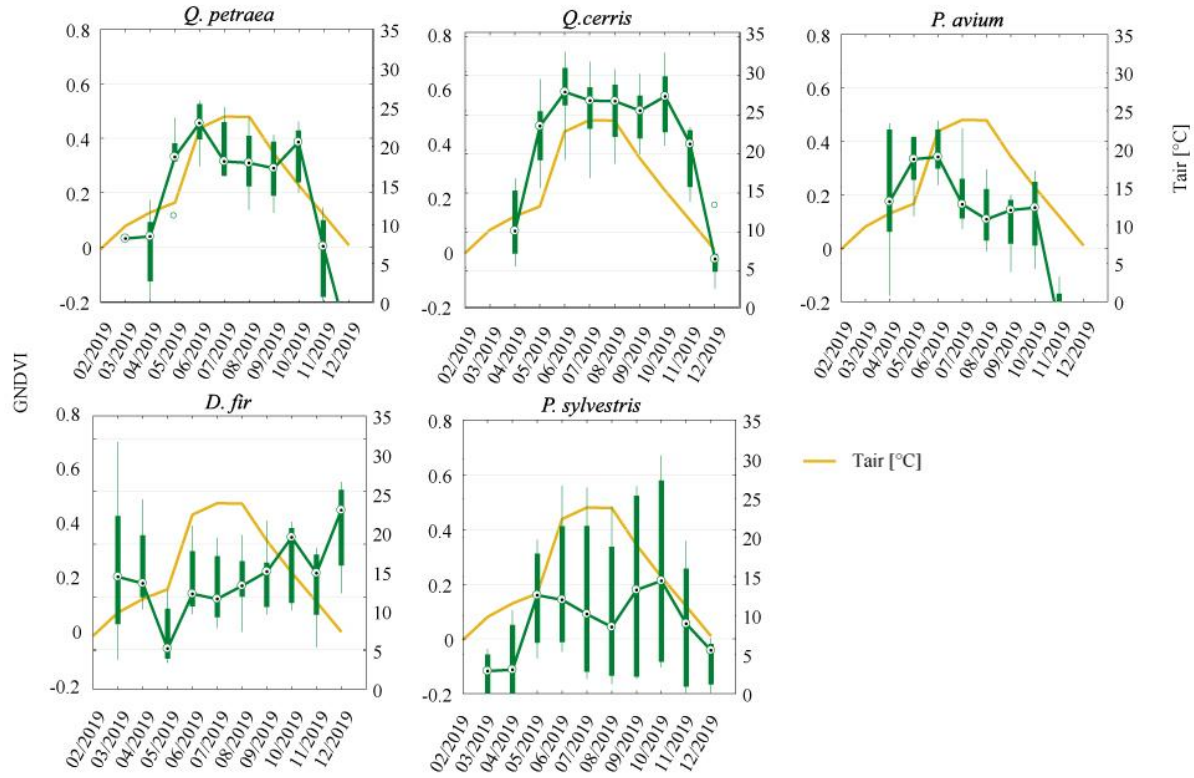


Fig. 21: Monthly GNDVI statistics for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{IQR}$). The yellow line represents the monthly average air temperature (to keep in check if certain degree of temperature has any noising effect on the spectrometer).

Because of using two different datasets, system in use (Tree Talker) showed at least fall decrease in deciduous which was very clear whereas changes in deciduous species did not show clear consistency (Table 2-3). Further tests and techniques are under discussion to develop a different type of device which can be installed at a tower height to record reflectance data which would be very helpful to calculate these indices in a more reliable and consistent manner. Nonetheless, the sensitivity of the spectrometer showed decent results when tested both in lab and field conditions which is an important step to develop and improve the capability of the system in use.

	AMJ		JAS		OND	
TT+ id	Mean	std	Mean	std	Mean	std
<i>Quercus petraea</i>	0.41	0.19	0.5	0.14	0.21	0.15
<i>Quercus cerris</i>	0.39	0.16	0.6	0.18	0.29	0.18
<i>Prunus avium</i>	0.58	0.16	0.41	0.15	0.07	0.14
<i>Pseudotsuga menziesii</i>	0.14	0.2	0.22	0.2	0.31	0.27
<i>Pinus silvestris</i>	0.24	0.13	0.29	0.14	0.28	0.18

Table 2. Seasonal statistics of NDVI for single groups. April, May, June (**AMJ**) - June, July, August (**JAS**)– October, November, December (**OND**)

Considering both NDVI and GNDVI indices, in deciduous species except *Prunus avium*, both *Quercus cerris* and *Quercus petraea* showed decrease with the moving monthly groups of spring but in peak summer it was relatively high and then receded in fall season. Whereas *Prunus avium* showed lower values as the time progressed through spring to summer and then summer to autumn and winter. It should be noted that sap flow values correspond with *Pseudotsuga menziesii* F. as during March to April, the sap flow was observed to be very high which corresponds to high vegetation index reflecting high growth which was also observed in radial growth parameter. This can be seen in both NDVI and GNDVI indices. This as compared to *Pinus sylvestris* L. was very different as it showed stable growth rate which was also the case in NDVI but not in GNDVI where it has almost doubled in summer (Table 2-3).

