Dendrometer*

Why do we need dendrometers?

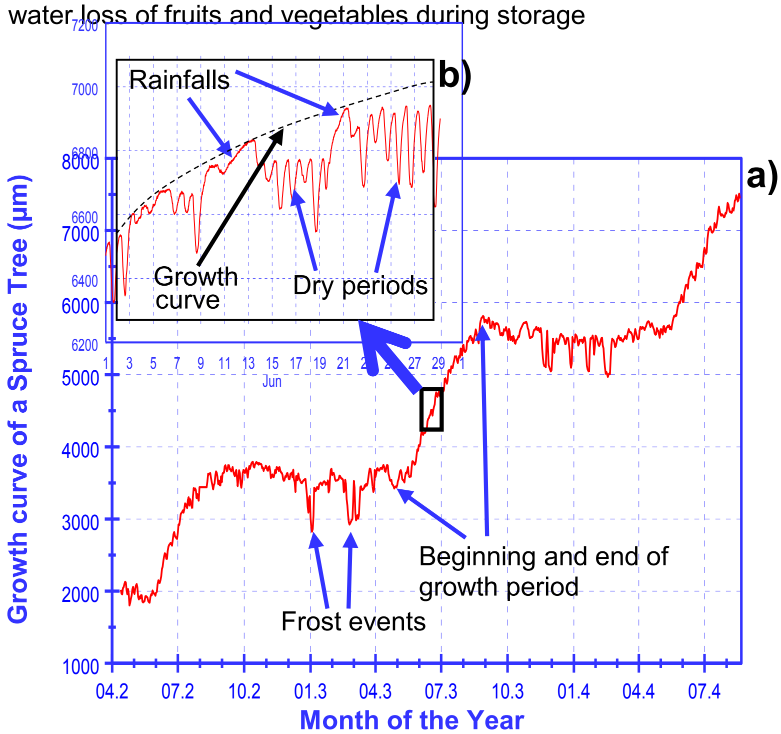
Electronic dendrometers are highly precise instruments for the continuous measurement of changes in diameter, circumference or length of different plant parts (i.a. growth dynamic and diurnal diameter changes of tree stems or fruits). Dendrometer signals document the response of plants to their environment in high temporal resolution.

In plant research the time scale of interest ranges between decades and minutes, depending on the specific research question. In contrast to other plant and environmental parameters measured with high temporal resolution (hourly or shorter), changes in yield, biomass and tree ring width are commonly only available annually.

Electronic dendrometers allows us to record size changes of the instrumented plant parts at high temporal resolution and hence permit the direct assignment of plant responses to environmental factors. Dendrometer are therefore a useful and thereby cost-effective tool in plant research

Applications

- Monitoring of growth processes of plants
- Monitoring the water status of plants, i.a.:
  - ecological research
  - irrigation control
  - building activities affecting the ground water table
- Examination of the influence of environmental factors on plant growth
- Precise dating of the beginning and end of growing season
- Precise determination of the occurrence of frost events
- Estimation of the water content and water storage pools in plants (in combination with sap flow measurement the transpiration can be calculated continuously)
- Monitoring and investigation of the stability of road and park trees or branches
- water loss of fruits and vegetables during storage



Benefits of Ecomatik Dendrometers

- Technically mature equipment with more than 15 years of worldwide use in over 40 countries (polar to tropical regions, high elevation sites, under water)
- High resolution of up to 0.2 microns (depending on data logger)
- Temperature effect compensated
- Large selection for different measurement requirements: radius, diameter, circumference, fruit, vegetables, vertical changes
- Low power consumption, allowing more than one year of continuous records only with an internal battery (in combination with the Dendrometer logger DL18, provided by Ecomatik)
- Compatible with all popular data loggers (e.g. Campbell, Delta-T, Datataker).

Available Dendrometer Types

Name	Abbre viation	Suitable for diameter of
Radius dendrometer	**DR**	>8 cm
Diameter dendrometer small	**DD-S**	0-5 cm
Diameter dendrometer large	**DD-L**	3-30 cm
Circumference dendrometer 1	**DC1**	5-30 cm
Circumference dendrometer 2	**DC2**	>5 cm
Circumference dendrometer 3	**DC3**	>5 cm
Roots and aquatic Plants dendrometer	**DRO**	0-2 cm
Fruit, vegetable dendrometer	**DF**	0-11 cm
Vertical dendrometer	**DV**	>8 cm

Data sample: How a typical dendrometer curve looks like

At the monthly time scale (Fig. a), continuous data reveals intra- and inter-annual differences in dynamics of diameter growth, i.e. beginning and end of the growth period and rate of diameter increment (slope). At the diurnal time scale (Fig. b) the course of diameter variation reveals periods of high transpirational water demand with significant depletion of stem water storage (during dry periods) as indicated by strong shrinking and swelling of the trunk (high diurnal diameter amplitudes). During rainfalls transpirational water consumption is marginal and water storage pools are replenished as indicated by completely dampened diurnal amplitudes and the return of the diameter to the growth curve. (For further reading klick: 1, 2, 3, 4, 5; cf. also literature list at the end of the dendrometer section of this catalog). The occurrence of frost events is indicated by strong transient diameter decreases during winter (Fig. a).

DR Radius Dendrometer

The sensor is anchored by two special screws in the heartwood. The changes outside of the heartwood correspond to radial growth and diurnal diameter variation. The arrangement ensures high stability for long-term measurements.

Advantages
- Stability against wind, snow, falling branches and fruits
- Low pressure at the measuring point
- Suitable for large trees (diameter> 8 cm)
- Ideal for long-term measurement with less manpower

Limits
- Trunk is injured by drilling (the damage can be minimized by tree resin)
- Suitable only for larger trees (diameter > 8 cm)

Delivery
- Complete with 5 m cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Installation tools (tree resin, hand drill)
- Data Logger

Technical specifications

Name	**Radius Dendrometer (DR)**
Suitable for plant size	Diameter > 8 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	<1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0 to 100%

DRW Radius Dendrometer Rugged

The DRW is the ruggedized version of the DR dendrometer type. Additionally to the features of the simple DR version, the DRW dendrometer is modified for the use under especially harsh environmental conditions. A soft, weather-resistant rubber coating, protects the whole sensor from ingress of water and solid particles.

Advantages (additionally to DR type)
- Suitable for measurements underwater, under snow cover and under heavy exposure to dust (e.g. volcanic ashes, desert dust, etc.)
- Suitable under exposure to corrosive seawater spray

Limits
- Trunk is injured by drilling (the damage can be minimized by tree resin)
- Suitable only for larger trees (diameter > 8 cm)

Delivery
- Complete with 5 m cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Installation tools (tree resin, hand drill)
- Data Logger

Technical specifications

Name	**Rugged Radius Dendrometer (DRW)**
Suitable for plant size	Diameter > 8 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	<1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0 to 100%

DD-L Diameter Dendrometer Large


The DD-S is designed specifically for agricultural plants, small trees and branches (diameter < 5 cm). Due to the patented mounting method, the dendrometer provides stable readings also for very small plants. The sensor remains stable fixed at the measuring point without exerting excessive pressure on the measuring point.

Advantages
- Suitable for small trees and agricultural plants
- Plants do not have to bear the weight of the dendrometer (separate braces for small plants)
- No injury to plants
- Minimal contact pressure on the plant
- Stability against wind, snow, falling small branches and small fruits
- Plant size specific ordering possible within the 0 to 5 cm diameter range

Limits
- Not suitable for diameter greater than 5 cm (see Type DD-L)

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools (wrench)

Options / Ordering Information
- Cable extension (please specify in meters)
- If necessary, different frame size
- Data Logger

Technical specifications

Name	**Diameter Dendrometer Small (DD-S)**
Suitable for plant size	Diameter 0 -5 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0-100

DD-S Diameter Dendrometer Small

The sensor is mounted with a patented fixture at the plant. The sensor remains stable fixed at the measuring point without exerting excessive pressure on the measuring point. The model is suitable for diameter of 3-30 cm.

Advantages
- Suitable for diameter 3-30 cm
- No injury to plants
- Minimal load on the target
- Stability against wind, snow, falling small branches and small fruits
- Plant size specific ordering possible within the 3 to 30 cm diameter range

Limits
- Not suitable for diameter greater than 30 cm

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools (wrench)

Options / Ordering Information
- Cable extension (please specify in meters)
- If necessary, different frame size
- Data Logger

Technical specifications

Name	**Diameter Dendrometer Large (DD-L)**
Suitable for plant size	Diameter 3-30 cm (range on request reducible)
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0 to 100%

DDW Diameter Dendrometer Rugged

The DDW is the ruggedized version of the DD-L dendrometer type. Additionally to the features of the simple DD-L version, the DDW dendrometer is modified for the use under especially harsh environmental conditions. A soft, weather-resistant rubber coating, protects the whole sensor from ingress of water and solid particles.

Advantages (additionally to DD-L type)
- Suitable for diameter 2-20 cm
- Suitable for measurements underwater, under snow cover and under heavy exposure to dust (e.g. volcanic ashes, desert dust, etc.)
- Suitable under exposure to corrosive seawater spray
- Plant size specific ordering possible within the 2 to 20 cm diameter range

Limits
- Not suitable for diameter greater than 20 cm

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools (wrench)

Options / Ordering Information
- Cable extension (please specify in meters)
- If necessary, different frame size
- Data Logger

Technical specifications

Name	Rugged Diameter Dendrometer Large (DDW)
Suitable for plant size	Diameter 2-20 cm (range on request extendable)
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0 to 100%

DC1 Circumference Dendrometer

The Circumference Dendrometer 1 is the simple version for the measurement of circumference changes of plants. The sensor is mounted on the plant with a wire cable with a very low coefficient of thermal expansion. The slide rings reduce the friction between the wire cable and the tree bark. They also decrease the pressure of wire cable on the tree.

