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- Plant Growth
- Sap Flow
- Leaf Temperature
- Soil Moisture

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Dendrometers Page 1-14

Highly precise, flexible and convenient instruments for continuous measurement of changes in radius, diameter, circumference and length of various plant parts, e.g. Stem, root or fruit.

Sap Flow Sensors Page 15-18

SF-L: Highly accurate Sap Flow Sensor
SF-G: The conventional thermal dissipation probe (TDP) developed by Granier.

**Leaf Sensors
(NEW MODELS)** Page 19-22

Extremely lightweight and precise sensors for continuous measurements of leaf and air temperature.

Equitensiometers Page 23-26

Highly accurate and maintenance-free instrument for measuring soil matric potential (plant relevant availability of soil water, 0 to -15 bar).

Worldwide References Page 27-28

Dendrometer *

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Well proven instruments for high precision applications in environmental research

Ecomatik dendrometers continuously measure growth (e.g. stem, root, fruit, etc.) and water status related diameter variation of plants in response to their growth environment. Recorded with the same high temporal resolution as e.g. meteorological parameters, dendrometer signals allow the direct attribution of yield changes, biomass allocation or plant water status to the corresponding driving environmental factors (e.g. drought stress). Ecomatik dendrometers are hence widely used and well proven instruments in different fields of plant physiological and environmental research.

Efficient tools for new applications in precision farming

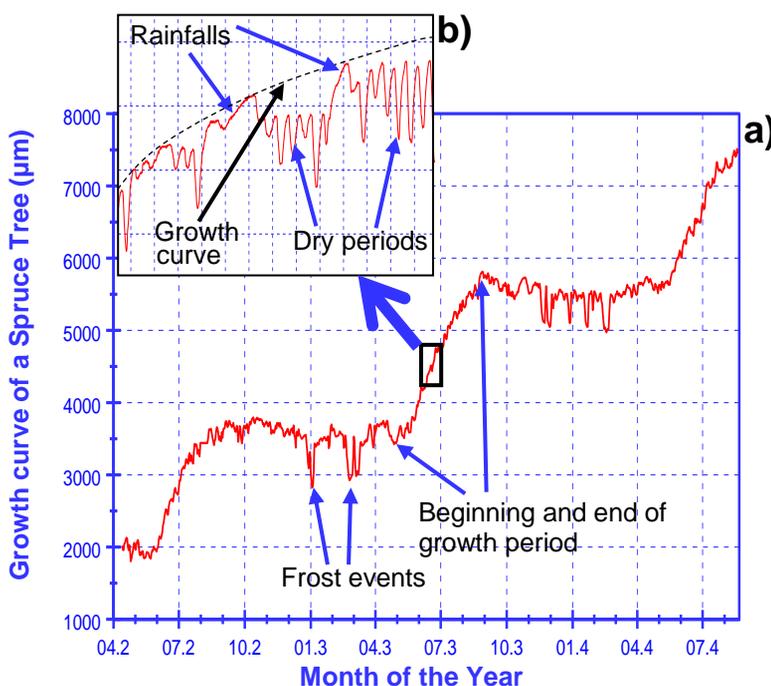
Technological advances and new applications in the field of precision agriculture benefit substantially from findings in plant physiological basic research. For example, understanding the relationship between dendrometer signals and plant water status. This relationship allows to make use of the simple, cost and energy efficient method of electronic dendrometry to continuously monitor plant water status and, where applicable, the automated control of irrigation. Together with the possibility of continuous growth monitoring (e.g. stem, root, fruit, etc.), electronic dendrometry provides crucial data for more precise yield projections and optimization of water use efficiency in production.

Applications

- Monitoring of growth processes of plants and fruits
- Monitoring of plant water status, i.a. in the context of:
 - ecological research
 - irrigation control
 - building activities affecting the ground water table
- Examination of the influence of environmental factors on plant growth
- Precise dating of beginning and end of the 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 60 countries (polar to tropical regions, high elevation sites, underwater, in soil)
- 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, roots, 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, as well as certain Arduino-based logging systems).



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 dampened diurnal amplitudes and the return of the diameter to the growth curve. (For further reading click: [1](#), [2](#), [3](#), [4](#), [5](#); or cf. 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).