	AMJ		JAS		OND	
TT+ id	Mean	std	Mean	std	Mean	std
<i>Quercus petraea</i>	0.25	0.16	0.32	0.12	0.04	0.13
<i>Quercus cerris</i>	0.17	0.13	0.38	0.13	0.09	0.16
<i>Prunus avium</i>	0.32	0.17	0.22	0.12	-0.07	0.11
<i>Pseudotsuga menziesii</i>	0.2	0.16	0.26	0.16	0.35	0.22
<i>Pinus silvestris</i>	0.08	0.12	0.15	0.11	0.07	0.13

Table 3. Seasonal statistics of GNDVI for single groups. April, May, June (**AMJ**) - June, July, August (**JAS**)– October, November, December (**OND**)

5.3 XYLEM MOISTURE

Xylem moisture provides information about the internal water storage to water consumption. Overall, xylem moisture is broadly synchronous with precipitation events, decreases in very hot days and increases in relative cold-wet days. Moreover, a negative balance between canopy transpiration and basal sap in the afternoon allows for the stem water recharge before night (Wang et al., 2008).

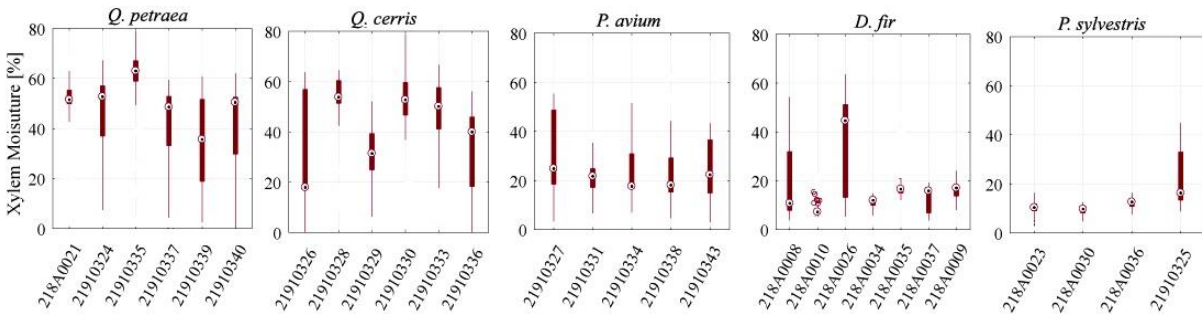


Figure 22a. Synthetic boxplot of daily xylem moisture for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles.

Xylem moisture has a sudden effect on stem diameter size, with a time lag between stem moisture changes and diameter variation that can be of few minutes (Simonneau et al., 1993). As a consequence, stem moisture, radial growth, sap flow and meteorological condition are all strongly related and broadly affecting the whole plant water use. Statistics from individual trees (Fig. 22) shows that the sapwood of deciduous species generally has larger water content than evergreens and are more prone to a wide variability. Looking at the time series (Fig. 22a, 22b), it emerges that with the exception of *Pinus sylvestris*, all the species have constantly increased the sapwood water content during 2019 until reaching values ranging from 3 times *Douglas fir* to 6 times *Quercus cerris* as much in just 9 months.

The ranges are in line with what has been observed in the literature (Sparks et al., 2001). This evidence could be explained by two factors: in summer most of the plants control the opening of the stomata and reduce perspiration despite the high VPD allowing the plant to preserve some water reserves and/or recharge them during the nights and a moderate yet constant precipitation in the summer has helped to preserve water reserves during the hottest time of the year.

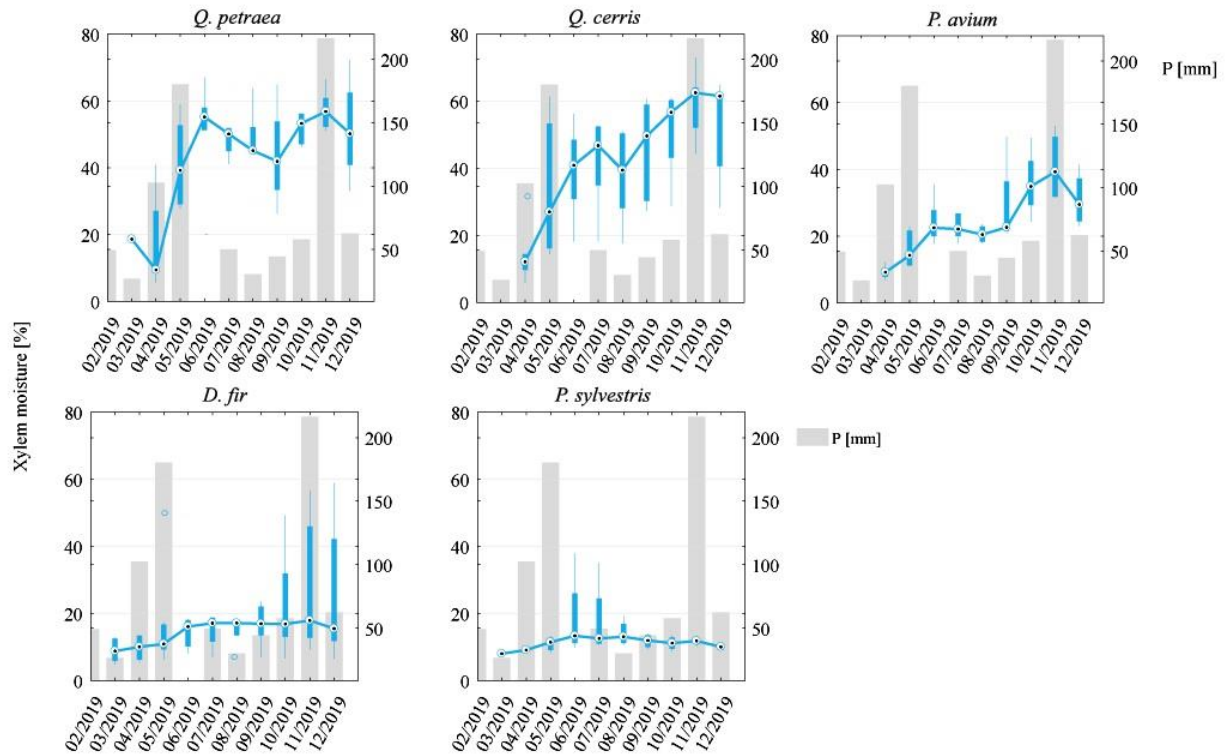


Figure 22b. Monthly xylem moisture statistics for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{IQR}$).