Advantages
- Suitable for diameter 5-30 cm
- No injury to plants
- Easy installation
- Stability against wind, snow, falling small branches and small fruits
- Readings directly correspond to the circumference changes

Limits
- Because the elastic force of the sensor is exerted in tangential direction (wire tension), the contact pressure between cable wire and stem depends on the curvature of the stem, i.e. the stem diameter (analog to interrelation described by the Young-Laplace equation) The result is that the larger the stem radius, the lower the contact pressure between cable wire and stem surface. Measurement data between stems of highly divergent radiuses is therefore not comparable (cf. DC2).

Delivery
- Complete with 5 m cables and 1 m wire cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Extension of the wire cable (please specify in meters)
- Data Logger

Technical specifications

Name	Circumference Dendrometer 1 (DC1)
Suitable for plant size	Diameter 5-30 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Thermal expansion coefficient of the wire cable	$<1.4 \times 10^{-6}$/K
Operating conditions	Air temperature:-25 to 70 °C, air humidity: 0 to 100%

DC2 Circumference Dendrometer 2

The DC2 is the improved version of the DC1. The elastic force of the sensor is not applied in tangential, but in radial direction. With this physical layout, the pressure of the wire cable to the tree adjusts automatically with the diameter (for further information please visit our internet page). The data of different tree sizes is comparable. The sensor is mounted on a wire cable with very low thermal expansion coefficient at tree. The slide rings reduce the friction between the wire cable and the tree bark. They also decrease the pressure on the tree.

Advantages
- Suitable for all tree sizes (> 5 cm)
- Contact pressure between wire cable and tree adjusts with tree diameter
- Automatic adjustment of the tension, sensitive measurements even with very large trees
- No injury to plants
- Stability against wind, snow, falling small branches and small fruits
- Easy installation
- Easy adjustment by the integrated turnbuckle

Limits
- The data must be converted (free Excel program)
- The tree must be roughly circular

Delivery
- Complete with 5 m cable and 1 m wire cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Extension of the wire cable (please specify in meters)
- Free Excel program for data conversion
- Data Logger

Technical specifications

Name	Circumference Dendrometer 2 (DC2)
Suitable for plant size	Diameter > 5 cm
Range of the sensor	15 mm
Range in diameter	Because of the unique design the real measuring range in diameter is depen-dent from the tree size. Tree Diameter (cm) / Measuring Range (mm) 10 / 9.9 50 / 6.6 100 / 5.2
Accuracy	±2 µm ±0.12% (CR1000 data logger)
Resolution	0.3 – 3.6 µm (dependent on data logger used)
Linearity	2%
Thermal expansion coefficient of sensor	<0.1 µm/K
Thermal expansion coefficient of the wire cable	$<1.4 \times 10^{-6}$/K
Operating conditions	Air temperature: -25 to 70 °C, air humidity: 0 to 100%

DC3 Circumference Dendrometer 3

The DC3 has the same structure as DC2. Only the sensor measuring range is greater than DC2. This meets the measurement requirements of fast-growing trees.
The **advantages, limits, delivery**, and **ordering information** of DC3 is the same as that of DC2.

Technical specifications

Name	Circumference Dendrometer 3 (DC3)
Suitable for plant size	Diameter > 5 cm
Range of the sensor	25 mm
Range in diameter	Tree Diameter (cm) / Measuring Range (mm) 10 / 16.2 50 / 11.3 100 / 9.0
Accuracy	±3.3 µm ±0.12% (CR1000 data logger)
Resolution	0.4 – 6 µm (dependent on data logger used)
Linearity	0.7%
Thermal expansion coefficient of sensor and wire cable, and Operating conditions are the same as that of DC2	

DF Fruit and Vegetable Dendrometer

The Fruit and Vegetable Dendrometer is the special dendrometer version for measurements on circular fruiting bodies. The fruit in the measuring frame is firmly fixed without affecting its growth. The frame sustains the weight of the target and relives the peduncle.

Advantages
- Suitable for diameter between 0 and 11 cm (other size on request)
- Fruits do not have to bear the weight of the dendrometers
- Measures diameter changes
- No Injury to fruits
- Stability against wind, snow, falling small branches and small fruits

Limits
- Not suitable for very soft fruit and vegetables (such as ripe tomatoes)

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools (wrench)

Options / Ordering Information
- Cable extension (please specify in meters)
- If necessary, different frame size
- Data Logger

Technical specifications

Name	**Fruit and Vegetable Dendrometer (DF)**
Suitable for fruit / vegetable size	Diameter 0 -11 cm (range on request reducible)
Range of the sensor	15 mm
Accuracy	±2 µm ±0.12% (CR1000 data logger)
Resolution	0.3 – 3.6 µm (dependent on data logger used)
Linearity	2%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Air temperature: -25 to 70 °C, air humidity: 0 to 100%

DV Vertical Dendrometer

The Vertical dendrometer is designed to determine vertical changes (not growth) of trees continuously. Tree stems and their respective sections vary in length and curvature, according to water status (short- to mid-term) wind direction and wind speed (short-term to permanent), snow and fruit load (mid-term to permanent), unbalanced growth or loss of crown parts (long-term to permanent). vertical changes are a valuable measure to assess water status and static characteristics, such as mechanical stress-strain relationships and mechanical stability of trees. In order to disentangle the different causes (water status, mechanical stress), parallel measurements with three vertical dendrometers, oriented in three different cardinal directions are necessary.

Advantages
- Assessment of mechanical stress-strain relationships
- Suitable for large trees (diameter>8 cm)
- Robust installation, resistant against wind, snow, falling branches and fruits

Limits
- Trunk is injured by drilling (the damage can be minimized by tree resin)

Delivery
- Complete with 5 m cable and 1 m wire cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Installation tools (tree resin, hand drill)
- Data Logger

Technical specifications

Name	**DV Vertical Dendrometer**
Suitable for plant size	Diameter > 8 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Thermal expansion coefficient of the wire cable	$<1.4 \times 10^{-6}$/K
Operating conditions	Air temperature: -25 to 70 °C, air humidity: 0 to 100%

DRO Root and Aquatic Plant Dendrometer

The DRO Dendrometer is designed for continuous measurement of roots, aquatic plants and creepers. A soft, light resistant rubber coating protects the whole sensor from ingress of moisture, the device is waterproof. A metal clamp protects the sensor from excessive pressure exerted from overlying soil. The specific weight of the unit is similar to water. When used underwater, no extra load is charged on target plants by the floating instrument. It is easy to install and maintenance free. Its suitability has been proven in long-term tests (> 1 year) under below ground field conditions.

Advantages
- Waterproof, suitable for use in/on the soil and under water
- Low pressure at the measuring point
- Under water, no extra load on target
- Ideal for long-term measurement with less manpower

Limits
- Only for diameter smaller than 2 cm

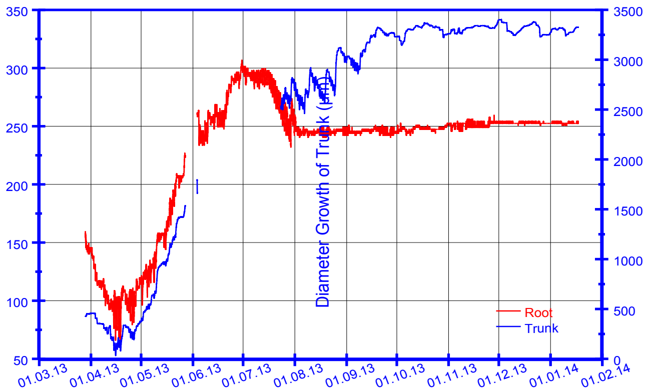
Delivery
- Complete with 5 m cable

Options / Ordering Information
- Cable extension (please specify in meters)
- Data Logger

Technical specifications

Name	Root Dendrometer (DRO)
Suitable for plant size	Diameter <2 cm
Range of the sensor	11 mm
Accuracy	±1.5 µm ±0.12% (CR1000 data logger)
Resolution	0.2 - 2.6 µm (dependent on data logger used)
Linearity	<1%
Thermal expansion coefficient of sensor	<0.1 µm/K
Operating conditions	Temperature: -25 to 70 °C, in and on soil, under water

Data sample: Growth dynamics of stem and root in an 80-year-old spruce tree



Measurements were conducted on a mature spruce tree at the experimental site “Kranzberger Forst” of TU Munich. The stem was equipped with a circumference dendrometer (DC1) at a height of 1.3 m (diameter=44 cm). A root with a diameter of about 5 mm in a depth of 5 cm in the mineral soil was equipped with a root dendrometer (DRO). After installation, the small pit was refilled with the original soil. The measurement started at the end of March 2013 and ended in January 2014. The water-tight root dendrometer remained buried in the soil, during the whole time of investigation of more than nine months. Apart from interruptions in June and July due to a failure of the data logger, both dendrometers worked without any problems.

The graph shows growth dynamics of trunk (blue line, right scale) and root (Φ 5 mm, red line, left scale). Before July 2013, the root exibited a similar growth pattern to that of the trunk. In the beginning of the measurements in March 2013, both tree parts showed a reduction of the diameter. This phenomenon can be attributed to changes in the osmotic regulation of cells, which adjusts the freezing point of cells in the course of the year (Gross et al., 1980). Radial growth started in mid-April. By the end of June, the root grew in diameter by 200 µm, while the trunk increased its diameter by 2000 µm. While the trunk showed significant growth activities during the entire growth period, the root shrank from July 2013 drastically by about 50 µm and remained until the end of the measurement with only minimal changes. Drought especially affects roots in the upper soil layers. Based on the results, we hence conclude that the root had died during the summer drought event which occurred in July/August 2013.

Data Logging

ECOMATIK dendrometers are compatible with all popular data loggers (e.g. Campbell, Delta-T, DT80). We give you support for connecting our dendrometers with the data loggers.

ECOMATIK provides the dendrometer data logger DL18 which covers all features and logging options relevant for precise and efficient dendrometer measurements

Dendrometer Data Logger (DL18)

The DL18 is a battery powered, weather proof, 4-channel data logger. It runs on an internal battery more than one year. It is suitable for long-term monitoring tree growth.

Technical specifications

Name	**Dendrometer Data Logger (DL18)**
Memory	1 900 000 readings If you connect 4 dendrometers, and collect data every 5 minutes, the memory will store data of more than 3 years
Resolution	0.2 µm for Dendrometer types: DD-L, DD-S, DC1, DR, DV, DRO 0.3 µm for Dendrometer types: DC2, DF 0.5 µm for Dendrometer type: DC3
Accuracy	±0.1% of reading
Interface	USB interface to PC
Channel	4, for connecting up to 4 dendrometers
Logging Interval	1 sec. to 18 hours, user selectable
Power supply	Two AAA batteries, user replaceable. New batteries will typically last one year with a logging rate of 1 minute and a sampling interval of 15 seconds or greater.
Environment	Suitable for outdoor conditions Temperature: -20 to +70 °C (-4 to 158 °F); Air humidity: 0 to 95% RH (non condensing)

Worldwide users of our dendrometers in more than 40 countries

Universitat Politècnica de Catalunya, Barcelona
Chinese Academy of Forestry, Beijing
Swiss Federal Institute for Forest, Snow and Landscape, Birmensdorf
Universität Bonn, Dendroökologisches Labor, Bonn
Deutsche Forschungsgemeinschaft, Bonn
DBIO-APNA, Brussels
Vrije Universiteit Brussel, Brussels
INRA-EPHYSE, CESTAS Cedex
Brandenburgische Technische Universität, Cottbus
Debrecen University, Debrecen
Johann Heinrich von Thünen-Institut, Eberswalde
University of Erlangen-Nuremberg, Erlangen
University Duisburg-Essen,Essen
Technische Universität München, Freising
Bayerische Landesanstalt für Landwirtschaft, Freising
Justus-Liebig Universität, Gießen
Thüringer Landesanstalt für Wald, Jagd und Fischerei, Gotha
Ernst-Moritz-Arndt-Universität, Greifswald
Universität Hamburg, Hamburg
Leibniz Universität, Hannover
Universität Innsbruck, Innsbruck
BFW, Innsbruck
Max-Planck-Institut für Biogeochmie, Jena
University of Western Ontario,London
Lund University, Lund
Johannes Gutenberg University Mainz, Mainz
Ludwig-Maximilians-University Munich, München
Helmholtz Zentrum München, Neuherberg
Tulane University, New Orleans
Lamont-Doherty Earth Observatory of Columbia, New York
USDA Forest Service, Olympia
Norwegian Univ of Life Sciences, Oslo
University of Oxford, Oxford
Helmholtz-Zentrum Potsdam, Potsdam
Beuth Hochschule für Technik Berlin, Potsdam-Bornim
CSIR Natural Resources and the Environment, Pretoria
Direction de la recherche forestière, Québec
McGill University, Québec
O3HP, St Paul-lez-Durance
National Taiwan University, Taipei
Bayerisches Amt für forstliche Saat- und Pflanzenzucht, Teisendorf
Technische Universität Dresden, Tharandt
University of Aarhus, Tjele
University of Arizona,Tucson

Scientific publications related to Ecomatik Dendrometers

Atay, E., Hucbourg, B., Drevet, A., & Lauri, P. E. (2016). Growth responses to water stress and vapour pressure deficit in nectarine. In D. Milatovic, D and Milivojevic, J and Nikolic (Ed.), III BALKAN SYMPOSIUM ON FRUIT GROWING (Vol. 1139, pp. 353–357). PO BOX 500, 3001 LEUVEN 1, BELGIUM: INT SOC HORTICULTURAL SCIENCE. **GO TO**

Ford, K. R., Harrington, C. A., Bansal, S., Gould, P. J., & St. Clair, J. B. (2016). Will changes in phenology track climate change? A study of growth initiation timing in coast Douglas-fir. *Global Change Biology*, *22*(11), 3712–3723. **GO TO**

Hiltner, U., Bräuning, A., Gebrekirstos, A., Huth, A., & Fischer, R. (2016). Impacts of precipitation variability on the dynamics of a dry tropical montane forest. Ecological Modelling, 320, 92–101. **GO TO**

He, M., Yang, B., Wang, Z., Braeuning, A., Pourtahmasi, K., & Oladi, R. (2016). Climatic forcing of xylem formation in Qilian juniper on the northeastern Tibetan Plateau. TREES-STRUCTURE AND FUNCTION, 30(3), 923–933. **GO TO**

Hu, L., & Fan, Z. (2016). Stem radial growth in response to microclimate in an Asian tropical dry karst forest. Acta Ecologica Sinica, 36(5), 401–409. **GO TO**

Lechthaler, S., Robert, E. M. R., Tonne, N., Prusova, A., Gerkema, E., Van As, H., … Windt, C. W. (2016). Rhizophoraceae Mangrove Saplings Use Hypocotyl and Leaf Water Storage Capacity to Cope with Soil Water Salinity Changes. FRONTIERS IN PLANT SCIENCE, 7. **GO TO**

Lindén, J., Fonti, P., & Esper, J. (2016). Temporal variations in microclimate cooling induced by urban trees in Mainz, Germany. Urban Forestry & Urban Greening, 20, 198–209. **GO TO**

Ruehr, N. K., Gast, A., Weber, C., Daub, B., & Arneth, A. (2016). Water availability as dominant control of heat stress responses in two contrasting tree species. TREE PHYSIOLOGY, 36(2), 164–178. **GO TO**

Siegmund, J. F., Sanders, T. G. M., Heinrich, I., van der Maaten, E., Simard, S., Helle, G., & Donner, R. V. (2016). Meteorological Drivers of Extremes in Daily Stem Radius Variations of Beech, Oak, and Pine in Northeastern Germany: An Event Coincidence Analysis. FRONTIERS IN PLANT SCIENCE, 7. **GO TO**

Spannl, S., Volland, F., Pucha, D., Peters, T., Cueva, E., & Braeuning, A. (2016). Climate variability, tree increment patterns and ENSO-related carbon sequestration reduction of the tropical dry forest species Loxopterygium huasango of Southern Ecuador. TREES-STRUCTURE AND FUNCTION, 30(4), 1245–1258. **GO TO**

Wang, W., Zhang, F., Yuan, L., Wang, Q., Zheng, K., & Zhao, C. (2016). Environmental Factors Effect on Stem Radial Variations of Picea crassifolia in Qilian Mountains, Northwestern China. FORESTS, 7(10). **GO TO**

Zhang, R., Yuan, Y., Gou, X., Zhang, T., Zou, C., Ji, C., … Li, X. (2016). Intra-annual radial growth of Schrenk spruce (Picea schrenkiana Fisch et Mey) and its response to climate on the northern slopes of the Tianshan Mountains. DENDROCHRONOLOGIA, 40, 36–42. **GO TO**

Jiang, Y., Wang, B.-Q., Dong, M.-Y., Huang, Y.-M., Wang, M.-C., & Wang, B. (2015). Response of daily stem radial growth of Platycladus orientalis to environmental factors in a semi-arid area of North China. Trees, 29(1), 87–96. **GO TO**

Oberhuber, W., Kofler, W., Schuster, R., & Wieser, G. (2015). Environmental effects on stem water deficit in co-occurring conifers exposed to soil dryness. INTERNATIONAL JOURNAL OF BIOMETEOROLOGY, 59(4), 417–426. **GO TO**

Urrutia-Jalabert, R., Rossi, S., Deslauriers, A., Malhi, Y., & Lara, A. (2015). Environmental correlates of stem radius change in the endangered Fitzroya cupressoides forests of southern Chile. AGRICULTURAL AND FOREST METEOROLOGY, 200, 209–221. **GO TO**

Wang, Z., Yang, B., Deslauriers, A., & Braeuning, A. (2015). Intra-annual stem radial increment response of Qilian juniper to temperature and precipitation along an altitudinal gradient in northwestern China. TREES-STRUCTURE AND FUNCTION, 29(1), 25–34. **GO TO**

Xiong, W., Oren, R., Wang, Y., Yu, P., Liu, H., Cao, G., … Zuo, H. (2015). Heterogeneity of competition at decameter scale: patches of high canopy leaf area in a shade-intolerant larch stand transpire less yet are more sensitive to drought. Tree Physiology, 35(5), 470. **GO TO**

Robert, E. M. R., Jambia, A. H., Schmitz, N., De Ryck, D. J. R., De Mey, J., Kairo, J. G., … Koedam, N. (2014). How to catch the patch? A dendrometer study of the radial increment through successive cambia in the mangrove Avicennia. ANNALS OF BOTANY, 113(4), 741–752. **GO TO**

Scientific publications related to Ecomatik Dendrometers

Garcia-Orellana, Y., Ortuno, M. F., Conejero, W., & Ruiz-Sanchez, M. C. (2013). Diurnal variations in water relations of deficit irrigated lemon trees during fruit growth period. SPANISH JOURNAL OF AGRICULTURAL RESEARCH, 11(1), 137–145. **GO TO**

Homeier, J., Leuschner, C., Bräuning, A., Cumbicus, N. L., Hertel, D., Martinson, G. O., … Veldkamp, E. (2013). Effects of Nutrient Addition on the Productivity of Montane Forests and Implications for the Carbon Cycle. In J. Bendix, E. Beck, A. Bräuning, F. Makeschin, R. Mosandl, S. Scheu, & W. Wilcke (Eds.), Ecological Studies. Ecosystem Services, Biodiversity and Environmental Change in a Tropical Mountain Ecosystem of South Ecuador (pp. 315–329). Berlin, Heidelberg: Springer Berlin Heidelberg. **GO TO**