	Apr-May-Jun				Jul-Aug-Sep				Oct-Nov-Dec			
TT+ id	Mean	std	min	max	Mean	std	min	max	Mean	std	min	max
<i>Q. petraea</i>	36.3	8.8	3.7	64.2	46.9	6.6	31.1	61.1	55.3	4.2	39	63.5
<i>Q. cerris</i>	30.5	8.2	2.8	50.8	43.6	3.3	28.5	54	56.5	2.8	47.3	65.5
<i>P. avium</i>	17.3	3.9	3.2	35.2	27.4	4.4	18	43.7	37.7	5.1	22	48.7
<i>P. menziesii</i>	14.9	1.9	8.3	23.5	19.2	1.7	15.6	25.9	24.7	1.9	18.2	33
<i>P. sylvestris</i>	17.5	1.8	14.1	22.3	14.5	1.1	11.1	20.6	11	0.8	7.9	13.3

Table 4. Seasonal statistics of xylem moisture for single groups

Xylem moisture observed in both evergreen and deciduous species showed increasing pattern throughout the period except scot pine, reflecting the sufficient water transport. High mean values can also be because of high rainfall in late October and November during the period (also

shown earlier in the graphs). However mean values of both oak species had almost double the values than that of evergreen species showing higher water intake and water use during the period. *P. sylvestris* had a little decrease in later part of the period (October to December). This can be because of higher adjoining plants competition or lower availability of water in the soil (Barbour and Whitehead 2003, Fernandez and Gyenge 2009, Mitchell et al., 2012, Kallarackal et al. 2013). Looking at the data in specific periods it was observed that there was a clear drop in xylem moisture during peak summer (August) in broadleaf species as compared to deciduous (conifers) clearly indicating that conifers particularly in summer (August) are more conservative in terms of xylem moisture.

5.4 RADIAL GROWTH

Radial growth is a measure of the trunk diametric increase and it is regarded as a proxy of plant productivity, plant stress and carbon sequestration (Burgess et al., 2008). The results here shown represent the changes in radial growth with respect to the first 48 measurements (i.e. two days).

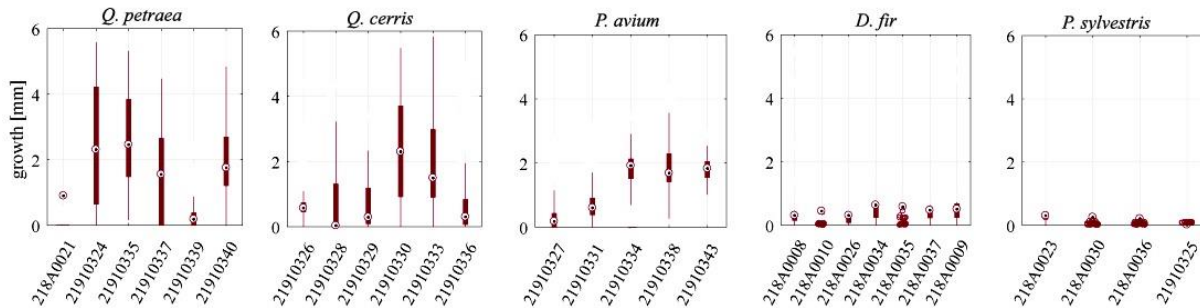


Figure 23. Synthetic boxplot of daily radial growth for single trees. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{Interquartile Range}$, IQR).

Due to temperature sensitivity of the sensor that measured the radial growth, it was necessary to use the data for moving averages and calculate relative radial growth which was more explanatory than simple timeseries which showed some gaps and hence creating some minor redundancies in the results.

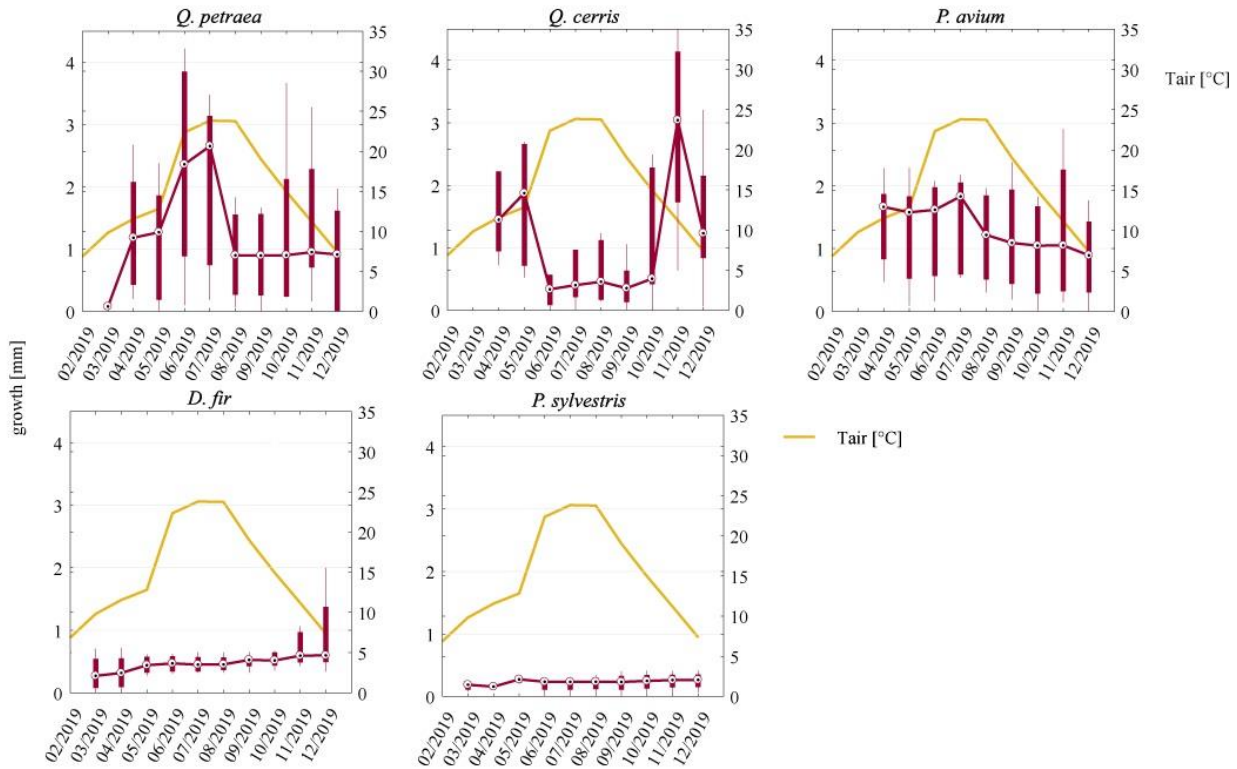


Figure 24. Monthly radial growth statistics for single groups. In each box, the dotted circle is the median, the edges of the box are the 25th and 75th percentiles and empty circles are outliers (i.e. data larger than $1.5 \times \text{IQR}$).

The yellow line represents the monthly average air temperature since sensor showed sensitivity to the temperature so it was used as noise detector in the obtained data in this parameter as well. Overall, all the trees show a positive increase in radial diameter (Fig. 23-24) that is apparently more pronounced in deciduous species (up to 4mm over the timeline) than in evergreens species.

However, the sampled species have different heights (average of 9m and 17m for deciduous and evergreens, respectively) and circumference (averages of 0.70m and 1.3m for deciduous and evergreens, respectively).

Hence, to compare the results between trees, the values of radial growth are scaled with respect to the tree radius to obtain a relative growth rate (RGR) over the whole timeline (Table. 5).

	AMJ		JAS		OND	
TT+ id	Mean	std	Mean	std	Mean	std
<i>Quercus petraea</i>	1.56	0.51	1.26	0.37	1.29	0.64
<i>Quercus cerris</i>	1.49	0.57	0.68	0.33	1.73	0.93
<i>Prunus avium</i>	1.2	0.51	1.19	0.27	1.24	0.79
<i>Pseudotsuga menziesii</i>	0.41	0.04	0.45	0.03	0.68	0.31
<i>Pinus sylvestris</i>	0.17	0.02	0.2	0.01	0.24	0.02

Table 5. Seasonal statistics of radial growth for single groups. April, May, June (**AMJ**) - June, July, August (**JAS**)– October, November, December (**OND**)

In deciduous species, relative growth rate was observed to be following a cyclic pattern however in evergreen species it was constantly increasing. Showing a spring onset, decline in summer period and then regrowth period in fall period. While onset of radial growth in April through early May is considerably preceded by onset of shoot growth in *Pinus sylvestris* but it can occur quite simultaneously with onset of shoot growth in other conifer species e.g. *Picea abies*. Phenological observations of conifers exposed to drought show that the tree water status early during the growing season determines total annual aboveground growth and besides temperature, species-specific endogenous and/or environmental factors (most likely photoperiod or different threshold temperatures) are involved in controlling apical and lateral growth resumption after winter dormancy which can cause slow but stable radial growth (Swidrak, Schuster and Oberhuber, 2013).

The duration of growth also defines the period where damage from extreme weather events like late or early frost, drought or heat waves may occur (Cannell and Smith, 1986). Tree phenology and radial growth is also responsive to rainfall and water availability that was reported for Mediterranean regions and tropical dry forests (e.g., Bernal et al., 2011, Borchert, 1994) and the data collected from deciduous species corresponded very closely to water availability during the rainfall which lead to high values of relative growth in November where monthly rainfall was maximum during the whole year. *Quercus cerris* showed very low rate of growth which can be attributed to pathogenic infestation during high rain fall and increased moisture.