Vieira, J., Rossi, S., Campelo, F., Freitas, H., & Nabais, C. (2013). Seasonal and daily cycles of stem radial variation of Pinus pinaster in a drought-prone environment. AGRICULTURAL AND FOREST METEOROLOGY, 180, 173–181. **GO TO**

Krepkowski, J., Bräuning, A., & Gebrekirstos, A. (2011). Growth dynamics of Podocarpus falcatus. In M. Maaten-Theunissen, H. Spiecker, H. Gärtner, G. Helle, & I. Heinrich (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology (pp. 6–12). Potsdam, Germany. **GO TO**

De Swaef, T., & Steppe, K. (2010). Linking stem diameter variations to sap flow, turgor and water potential in tomato. FUNCTIONAL PLANT BIOLOGY, 37(5), 429–438. **GO TO**

Bräuning, A., Von Schnakenburg, P., Volland-Voigt, F., & Peters, T. (2008). Seasonal growth dynamics and its climate forcing in a tropical mountain rain forest in southern Ecuador. In D. Elferts, G. Brumelis, H. Gärtner, G. Helle, & G. Schleser (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology (pp. 27–30). Riga, Latvia. Retrieved from **GO TO**

Otieno, D. O., Kurz-Besson, C., Liu, J., Schmidt, M. W. T., Do, R. V.-L., David, T. S., … Tenhunen, J. D. (2006). Seasonal variations in soil and plant water status in a Quercus suber L. Stand: roots as determinants of tree productivity and survival in the mediterranean-type ecosystem. PLANT AND SOIL, 283(1–2), 119–135. **GO TO**

Bräuning, A., & Burchardt, I. (2006). Detection of growth dynamics in tree species of a tropical mountain rain forest in southern Ecuador. In I. Heinrich, H. Gärtner, M. Monbaron, & G. Schleser (Eds.), TRACE - Tree Rings in Archaeology, Climatology and Ecology (pp. 127 – 131). Fribourg, Switzerland. **GO TO**

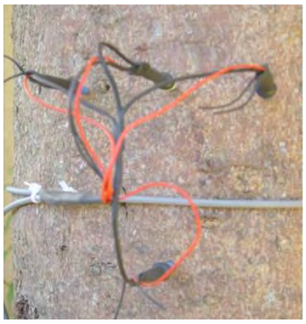
Liu J.C., Firsching B.M., Payer H.D. (1995): Untersuchungen zur Wirkung von Stoffeinträgen, Trockenheit, Ernährung und Ozon auf die Fichtenerkrankung am Wank in den Kalkalpen. GSF-Bericht 18/95, 236 S.

Liu J.C. (1995): Eine Methode zur Messung des vom Wassereffekt bereinigten Dickenzuwachses. Forstliche Forschungsberichte München, 153, 40-44.

Liu J.C., Häberle K.H., Loris K. (1994): Untersuchungen zum Einfluß des Matrixpotentials auf Stammdicken-änderungen von Fichten (Picea abies (L.) Karst.). Pflanzenern. Bodenk., 158, 231-234.

Not enough? Take a look at Google Scholar: (ecomatik OR ecomatic) AND dendrometer (GO TO SEARCH)

SF-L Sap Flow Sensor*



- Continuous monitoring of sap flow in trees
- Improved “well known” Granier Sap Flow Sensor
- Accurate measurement of night-time sap flow
- Enhanced accuracy and reliability
- Simplified data processing
- Complete installation tools available

Introduction

The well known Granier sap flow sensor, i.e. thermal dissipation probe (Granier, 1985) uses heat as a tracer of sap flow. Due to its simplicity, reliability and affordability, Granier type sensors have become a standard technique for measuring sap flow, that is used by numerous scientists all over the world. However, the technique has always had some shortcomings, which include:

a) Granier technique determines arbitrarily the sap flow to a zero value every night. This contravenes the possibility of night-time transpiration (Granier, 1987) and the fact of refilling process of tree body during the night. (Do and Rocheteau, 2002).

b) The technique ignores the effect of natural temperature gradients within the sap-wood. Such temperature gradients can range between +/- 1.5 °C (Fig. 1), causing considerable error in the results (DO and Rocheteau, 2002).

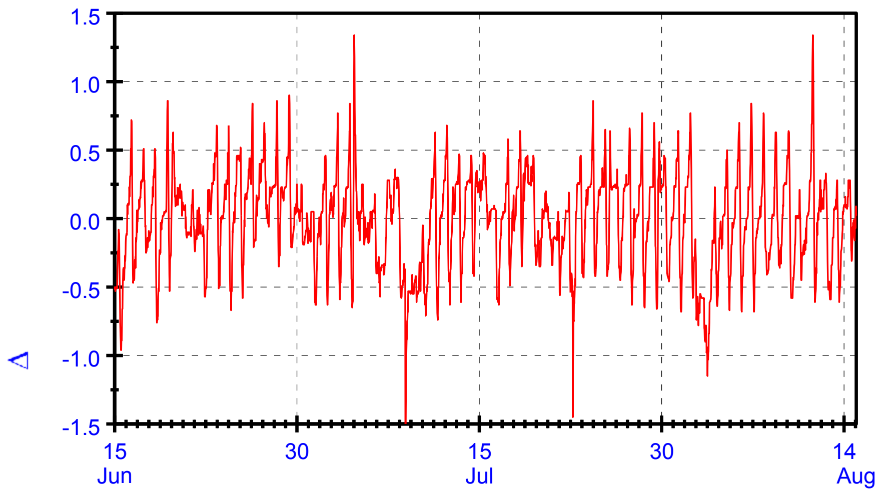


Fig.1 Vertical temperature gradients of a 40-year old spruce tree, measured with a Granier sensor without heating.

The SF-L Sensor

The principle of the SF-L sensor accounts for variations in the natural temperature gradients within the sapwood. The method is based on two reference thermocouples (between S1 and S2, S1 and S3) to continuously record background temperature gradients (ΔTR1, ΔTR2; Fig. 2) within the sapwood. During data processing, values of the temperature differences between the heated needle (S0) and the sapwood ambient temperature (ΔT, between S1 and S0) are corrected by the arithmetic mean of *ΔTR1, ΔTR2*.

The new sensor therefore considerably enhances accuracy and reliability in sap flow measurements through continuous correction of natural temperature gradients in the sapwood. In contrast to the Granier technique, the SF-L sensor provides a very stable and more accurate ΔTmax value (temperature difference between the heated needle and the sapwood ambient temperature when sap flow=0). The ΔTmax value is attained under conditions of zero transpiration and zero tree body refilling. This means 100% air humidity and zero tree diameter expanse. The diameter changes are detectable with high accuracy Ecomatik dendrometer (Fig. 3).

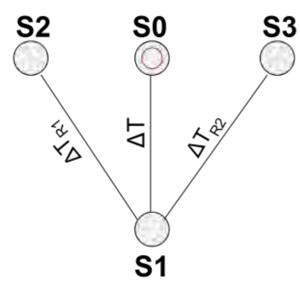


Fig. 2 Schematic diagram of the SF-L sensor

Usually there is only one universal value of ΔTmax in a growth period of a tree. The ΔT values in the night are dependent on the refilling state of the tree and the transpiration demand and rarely attain ΔTmax. Correct determination of Δtmax enables accurate measurements of the night sap flow. With the SF-L sensor, data processing is also highly simplified because it is no longer necessary to search for maximum temperature differences every night.

The SF-L sensor is easy to use. All necessary tools and spare parts are available at ECOMATIK.

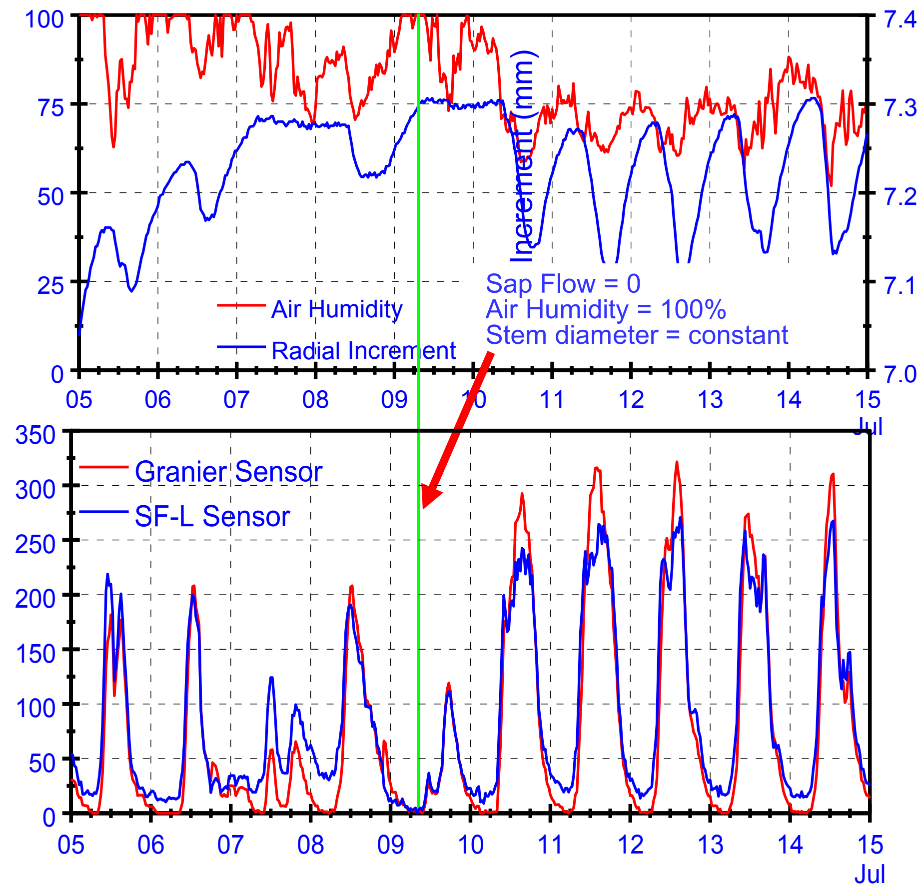


Fig. 3

Above: *Air humidity and radial changes of a 40-year old spruce tree measured with an Ecomatik dendrometer type DD. Increase in diameter at night indicates that the tree continues to take up water even during nighttime hence sap flow is not zero.*