6. CONCLUSIONS

IoT system used (Tree Talkers) in the conducted experiment was a compact tool designed specifically for collective monitoring of different parameters in a forest or a plantation. It provided commulative profile of different deciduous and evergreen species consisting of sap flux density, xylem moisture, foliar transmitted light components and radial growth. These parameters are integral part of constructing a physiological pool of different plant species. Furthermore, transmitted NDVI and green NDVI provided a clear picture of canopy changes, vegetation health and overall situation of forest part which is very helpful in terms of monitoring forest health. With the help of the cloud based data feed, it was possible to visualise the real time data of different plant species in order to know better at a certain point of time if a tree has suffered from a severe attack from pests or certain environmental conditions lead to the mortality of a tree. As sap flux density plays a key role in evaluating plant transpiration and understanding the soil-plant atmosphere system. The probes and sensors (heating probe and non-heating probe) used in the devices provide continuous data and are reliable in different climates and regions which is necessary for obtain absolute and accurate sap flux density measurements. The cloud-based system is used in order to back up the data in each device, the cloud and the server itself where it is sent by GPRS system. The new techniques to monitor big forests are very helpful to study the vegetation at long term basis since these IoT devices work as automated devices. In terms of health of a vegetation present at a certain area, NDVI is often used to investigate the canopy richness or vegetation quality based on crown and light interaction in dense forests and rangelands and it is a good parameter to determine the health of a forest with respect to its leaf density presence and overall canopy thickness. It is also used for drought monitoring and famine early warning (Javadnia, Mobasheri and Kamali, 2009). Obtained data and analysed results indicate that in 2019 during the decline in the mid-summer to late autumn period (deciduous species) which is embracing the conventional understanding of the index. Evergreen species had somewhat consistent mean values because of lack of leaf shedding phenomenon in autumn and winter (Agenagew et al., 2019). Green NDVI is more focused on chlorophyll activity and is widely used as parameter to determine the vigour and chlorophyll absorption of light. In the study conducted the Green NDVI observed showed a clear decline in fall season indicating the abscission onset

(deciduous species) (Shahrokhnia et al., 2019). The system installation showed consistent results of light sensitivity and since the ground NDVI had similar pattern as normal NDVI, so it is investigated consistently so to have a diverse picture overall of the vegetation. Xylem moisture data showed that the mean values were high in period of high precipitation but only in deciduous species and this was inverse in evergreen species which was also the case found in studies (Hasselquist, Allen and Santiago, 2010). Tree radial growth is a measure of the trunk diametric increase and it is regarded as a proxy of plant productivity, plant stress and carbon sequestration. With the help of Sharp sensor, it was possible to measure continuous radial growth of different species from April 2019 to December 2019. Since among different tree species belonging to both deciduous and evergreen groups that were monitored had different age, diameter and height so it was deemed better to check the relative growth rate across different monthly groups which showed a better picture indicating the linear as well as cyclic growth pattern in both group of species. Deciduous trees showed cyclic relative growth pattern but evergreen species showed moderate yet constant increase throughout the period. During April, May and June of 2019, deciduous species had increased relative growth pattern but during July, August and September it was relatively less but increased again in October, November and December. This observation can be attributed to precipitation which was persistent in first three months which was followed by a minute drought period with scarce rain. As precipitation frequency increased at the end of the year, relative radial growth was also increased. Overall the IoT system showed promising results given the conditions and shortcomings such as regular battery substitution which lead some minor gaps of some days but sensors used were consistent during overall period of the study (2019) which is an important step towards further improvements and capability enhancement of any remote system to be used in urban as well as wild area such as forests, protected areas where access is always limited.

7. FUTURE PERSPECTIVES AND RECOMMENDATIONS

There has been a rapid growth and prevalence of smart forestry consisting of similar IoT systems that were used in the current study which has a great impact on different concepts of forest monitoring. This can be said about drought stress monitoring systems, biotic hazard warning systems, meteorological and climatic prediction models, forest mensuration and wood industrial applications, urban and peri-urban plant protection systems and so on. The major component of any experiment or case study related to these systems is access to the area which is not a problem if smart tools such as tree talkers or any other IoT systems are already in place. Secondly, the consistency of any forest technician or scientist may leave some error at some point which can have a deep impact on the data but with the help of smart tools even the errors are consistent and now we are able to even program the devices in case the data or readings are not right which helps us later to pin point the problems in the data. Parameters studied in the study were some core mechanisms that help profile and understand certain behaviour of any tree species in question at any given time. Although there are many variations of the devices now available that are more focused on selective parameters. For example, in urban areas there is a common problem of tree felling that endangers both humans and native wildlife. Tree talker gravity (TTG) is a compact device with sole purpose of continuous angular movements of the tree. With the help of wind speed data and meteorological observations it is predictable whether a tree is losing its normal erection and is about crossing the threshold angular movement limit hence alarming humans to take some actions. Another variation is tree talker soil (TTS) which measures soil parameters such as humidity, nutrients concentration, pH, soil respiration (both aerobic and anaerobic).

Sap flow is one of the very important component in profiling any tree species. Based on the performance, viability and consistency of the IoT system used. This can be an important tool for measuring a large area of forest under attack from insect pests or microbes. In Italy, parco monte san biagio and monte ausoni (located in rome) there has been a recent jump in decline of ever green oak (*Quercus ilex*) by *Phytophthora cinnamomic*. It can be very useful to continuously analyse how the trees respond to these infestations showing detailed resistance and resilience patterns which can later provide the physiological profiles of the trees.

Radial growth combined with xylem moisture and foliar decline across different seasons can provide some good model data which can translate the concepts and answer some questions that are very important for science e.g.

- What is the tipping point of a certain tree species for certain stress type e.g. drought in arid areas or salinity in coastal areas ?
- How sap flow and other parameters show some compensation stimulated by the tree when above mentioned stresses are induced ?
- Is there any evidence of shoot competition within a tree if a certain part or major shoot of the tree is damaged, infested or injured ?
- Is there any evidence of plant forming bark fissures as defensive mechanism providing housing for small wild animals against insects pests ?