Below: *Comparison between sap flow measured with Granier sensor (red line) and with SF-L sensor (blue line). The Granier sensor shows zero sap flow every night while the SF-L detects zero value only on the night of 9. July, when air humidity reached 100% and the tree body fully saturated with water. Averaging the whole measurement period of more than two month (data not shown), the mean sap flow estimated via Granier and the SF-L sensor was almost identical with 75.0 and 75.22 µl cm^{-2} min^{-1} respectively. However at the short-term scale (hourly, daily), natural temperature gradients within the sapwood can occasionally lead to extensive errors of up to 50% in sap flow estimates (cf. also* Do, F., & Rocheteau, A., 2002)

Technical specifications

Sensor	
Sensor composition	4 needles
Needle size	33 mm length, 1.5 mm diameter
Heating zone	20 mm from top of the needle
Cable length	5 m, extendable to 20 m
Tree size	Diameter>20 cm
Power consumption	0.2 W +/-5%, 84 mA DC, stabilized
Output	-100 µV to 1000 µV DC
Data Recording	3 differential channels required
Power supply	
Input	12 V DC
Output	84 mA stabilized, suitable for 1 to 3 SF-L sensors

Cited references

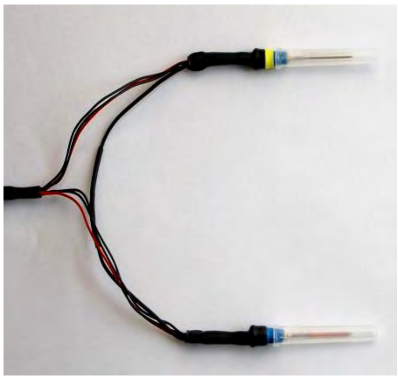
Do, F., & Rocheteau, A. (2002). Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. *TREE PHYSIOLOGY*, *22*(9), 641–648. **GO TO**

Do, F., & Rocheteau, A. (2002). Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 2. Advantages and calibration of a noncontinuous heating system. *TREE PHYSIOLOGY*, *22*(9), 649–654. **GO TO**

Granier, A. (1987). SAP FLOW MEASUREMENTS IN DOUGLAS-FIR TREE TRUNKS BY MEANS OF A NEW THERMAL METHOD. *ANNALES DES SCIENCES FORESTIERES*, *44*(1), 1–14. **GO TO**

Granier, A. (1985). A NEW METHOD OF SAP FLOW MEASUREMENT IN TREE STEMS. *ANNALES DES SCIENCES FORESTIERES*, *42*(2), 193–200. **GO TO**

SF-G Sap Flow Sensor



Introduction

The SF-G is the well-known thermal dissipation probe (TDP) developed by Granier (1985) for measuring sap flow in trees. The sensor consists of two identical manufactured needles with copper-constantan thermocouples and a special heating wire. The two needles are inserted into the sapwood, one above the other 15 cm apart directly below. The top needle is heated with constant energy supply (=constant current source). The resulting temperature difference (*ΔT*) between the two needles (above heated and below unheated) correlates with the sap-flow-density.

Technical Specifications

Sensor composition	2 needles
Needle size	33 mm length, 1.5 mm diameter
Heating zone	20 mm from top of the needle
Cable length	5 m, extendable to 20 m
Tree size	Diameter>5 cm
Power consumption	0.2 W +/-5%, 84 mA DC, stabilized
Output	100 µV to 800 µV DC
Logger requirement	1 differential channel

Scientific publications related to Ecomatik sap flow sensors

Li, Z., Yu, P., Wang, Y., Webb, A. A., He, C., Wang, Y., & Yang, L. (2016). A model coupling the effects of soil moisture and potential evaporation on the tree transpiration of a semi-arid larch plantation. *Ecohydrology*, n/a--n/a. **GO TO**

Lindén, J., Fonti, P., & Esper, J. (2016). Temporal variations in microclimate cooling induced by urban trees in Mainz, Germany. *Urban Forestry & Urban Greening*, *20*, 198–209. **GO TO**

Liu, X., Nie, Y., Luo, T., Yu, J., Shen, W., & Zhang, L. (2016). Seasonal Shift in Climatic Limiting Factors on Tree Transpiration: Evidence from Sap Flow Observations at Alpine Treelines in Southeast Tibet. *Frontiers in Plant Science*, *7*. **GO TO**

Peng, S., Chen, Y., & Cao, Y. (2016). Simulating Water-Use Efficiency of Piceacrassi folia Forest under Representative Concentration Pathway Scenarios in the Qilian Mountains of Northwest China. *Forests*, *7*(7), 140. **GO TO**

Rabbel, I., Diekkrüger, B., Voigt, H., & Neuwirth, B. (2016). Comparing ∆Tmax Determination Approaches for Granier-Based Sapflow Estimations. *Sensors*, *16*(12). **GO TO**

Bogena, H. R., Bol, R., Borchard, N., Brueggemann, N., Diekkrueger, B., Druee, C., … Vereecken, H. (2015). A terrestrial observatory approach to the integrated investigation of the effects of deforestation on water, energy, and matter fluxes. *SCIENCE CHINA-EARTH SCIENCES*, *58*(1), 61–75. **GO TO**

Jian, S., Zhao, C., Fang, S., & Yu, K. (2015). Effects of different vegetation restoration on soil water storage and water balance in the Chinese Loess Plateau. *Agricultural and Forest Meteorology*, *206*, 85–96. **GO TO**

Xiong, W., Oren, R., Wang, Y., Yu, P., Liu, H., Cao, G., … Zuo, H. (2015). Heterogeneity of competition at decameter scale: patches of high canopy leaf area in a shade-intolerant larch stand transpire less yet are more sensitive to drought. *Tree Physiology*, *35*(5), 470. **GO TO**

Chu, H.-S., Chang, S.-C., Klemm, O., Lai, C.-W., Lin, Y.-Z., Wu, C.-C., … Hsia, Y.-J. (2014). Does canopy wetness matter? Evapotranspiration from a subtropical montane cloud forest in Taiwan. *Hydrological Processes*, *28*(3), 1190–1214. **GO TO**

Yu, P., Wang, Y., Du, A., Guan, W., Feger, K.-H., Schwärzel, K., … Pan, S. (2013). The effect of site conditions on flow after forestation in a dryland region of China. *Agricultural and Forest Meteorology*, *178–179*, 66–74. **GO TO**

Lin, Y., Wang, G. X., Guo, J. Y., & Sun, X. Y. (2012). Quantifying evapotranspiration and its components in a coniferous subalpine forest in Southwest China. *Hydrological Processes*, *26*(20), 3032–3040. **GO TO**

Escalona, J. M., & Ribas-Carbó, M. (2010). Methodologies for the Measurement of Water Flow in Grapevines. In *Methodologies and Results in Grapevine Research* (pp. 57–69). Dordrecht: Springer Netherlands. **GO TO**

Kanalas, P., Fenyvesi, A., Kis, J., Szőllősi, E., Oláh, V., Ander, I., & Mészáros, I. (2010). Seasonal and diurnal variability in sap flow intensity of mature sessile oak (Quercus petraea (Matt.) Liebl.) trees in relation to microclimatic conditions. *Acta Biologica Hungarica*, *61*(Supplement 1), 95–108. **GO TO**

Liu J C, Firsching B M, Payer H D (1995): Untersuchungen zur Wirkung von Stoffeinträgen, Trockenheit, Ernährung und Ozon auf die Fichtenerkrankung am Wank in den Kalkalpen. GSF-Bericht 18/95, 236 S.

Not enough? Take a look at Google Scholar: (ecomatik OR ecomatic) AND “sap flow” (GO TO SEARCH)

Leaf Temperature Sensor

Type ΔLA-B: Broad leaf version of the ΔLA-Sensor (**Δ**T **L**eaf-to-**A**ir)

- Direct, continuous and highly accurate, measurements of the temperature difference between leaf surface and air (ΔT).
- Small and light-weight sensor with minimum load on the leaf
- Multiple measurement points distributed over the leaf surface provide a spatially integrative temperature signal
- Sensor signal in mV, recordable with most common data loggers
- No calibration is needed for the simple and exact transformation of the mV-signal into ΔT in °C
- Suitable for measurements under field conditions
- No power consumption
- Easy installation

What are the causes of leaf-to-air temperature differences?

It is an everyday experience that surface temperatures of sun exposed, non-heated objects diverge from actual ambient air temperature (ΔT). Simplified the phenomenon can be reduced to three main components:

1. Different energy influx:

Exposed to electromagnetic radiation (solar radiation), differing optical properties (absorptivity, reflectivity and transmissivity) of the regarded object and the air lead to different magnitudes of energy input that is converted into heat energy.

2. Different heat storage capacity:

The specific capacity of a substance to store heat energy is defined as the amount of energy that is needed to increase the temperature of one mole of the respective substance by 1 Kelvin. Objects of different composition and/or density therefore diverge in their heat storage capacity and hence in their temperature change at equal energy input.