In industrial sector the wood quality and need of certain integrated management practices can also be assured by using smart IoT systems such as tree talkers. Trends of seasonal wood growth and incremental production of wood can help forest land owners and companies to change modify or continue the protection measures against invading species, transforming marginal lands into productive investments in eco-friendly industries such as horticulture, agronomy, floriculture and tree plantations. In a broader sense the system can also be used to monitor short trials of introducing and/or reintroducing tree species in different areas for the purpose of reforestation ,afforestation conservation of habitat for wild flora and fauna. Currently many modifications are being made in tree talkers to make it more consistent in extreme weather conditions to prepare for the goal of large scale web monitoring systems which is already in place across many continents including Asia and Europe. Sensors are also being modified and devices are being made longer lasting with the help of powerful but cost effective battery source. As the smart IoT used in the current study is improving and growing there is a lot of work being done on software side e.g. real time analysed assays, models and warning methods time series growth chronology etc. which is remarkable feat reflecting the future where all this can be seen and accessed with just a click on our smart phone or personal computer.

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9. Appendixes

Appendix. 1a: IoT system Device/identification and installation information (Site 1)

Serial No	Tree Talker ID	Species	Tree Height (m)	Height of TT from ground (m)	Circumference (m)	diameter (m)
1	218A0008	<i>Douglas fir (Pseudotsuga menziesii)</i>	19	1.45	1.15	0.36624204
2	218A0035	<i>Douglas fir (Pseudotsuga menziesii)</i>	21	1.50	1.9	0.60509554
3	218A0021	<i>Quercus petraea</i>	19	1.65	2.27	0.72292994
4	218A0034	<i>Douglas fir (Pseudotsuga menziesii)</i>	19	1.45	1.34	0.42675159
5	218A0026	<i>Douglas fir (Pseudotsuga menziesii)</i>	20	1.50	1.63	0.51910828
6	218A0030	<i>Pinus sylvestris</i>	18	1.50	1.15	0.36624204
7	218A0023	<i>Pinus sylvestris</i>	15	1.60	1.05	0.3343949
8	218A0010	<i>Douglas fir (Pseudotsuga menziesii)</i>	17	1.50	1.35	0.42993631
9	218A0009	<i>Douglas fir (Pseudotsuga menziesii)</i>	19	1.60	0.93	0.29617834
10	218A0024	<i>Douglas fir (Pseudotsuga menziesii)</i>	18	1.54	1.12	0.3566879
11	218A0037	<i>Douglas fir (Pseudotsuga menziesii)</i>	19	1.55	1.19	0.37898089
12	218A0036	<i>Pinus sylvestris</i>	15	1.40	1.29	0.41082803
13	21910325	<i>Pinus sylvestris</i>	14.5	1.40	1.1	0.3503184

Appendix. 1b: IoT system Device/identification and installation information (Site 2)

Serial No	Tree Talker ID	Species	Tree Height (m)	Height of TT from ground (m)	Circumference (m)	diameter (m)
1	21910323	TT Radiation				
2	21910324	<i>Quercus petraea</i>	6.5	1.35 meters	0.36	0.11465
3	21910326	<i>Quercus cerris</i>	8	1.54 meters	0.3	0.095541
4	21910327	<i>Prunus avium</i>	8	1.41 meters	0.74	0.235669
5	21910328	<i>Quercus cerris</i>	8.5	1.40 meters	0.39	0.124204
6	21910329	<i>Quercus cerris</i>	10.5	1.47 meters	0.69	0.219745
7	21910330	<i>Quercus cerris</i>	10	1.43 meters	1.1	0.350318
8	21910331	<i>Prunus avium</i>	8.5	1.46 meters	0.71	0.226115
9	21910333	<i>Quercus cerris</i>	11	1.51 meters	0.36	0.11465
10	21910334	<i>Prunus avium</i>	8	1.48 meters	0.46	0.146497
11	21910335	<i>Quercus petraea</i>	8.5	1.50 meters	0.59	0.187898
12	21910336	<i>Quercus cerris</i>	9	1.50 meters	0.76	0.242038
13	21910337	<i>Quercus petraea</i>	9	1.45 meters	0.67	0.213376
14	21910338	<i>Prunus avium</i>	5.8	1.50 meters	0.49	0.156051
15	21910339	<i>Quercus petraea</i>	7	1.53 meters	0.54	0.171975
16	21910340	<i>Quercus petraea</i>	8.5	1.51 meters	0.48	0.152866
17	21910343	<i>Prunus avium</i>	7.6	1.49 meters	0.46	0.146497

Appendix. 2: Descriptive seasonal statistics of daily SFD for single TT. **AMJ = April-May-June;**
JAS = July-August-September; OND = October-November-December.

	AMJ				JAS				OND			
TT+ id	Mean	std	min	max	Mean	std	min	max	Mean	std	min	max
218A0008	3.3	1.3	1.6	9.7	6.5	4.4	1.4	24.8	5.5	7.2	0.9	64.4
218A0010	12.1	9.6	3.3	51.4	9.6	3.4	4.5	16.8	29.9	30.5	8.7	108.6
218A0021	12.4	18.4	2.6	132.3	6	2.8	1.4	14.2	26.2	4.6	22.2	31.2
218A0023	7.1	1.1	5.4	9.5	5.5	1.4	1	12.7	4.2	1.4	0.9	11.1
218A0026	2.9	0.7	1.7	4.4	2.5	1.1	0.7	6.2	2.6	1.3	1.1	11.1
218A0030	4.5	2.6	2.9	19.8	3.2	1.2	1.1	9.6	3.5	1.9	1	12.9
218A0034	22.1	8.7	3.7	61	24.3	8.5	2.8	55.5	9.5	3	2.3	18.7
218A0035	2.5	1	1.2	6.1	1.6	0.8	0.8	4.7	3	1.9	1.3	8.9
218A0036	5.6	5	1.8	34	3.3	1.4	1.6	11.9	3	2.9	0.6	27.2
218A0037	2.5	0.7	1	4.1	2.1	0.6	1	5.7	2.9	1.1	1.3	9.3
218A0009	12.2	6.6	2.3	39.1	13.1	12.3	4.6	91	15.9	19.2	2.1	126.9
21910325	7.5	3	2	24.6	6	1.9	1.8	19.6	6.8	2.5	1.5	15.9
21910324	29.5	12.4	6	81.5	12	2.9	5.7	23.6	8.9	3.8	3.6	12.9
21910326	31.5	23	2.8	214.1	5.8	1.8	1.8	11.1	11.4	11.5	2.9	86.7
21910327	5.1	1.5	1.1	9.2	5.6	1.7	1.3	10	8.8	4.1	1.2	24.6
21910328	17.4	4.4	2.4	48.6	9.6	7.9	3	39.9	5.7	2.2	2.2	14.5
21910329	14.6	9.2	2.9	57.6	69.5	15	4.7	148.8				
21910331	6.1	1.6	2.9	12.2	7.1	1.6	1.8	10.7	8.9	5.3	3.2	32.6
21910333	10.3	3	2.6	23.3	11.7	4.6	3	37.5	6.6	2	1	15.5
21910334	23.9	22.8	3	179.3	12.4	7.5	4.6	59.1	6.3	3	0.7	20.1
21910335	5.9	4.8	2	49.8	5.3	2.8	1.5	14.9	13.3	12.8	2	88.3
21910336	11	6.2	1.7	46.5	24.7	6.4	4.6	44.6	20.3	17.6	10.2	70.6
21910338	8.7	1.8	2	13.5	7.7	2.2	3.7	20.7	5.2	1.6	0.9	10.6
21910339	9.9	3	2.1	21.2	11.1	5.1	3.1	39.4	11.7	7.4	1.3	52.6
21910340	32.4	22	3.3	155.3								
21910343	13.7	4	2.7	29.7	13.8	2.8	10.5	18.3				

Appendix. 3: Seasonal statistics of NDVI for single TT+. **AMJ = April-May-June; JAS = July-August-September; OND = October-November-December.**

	AMJ		JAS		OND	
TT+ id	Mean	std	Mean	std	Mean	std
218A0008	-0.02	0.2	0.17	0.22	0.32	0.31
218A0010	0.29	0.24	0.48	0.24	0.52	0.31
218A0021	0.31	0.19	0.54	0.15	0.38	0.18
218A0023	0.06	0.13	0.16	0.13	0.25	0.21
218A0026	0.45	0.21	0.42	0.19	0.56	0.24
218A0030	-0.06	0.15	-0.06	0.17	0.18	0.21
218A0034	0.3	0.23	0.36	0.2	0.19	0.22
218A0035	0.04	0.21	0.14	0.21	0.22	0.23
218A0036	0.39	0.14	0.59	0.15	0.43	0.16
218A0037	0.15	0.15	0.12	0.2	0.3	0.3
218A0009	-0.25	0.15	-0.17	0.17	0.07	0.29
21910325	0.55	0.09	0.46	0.11	0.25	0.13
21910324	0.32	0.22	0.4	0.12	0.06	0.14
21910326	0.35	0.19	0.58	0.23	0.24	0.24
21910327	0.78	0.13	0.49	0.12	0.06	0.13
21910328	0.46	0.04	0.67	0.14	0.29	0.1
21910329	0.3	0.21	0.46	0.25	0.12	0.21
21910330	0.52	0.17	0.73	0.15	0.45	0.16
21910331	0.62	0.17	0.63	0.15	0.22	0.15
21910333	0.3	0.18	0.58	0.16	0.38	0.18
21910334	0.55	0.16	0.21	0.17	-0.08	0.1
21910335	0.44	0.19	0.32	0.18	0.22	0.12
21910336	0.38	0.19	0.63	0.17	0.29	0.16
21910337	0.6	0.17	0.72	0.08	0.28	0.12
21910338	0.67	0.14	0.22	0.19	-0.13	0.15
21910339	0.25	0.23	0.35	0.2	0.03	0.16
21910340	0.55	0.16	0.66	0.13	0.3	0.15
21910343	0.49	0.19	0.26	0.09		

Appendix. 4: Seasonal statistics of GNDVI for single TT+. **AMJ = April-May-June; JAS = July-August-September; OND = October-November-December.**