3. Different energy outflux:

Electromagnetic energy flux: The ability of a surface to emit radiation energy (emissivity, ε) is defined relative to an idealized black body of the same temperature. Referred to a black body with $\varepsilon = 1$ the emissivity of a surface can range between 1 and 0. The ability of a surface to emit radiation energy thereby depends on its composition and optical properties.

Sensible heat flux: From an object with higher temperature than the surrounding medium (e.g. air), a large part of heat energy is dissipated via convection. The magnitude of this energy flux depends on various properties of the object and the medium (i.a. ΔT, thermal conductivity, heat capacity). In this context the calm layer above the object surface (boundary layer) is of special importance for the convective heat flux. Thickness and hence conductivity of the boundary layer depends on structure and seize of the surface and wind speed.

Latent heat flux: This part of the heat balance is relevant only in cases were a part of the heat energy is consumed for phase transition (e.g. liquid water to water vapor). In the same way how transpiration cools our skin when we are sweating, the leaf is cooled as a result of its transpiration
.

Why do we need to know leaf temperature?

For the growth of green plants, leaves play a central role as energy harvesting organs (conversion of solar energy to chemical energy via photosynthesis). In order to meet their function, leaves have to be located at exposed positions of the plant body and are hence strongly affected by instantaneous climatic conditions. Thereby, diurnal temperature changes of tens of °C are no exception. According to the Arrhenius equation, all chemical reactions and hence whole leaf physiology depends on leaf temperature. At both ends of the scale we observe species specific lethal temperature limits (chilling, heat stress).With respect to the principles explained in the preceding paragraph, it is clear that the question whether these temperatures are reached or not, can not be answered by merely measuring air temperature. The only reliable parameter to identify temperature stress (for monitoring as well as early-warning systems) is hence the actual leaf surface temperature. Actual leaf temperature is decisive for physiological functioning, at the leaf as well as the whole plant level and therefore a key parameter in plant ecological and physiological modelling (i.a. species distribution, transpiration, stomatal conductance, microclimate effect of the canopy, O_3-uptake, ^{13}C and ^{18}O of assimilates). Considering crucial but often unknown parameters, such as species specific optical properties of the leaves, transpiration rate, etc., a precise modeling of leaf temperature is not feasible in most cases. Acquiescing major errors, inaccurately modelled leaf surface temperatures or even mere air temperature are hence commonly employed as data basis in ecophysiological models. Continuous and precise measurements of the actual leaf temperature can substantially improve model reliability and hence results of plant ecological and physiological research.

The ΔLA sensor as solution and its principle of measurement

Air temperature is one of the central parameters in climate monitoring and existing measurement solutions are reliable and affordable. Hence, availability of air temperature data is usually high. Notwithstanding, the parameter cannot be readily employed as surrogate for leaf temperature (cf. explanation above). Additionally to air temperature data, only the temperature difference between ambient air and the leaf surface (**Δ**T **L**eaf-to-**A**ir) has to be known to calculate the actual leaf temperature.

Thermocouples are electronic devices to precisely measure temperature differences. Based on a thermo-electronic effect between different types of metals, temperature differences between the two measurement points of the instrument are directly traduced into a thermo-electronic voltage. However the voltage that is induced in one single thermocouple is very low. Measurements of small temperature differences would hence produce a very weak signal and consequently result in a very low signal resolution and signal-to-noise ratio.

In order to enable high resolution measurements, including very small temperature differences, the ΔLA sensor captures the additive thermo-electronic voltage of a very thin chain (10-fold) of thermocouples.

Advantages of the employed measurement principle

1. The additive signal of multiple thermocouples is strong enough for a direct recording with most of the available data loggers. Without the need for electronic or software based amplification, the measurement signal is obtained with the highest signal-to-noise ratio possible.
2. Multiple, spatially distributed measurement points in direct contact with the leaf, provide an integrative temperature signal of the leaf surface.
3. Consisting of very thin elements, the sensor stays lightweight and shading effects can be neglected, although the sensor may span a substantial part of the leaf.
4. Neglectable heat capacity and hence thermal inertia of the very thin thermocouples, enable measurements with high temporal resolution also under non-steady-state conditions.
5. Whereas unknown optical leaf properties (i.e. emissivity) affect the precision of optical temperature measurements, the direct measurement with the ΔLA sensor is free of such errors.

Data sample: Temperature difference between upper leaf surface and ambient air

Temperature differences between the upper leaf surface and ambient air (ΔT) were measured with a ΔLA-B sensor installed on a sun exposed leaf of a mature beech tree at the experimental site “Kranzberger Forst” of TU Munich. Shown is a two-week section of the total data series of over three months in 2016. Under conditions of ample soil water availability during the whole period, maximum ΔT values reached up to 4°C. However, substantially higher ΔT values are to be expected under drought, when plants reduce leaf transpiration to save water. Comparing the highlighted data (1.-2 and 6.- 8. of August) of ΔT, air temperature (Tair) and solar radiation (PPFD), it becomes evident that, ΔT depended mainly on solar radiation but not on Tair. Additionally to often unknown leaf transpiration rates (i.e. latent heat flux), this aspect illustrates another potential source of error, when mere Tair is employed as a surrogate for Tleaf in plant ecological modelling.

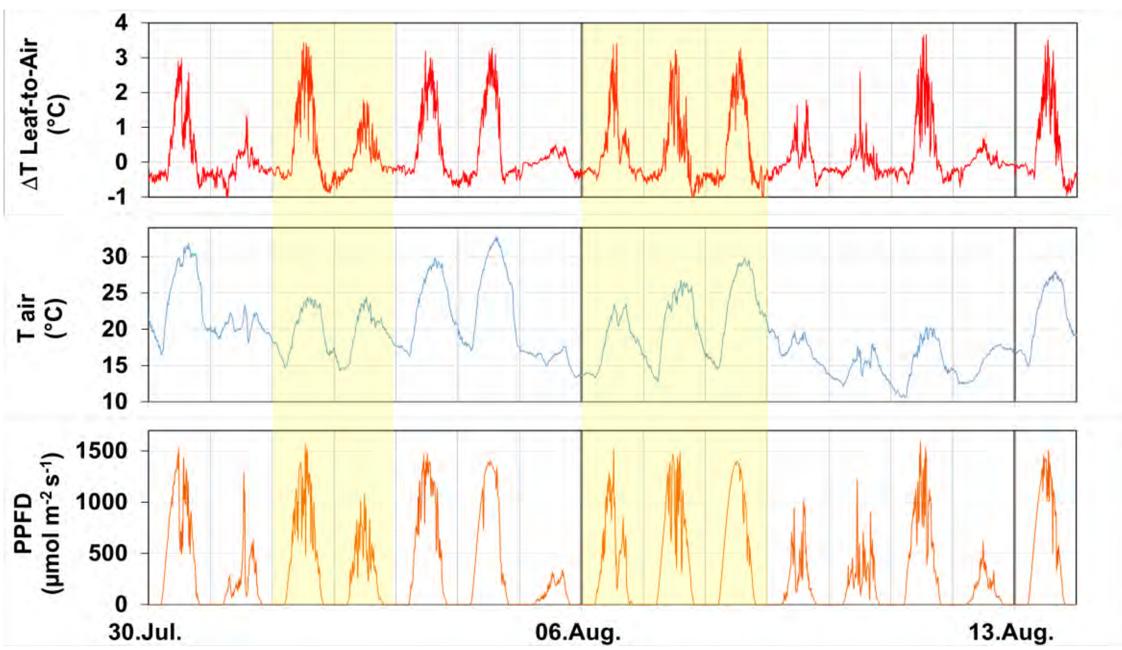


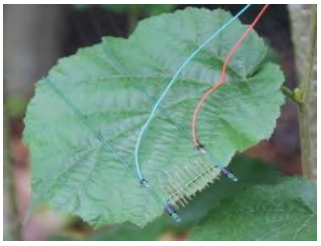
Fig. 1: Comparison of temperature difference between leaf surface and ambient air (ΔT), air temperature (Tair) and solar radiation (PPFD).

Upper: *Diurnal variations in temperature difference between upper leaf surface and ambient air (ΔT, measured via* ΔLA-B sensor*) of a sun exposed leaf of a mature beech tree at the experimental site “Kranzberger Forst” of the TU Munich.*

Middle: *Diurnal variations in air temperature (Tair), measured at canopy height (27m above ground)*

Lower: *Diurnal variations in solar radiation above canopy, given in photosynthetic photon flux density (PPFD)*

ΔLA-B ΔT Leaf-to-Air Sensor, broadleaf type



The ΔLA-B is a highly precise sensor for continuous measurements of temperature differences between leaf surface and ambient air. The signal is captured by means of a very thin chain (10-fold) of thermocouples. Distributed over the leaf surface, multiple measurement points are directly touching the leaf surface, providing a spatially integrative temperature signal. Designed for broad leaves, the sensor is mounted at the leaf with a light-weight wire frame.

Advantages
- Precise and continuous measurement of leaf-to-air temperature difference
- Multiple measurement points distributed over leaf surface, spatially integrative sensor signal
- Sensor output in mV, recordable with most of the common data loggers, no calibration for signal transformation in °C
- Minimal load on the target, no injury to plants
- Installation resistant against wind and rain
- Leaf size and shape specific ordering possible

Limits
- Not suitable for leaf sizes smaller than 2 cm

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools

Options / Ordering Information
- Cable extension (50m max, please specify in meters)
- If necessary, adjustments for different leaf sizes and shapes are possible
- Data Logger with integrated light, air humidity and air temperature sensors.