	AMJ		JAS		OND	
TT+ id	Mean	std	Mean	std	Mean	std
218A0008	0.09	0.13	0.22	0.15	0.28	0.21
218A0010	0.23	0.2	0.24	0.2	0.43	0.28
218A0021	0.19	0.14	0.34	0.14	0.09	0.2
218A0023	0.02	0.1	0.32	0.1	0.2	0.12
218A0026	0.28	0.18	0.39	0.18	0.5	0.27
218A0030	0	0.12	-0.13	0.09	-0.03	0.06
218A0034	0.38	0.19	0.41	0.16	0.46	0.2
218A0035	0.14	0.18	0.21	0.21	0.19	0.18
218A0036	0.27	0.1	0.53	0.09	0.33	0.17
218A0037	0.12	0.13	0.09	0.12	0.12	0.22
218A0009	0.15	0.12	0.22	0.09	0.46	0.2
21910325	0.02	0.16	-0.13	0.16	-0.23	0.17
21910324	0.2	0.17	0.23	0.1	-0.17	0.1
21910326	0.13	0.13	0.39	0.12	0.03	0.16
21910327	0.45	0.15	0.31	0.12	-0.09	0.11
21910328	0.12	0.09	0.3	0.15	0.04	0.16
21910329	0.29	0.16	0.53	0.16	0.15	0.17
21910330	0.35	0.15	0.53	0.14	0.28	0.16
21910331	0.27	0.21	0.17	0.15	-0.14	0.11
21910333	-0.04	0.14	0.14	0.1	-0.07	0.13
21910334	0.09	0.11	0.01	0.14	-0.3	0.09
21910335	0.16	0.15	0.19	0.15	0.04	0.11
21910336	0.44	0.14	0.64	0.08	0.25	0.13
21910337	0.31	0.18	0.47	0.08	0.03	0.14
21910338	0.43	0.18	0.12	0.13	-0.08	0.09
21910339	0.36	0.16	0.42	0.08	0.1	0.1
21910340	0.29	0.14	0.25	0.14	-0.1	0.14
21910343	0.24	0.2	0.07	0.12		

Appendix. 5: Seasonal statistics of daily xylem moisture (%) for single TT+. **AMJ = April-May-June; JAS = July-August-September; OND = October-November-December.**

	AMJ				JAS				OND			
TT+ id	Mean	std	min	max	Mean	std	min	max	Mean	std	min	max
218A0008	7.8	1.3	4.4	11.5	16	5.9	9.7	44.3	46.7	2.5	28.9	54.1
218A0010	8	2.1	5.4	20.8	6.9	0.4	5.5	8.1	7.4	2.5	4	17.3
218A0021	43.7	6.1	17	63.3	52.6	2	50.3	64.8	61.4	2.4	51.3	68
218A0023	11.4	1.4	8.5	16.4	10.3	0.5	9	12.3	9.7	0.9	6.5	12.9
218A0026	36.3	5.4	12.1	56.3	46.1	3.1	33.8	52.8	54.9	2	44.3	63.5
218A0030	8.7	0.8	6.9	11.5	11	0.5	9	12.5	9.8	0.8	7	11.7
218A0034	9.4	1.2	4.7	13.9	13.3	0.5	12	14.9	11.4	0.9	8.7	13.4
218A0035	15	1	12.8	20.3	17.2	0.5	15.6	20	20	3.9	14.3	45.3
218A0036	12.2	0.8	8.7	16.4	13.9	0.5	12.8	15.6	11.8	0.7	9.1	13.6
218A0037	11.1	1.3	5.5	17.8	17.2	0.4	16	19.3	15.7	0.7	13.3	17.3
218A0009	16.4	0.8	13.3	24.1	17.9	0.8	16.8	22.3	16.8	1	13.6	20.4
21910325	37.9	4.2	32.2	44.8	22.7	2.9	13.7	42.3	12.7	0.9	8.8	14.8
21910324	31.9	8.7	2.6	67.3	43.7	9.4	18.6	56.1	56.7	1.6	50.5	61.6
21910326	14.3	2.9	-1.5	21.6	27.6	5.5	16.7	53.5	59.7	1.2	52.7	63.8
21910327	17.8	6.2	3.4	48.5	31.3	2.2	17.1	51.4	47.9	4.2	30.1	55.4
21910328	49.7	7.4	6.1	62.1	54.8	2.3	42.5	62.1	62.2	0.8	59.2	64.6
21910329	25.9	7.7	3.3	52.2	32.4	2.9	26.7	40.3	33.7	6.2	17.5	50.3
21910331	32.8	13.7	2.3	59.9	53.9	3.4	18.1	59.7	66	3.7	57.7	82
21910333	12.9	1.5	3.1	22.9	21.7	2.6	16.8	31	26.4	4.1	17.3	38.6
21910334	29.7	9.3	3.8	58	49.4	2.3	38.6	54.2	60.8	2.2	49.5	66.8
21910335	13.8	1.4	7	20.6	19.3	3.3	14.9	30.3	38.4	6.2	15.8	51.5
21910336	55.6	8.8	1.9	75.2	65.1	5.1	58.8	78.8	72.2	3.1	69	81
21910338	20.9	7.3	-2	48	33.1	7	17.7	48.4	45.3	4.1	31.8	56
21910339	31.1	8.3	0	56.5	43	4.7	23	56	48.2	6.9	18.5	59.4
21910340	15.2	1.7	4.6	28.2	21.7	7.8	14.3	61.5	30.5	6.9	15.2	41.8
21910343	31.9	8.5	2.6	60.8	31.8	9.7	16.6	55.8	43.4	7.9	15.4	56.8

Appendix. 6: Top 2 (Left to right) pictures showing TT Cloud with antenna and solar panel and Tree talker device installed on *Quercus petraea* L. Bottom 2 (left to right) pictures showing site 1 and site 2.



Appendix. 7: Picture below showing completely shedded crown of *Quercus petraea* L. (site 1)
during December 2019