Technical specifications

Name	**ΔLA-B** : ΔT Leaf-to-Air Sensor, broadleaf type
Application position, suitable for leaf size	Leaf surface, standard size for leaves between 2 to 8 cm length
Range of the sensor	ΔT = +/- 20°C
Accuracy	Yoyo: +/-0,025°C; CR1000: +/-(0,06%*reading+0,01°C)
Resolution	Yoyo: 0,0004 °C; CR1000: 0,0025°C
Size and weight	3 cm x 3 cm x 0,1 cm, ca. 2 g
Output signal type	mVolt
Operating conditions	Air temperature:-25 to 70 °C, (CR1000: 0 to 40°C), air humidity: 0 to 100%

ΔLA-C ΔT Leaf-to-Air Sensor, conifer type

The ΔLA-C is a highly precise sensor for continuous measurements of temperature differences between conifer needle surface and ambient air. The signal is captured by means of a very thin chain (10-fold) of thermocouples. Designed for conifer needles, the sensor with its multiple measurement points is directly attached to different needles, providing a spatially integrative temperature signal.

Advantages
- Precise and continuous measurement of leaf-to-air temperature difference
- Multiple measurement points, spatially integrative signal
- Sensor output in mV, recordable with most of the common data loggers, no calibration for signal transformation in °C
- Minimal load on the target, no injury to plants
- Resistant against wind and rain

Limits
- Not suitable for conifer needles shorter than 3 mm

Delivery
- Complete with 5 m cable
- Fixing materials and installation tools

Options / Ordering Information
- Cable extension (50m max, please specify in meters)
- Data Logger with integrated light, air humidity and air temperature sensors

Technical specifications

Name	**ΔLA-C** : ΔT Leaf-to-Air Sensor, conifer type
Application position, suitable for needle size	Needle surface, needle length > 3mm
Range of the sensor	ΔT = +/- 20°C
Accuracy	Yoyo: +/-0,025°C; CR1000: +/-(0,06%*reading+0,01°C)
Resolution	Yoyo: 0,0004 °C; CR1000: 0,0025°C
Size and weight	ca. 0.1 g
Output signal type	mVolt
Operating conditions	Air temperature:-25 to 70 °C, (CR1000: 0 to 40°C), air humidity: 0 to 100%

Equitensiometer*

Type EQ15/Adapter: Equipped with screw adapter to connect with an extension tube, enabling deep soil installation

- Highly accurate instrument for measuring soil matric potential
- Due to a patented technique long-term measuring stability
- Covers a very wide range of matric potential that is most relevant for plant grow (from 0 to -1500 kPa)
- Individually calibrated sensors
- Maintenance-free for outdoor conditions, not affected by over-range
- Independent operation on a wide range of soil types and conditions
- Very low power consumption
- Easy installation
- Data recording with data logger or display with simple voltmeter
- More than 5 years field testing

What is matric potential?

There are two ways to measure soil moisture status, namely: Soil water content (swc) and soil water potential (ψs). Soil water content describes the amount of water in a given amount of soil relative to the mass of oven-dried soil. Matric potential (ψm), defined as the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water, identical in composition to the soil water , from a pool at an elevation and the external gas pressure of the point under consideration (Glossary of Soil Science Terms, Soil Science Society of America (SSSA), July 2000). If the specified quantity is volume, the potential is referred to as pressure (Pascal). Matric potential describes the moisture tension, or in other words the suction, resulting from combined effects of capillarity and adsorptive forces within the soil matrix. In non-saline soils, the osmotic component (ψo) of total soil water potential (ψs) can be neglected and matric potential remains the single main component of total soil water potential. The total soil water potential can be equated to the matric potential.

Why we need matric potential?

Plant-water relation studies, as well as irrigation control in automated agricultural production systems require meaningful and comparable information on soil water availability (dryness of soil). The plant physiologically relevant parameter for soil water availability is soil water potential (ψs), and not water content (swc). The two are however, related parameters:

Soil Water Availability = Water Potential
= f(Water Content, Soil Properties)

Soil water availability is, therefore, accurately described by its water potential, which is a function of water content and the soil properties. Hence, from soil water content alone it is neither possible to derive a physiologically meaningful quantification of soil water availability nor comparable results for different soil types. For example, a given plant could be turgid and growing very well in a sandy soil with 10% water content, but in clay soil with the same water content, the same plant could be wilting and dying.

Even if data on both water content and soil properties are available, the derivation of water potential from them is not simple, calling for actual measurements of soil water potential.

Due to lack of practicable instruments for measuring soil water potential under field conditions scientists have often used water content measurements to study soil-water–plant relationships. The disadvantage of such water content related studies is that the results cannot be reproduced and compared under different soil conditions. Many scientists have been working on plant-water relations to assist farmers identify the threshold value for irrigation water supply and several publications exist to the effect. However, none is able to answer the question; “How much soil moisture should I keep to meet optimal demands of my plants?” On a global context, this has lead to enormous loss of water resources. This problem could be solved, if future research efforts and the irrigation management strategies would be based on the quantification of soil water potential instead of soil water content.

* Patents pending

Principle of operation

Equitensiometer consists of two parts: water content sensor and equilibrium body. The water content sensor is permanently embedded in the equilibrium body and determines the water content of the equilibrium body instantaneously. The equilibrium body has a stable soil moisture characteristic.

During measurements, the equilibrium body acquires matric potential of the surrounding soil and the corresponding water content of the equilibrium body is recorded by the embedded water content sensor. The water content signal is then converted into matric potential, via the known, sensor specific calibration function.

Comparison of techniques for measuring matric potential

The concept of describing soil water availability for plants using water potential (Ψ) is known since 1907 (E. Buckingham). Scientists and engineers long recognized the importance of this measure and several attempts have been made in the last century to build equipment that can directly measure soil water potential (Ψs). Until the development of the EQ15 Equitensiometer there were only three existing techniques available namely: tensiometer, resistance block (gypsum block, watermark) and psychrometer. All three techniques however, have practical limitations with regard to range of operation, accuracy and costs (cf. Table below). With the EQ15, accurate monitoring of soil water potential under outdoor conditions is no longer just a pipe dream for scientists.

Comparison of techniques for measuring matric potential

Techniques	Range (kPa)	Advantages	Disadvantages
Resistance blocks	-100 to -700	1. Inexpensive	1. Must be calibrated individually by user 2. Unreliable measurement 3. Just for rough estimating the matric potential
Psychrometer	-200 to -10000	1. Useful in very dry soil 2. Measures totals water potential	1. Does not function in wet soil 2. Sensitive to temperature gradients in the soil 3. Expensive 4. Not suitable for outdoor conditions
Tensiometer	0 to -85	1. Relatively reliable	1. Does not function in dry soil 2. Costly maintenance and service 3. Not suitable for monitoring water availability for plants
EQ 15 Equitensiometer	0 to -1500	1. Reliable measurements 2. Covers a very wide range of matric potential that is most relevant for plant growth 3 Maintenance-free measurement	1. No linear output

Working with Equitensiometer

● Accuracy and Range

Equitensiometers are individually calibrated during production and every sensor has its own calibration certificate. This guarantees high sensor accuracy.

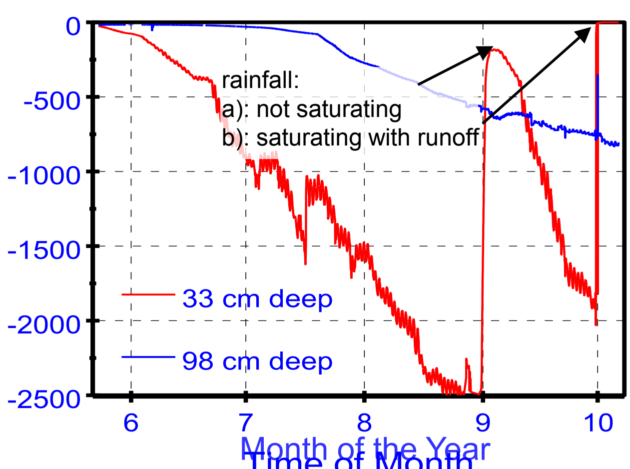


Fig.1 Course of matric potential in a Quercus suber Stand Very dry soil conditions in the upper soil (low matric potential, red line), relatively moist soil conditions in the lower soil (higher matric potential, blue line). Rainfall events: a, not saturating; b, saturating with runoff (peak of the blue graph).

A standard version sensor has a measuring range from 0 to -1500 kPa (0 to -15 bar). For special requirements, the range can be extended up to -2500 kPa (-25 bar; Fig. 1), but with reduced accuracy. A refill such as in transducer tensiometer is also not necessary.

● Effect of soil properties on the measurements

Unlike water content, water potential is an absolute measure and is independent of physical soil properties. For this reason the performance of Equitensiometer is not affected by the variation of physical soil properties (density, clay/sand/stone content and organic matter content).

The matric potential is derived from water content read within the equilibrium body. This is a decisive deviation from the gypsum block, which converts the electrical conductivity of soil solution to matric potential and is very sensitive to conductivity of the soil solution. Thus the EQ15 operates within a wide range of conditions and is independent of the soil chemical properties. However, in saline soils with conductivity>1 mS/cm, the results may be shifted to the dry range.

● Hysteresis

Equitensiometer is especially suitable for continuously monitoring matric soil water potential. The equilibrium body consists of materials with a higher water conductivity than any soil types. Under natural or irrigation conditions, the sensor can accurately follow any changes in soil matric potential without hysteresis (see fig. 2). But under artificial conditions if the matric potential is rapidly changed by more than 20 kPa/minute, the sensor may show a hysteresis effect. The necessary equilibration time limits the viability of instantaneous measurements with the Equitensiometer.

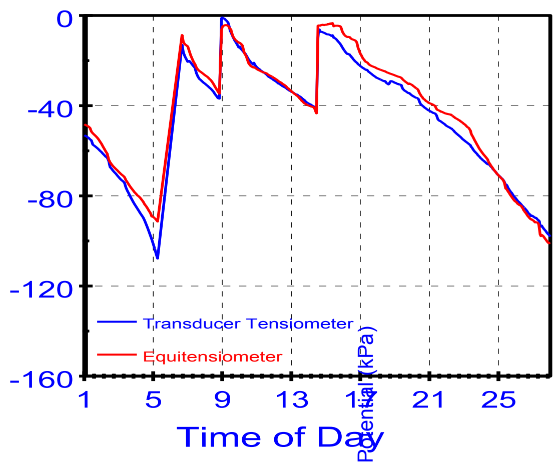


Fig. 2: Comparing the sensitivity of the EQ15 (red line) with transducer tensiometer (blue line). The soil was periodically irrigated. Either during the wetting or drying phases there were no significant differences between both sensors.

● Long term measurements

Fig. 4 shows results from Equitensiometer, when measurements were conducted in two neighbouring spruce and beech stands in Bavaria. The sensors worked for more than two years without any maintenance effort.

● Installation

The EQ15 is easy to install. The sensor is installed at the desired depth by burrowing and refilling the hole. In case of stony soil the sensor should be covered with quartz powder (or soil material with particle size between 20 to 100 µm) to improve the con-tact between the equilibrium body and soil. For installation in deep soil the use of the type EQ15/Adapter with an extension tube is re-commended. The disturbed soil structure does not affect the sensor performance.

● Data recording and Data processing

The Equitensiometer output is volt and ranges between 100 and 1000 mV. Any data logger with function of voltage measurement can be used for continuous data recording. For discontinuous measurements, the data can be read out with a simple voltmeter. Ecomatik supplies different logger types for different requirements.

Each Equitensiometer is provided with its own calibration certificate (Fig. 3), which gives the relationship between mV output, as read by the Equitensiometer, and its corresponding matric water potential in kPa. With the calibration certificate (Fig. 3), the data output can easily be automatically converted into kPa by data logger or by calculating using a computer.

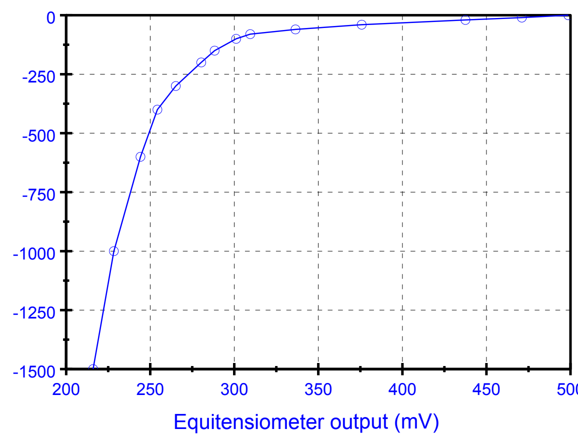


Fig. 3 Typical Calibration data of Equitensiometer

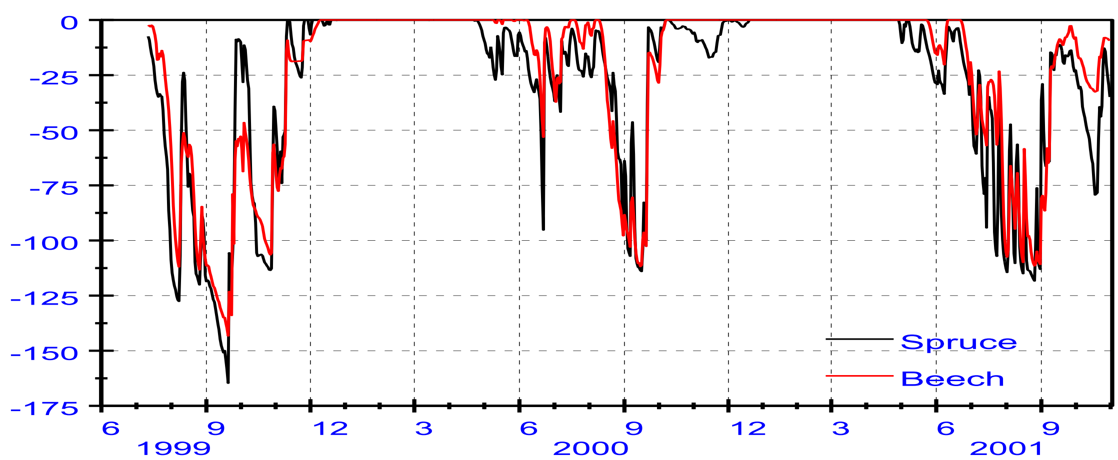


Fig. 4 Matric water potential in two neighbouring spruce and beech stands in Bavaria continu-ously measured with Equitensiometers. Corresponding to the transpiration characteristics the soil under spruce stand in Spring and in late Autumn is dryer than under beech stand (Unpublished data of Technical University of Munich).

Technical specification

Measuring parameter	Matric potential of the soil.
Range	0 to –1500 (-2500) kPa or 0 to –15 (-25) bar.
Accuracy	Between 0 kPa and -100 kPa: ±10 kPa. Between -100 kPa and -1500 kPa: 10%.
Hysteresis	Very low, can accurately follow any changes of matric potential in soils.
Use area	Monitoring of soil hydrology, plant physiology, soil water status, Irrigation control etc.
Environment	Wide range of soil types for long periods.
Interface	Input requirements: 5-15 V DC, Current consumption: max. 23 mA, Output signal: 100 -800 mV DC.
Case material	Stainless steel.
Dimensions and weight	Length × width × thickness = 17 cm × 4 cm × 2 cm, standard cable length: 5 m, max. Length: 100 m, weight: 350 g without cable.

Ordering Information

EQ15/Basic	Basic version for use in shallow soils
EQ15/Adapter	Equipped with a screw to connect with an extension tube, enabling installation in deep soils.
EQ15/Tube-1m	1 m PVC extension tube.
EQ15/Tube-2m	2 m PVC extension tube.
EQ15/Cable	Additional cable fitted to EQ15. Max. recommended length 100 m.
Quartz powder	To improve the contact of EQ15 to soil, recommended for use in stony soils.
Data Logger	On request.

Scientific publications related to Ecomatik equitensiometers

Gu, D., Zhen, F., Hannaway, D. B., Zhu, Y., Liu, L., Cao, W., & Tang, L. (2017). Quantitative Classification of Rice (Oryza sativa L.) Root Length and Diameter Using Image Analysis. *PLOS ONE*, *12*(1), e0169968. GO TO

Zeiter, M., Schärrer, S., Zweifel, R., Newbery, D. M., & Stampfli, A. (2016). Timing of extreme drought modifies reproductive output in semi-natural grassland. *Journal of Vegetation Science*, *27*(2), 238–248. GO TO

Schmidt, M. W. T., Schreiber, D., Correia, A., Ribeiro, N., Surový, P., Otieno, D., … Pereira, J. S. (2009). SAP FLOW IN CORK OAK TREES AT TWO CONTRASTING SITES IN PORTUGAL. *Acta Horticulturae*, (846), 345–352. GO TO

Otieno, D. O., Schmidt, M. W. T., Kurz-Besson, C., Do Vale, R. L., Pereira, J. S., & Tenhunen, J. D. (2007). Regulation of transpirational water loss in Quercus suber trees in a Mediterranean-type ecosystem. *Tree Physiology*, *27*(8), 1179–1187. GO TO

Kurz-Besson, C., Otieno, D., Lobo do Vale, R., Siegwolf, R., Schmidt, M., Herd, A., … Chaves, M. (2006). Hydraulic Lift in Cork Oak Trees in a Savannah-Type Mediterranean Ecosystem and its Contribution to the Local Water Balance. *Plant and Soil*, *282*(1–2), 361–378. GO TO

Werner, C., Unger, S., Pereira, J. S., Maia, R., David, T. S., Kurz-Besson, C., … Máguas, C. (2006). Importance of short-term dynamics in carbon isotope ratios of ecosystem respiration (? 13 C R) in a Mediterranean oak woodland and linkage to environmental factors. *New Phytologist*, *172*(2), 330–346. GO TO

Thomas, V. F. D., Braun, S., & Flückiger, W. (2006). Effects of simultaneous ozone exposure and nitrogen loads on carbohydrate concentrations, biomass, growth, and nutrient concentrations of young beech trees (Fagus sylvatica). *Environmental Pollution*, *143*(2), 341–354. GO TO

Otieno, D. O., Kurz-Besson, C., Liu, J., Schmidt, M. W. T., Do, R. V.-L., David, T. S., … Tenhunen, J. D. (2006). Seasonal variations in soil and plant water status in a Quercus suber L. Stand: roots as determinants of tree productivity and survival in the mediterranean-type ecosystem. *PLANT AND SOIL*, *283*(1–2), 119–135. GO TO

Wieser, G., Gigele, T., & Pausch, H. (2005). The carbon budget of an adult Pinus cembra tree at the alpine timberline in the Central Austrian Alps. *European Journal of Forest Research*, *124*(1), 1–8. GO TO

Thomas, V. F. D., Braun, S., & Flückiger, W. (2005). Effects of simultaneous ozone exposure and nitrogen loads on carbohydrate concentrations, biomass, and growth of young spruce trees (Picea abies). *Environmental Pollution*, *137*(3), 507–516. GO TO

Braun, S., Zugmaier, U., Thomas, V., & Flückiger, W. (2004). Carbohydrate concentrations in different plant parts of young beech and spruce along a gradient of ozone pollution. *Atmospheric Environment*, *38*(15), 2399–2407. GO TO

Wieser, G. (2004). Seasonal variation of soil respiration in a Pinus cembra forest at the upper timberline in the Central Austrian Alps. *Tree Physiology*, *24*(4), 475–480. GO TO

Not enough? Take a look at Google Scholar: (ecomatik OR ecomatic) AND (equitensiometer OR EQ*) (GO TO SEARCH)