* including several patented parts and techniques

Dendrometer

Available Dendrometer Types

Diameter dendrometers (small – large stems)

Name	Abbreviation	For diameter of
Diameter dendrometer small	DD-S1	0-5 cm
Diameter dendrometer small (quick mount version)	DD-S2	0-5 cm
Diameter dendrometer large	DD-L1	3-30 cm
Diameter dendrometer large (for fast growing species)	DD-L2	3-30 cm
Diameter dendrometer large (for very fast growing species)	DD-L3	3-30 cm
Diameter dendrometer (rugged)	DDW	3-20 cm

Radius dendrometers (medium – very large stems)

Name	Abbreviation	For diameter of
Radius dendrometer	DR1	>8 cm
Radius dendrometer (for fast growing species)	DR2	>8 cm
Radius dendrometer (with one instead of two mounting screws)	DR3	>5 cm
Radius dendrometer rugged	DRW	>8 cm

Circumference dendrometers (medium – very large stems)

Name	Abbreviation	For diameter of
Circumference dendrometer 1	DC1	5-30 cm
Circumference dendrometer 3	DC3	>5 cm
Circumference dendrometer 4 (for fast growing species)	DC4	>5 cm

Fruit and Vegetable dendrometers (small – large fruits)

Name	Abbreviation	For diameter of
Fruit, vegetable dendrometer (for small sized or slow growing fruits/vegetables)	DF1	0-11 cm (larger or smaller frame on request)
Fruit, vegetable dendrometer (small/medium sized and fast growing fruits and vegetables)	DF2	0-11 cm (larger or smaller frame on request)
Fruit, vegetable dendrometer (for fast growing fruits/vegetables)	DF3	0-11 cm (larger or smaller frame on request)

Dendrometers for special applications

Name	Abbreviation	For diameter of
Roots and aquatic Plants dendrometer	DRO	0-5 cm
Vertical dendrometer	DV	>8 cm

* including several patented parts and techniques

DR Radius Dendrometer

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DR-Type dendrometers are fixed with one (DR3) or two special screws (DR1 and DR2), anchored in the trunk wood. The changes outside of the trunk wood correspond to radial growth and water status related, diurnal diameter variation. The arrangement ensures high stability for long-term measurements.

Advantages

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

Delivery

- Complete with 5 m cable

Options / Ordering Information

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

Limits

- Trunk is injured by drilling (the damage can be minimized by tree resin)
- Suitable only for larger trees (diameter > 5 or 8 cm)

Technical specifications

Name of the Sensor	Radius dendrometer		
	Type DR1 (former name DR)	Type DR3	Type DR2
Scope of application	slow/normal growing species		fast growing species
Suitable for plant diameter	> 8 cm	> 5 cm	> 8 cm
Range of the sensor	11 mm		25.4mm
Resolution	The resolution of the sensor itself is infinite. Resolution of the sensor readings is determined by the connected data logger, e.g.		
	CR1000: 1.5 µm Dendrometer logger DL18: 0.2 µm		CR1000: 3.3 µm Dendrometer logger DL18: 0.5 µm
Accuracy	Dendrometer dependent: Max. ± 4.5% of reading (stable offset)		
			Max. ± 1.97% of reading (stable offset)
	Data logger dependent, e.g.:		
	CR1000: ±(0.04% of reading + 4.4µm) Dendrometer logger DL18: ±0.1%		CR1000: ±(0.04% of reading + 10µm) Dendrometer logger DL18: ±0.1%
Temperature coefficient of the sensor	< 0.2 µm / °C in the whole range		
Linearity	< 1%		< 0.7%
Environment	Outdoor condition: -25 to 70°C air temperature, 0 to 100% relative air humidity		
Weight of the sensor without cable	13 g		33 g
Power supply	Stabilized Vex of 0.5 – 10 VDC, power consumption practically zero		
Material	Stainless steel and Aluminium		
Cable length	5 m, extendable up to 100 m		

DRW Radius Dendrometer Rugged

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The DRW is the ruggedized version of the DR1 dendrometer type. In addition to the features of the simple DR1 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

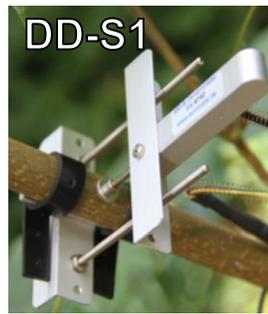
- Cable extension (please specify in meters)
- Installation tools (tree resin, hand drill)
- Data Logger

Technical specifications

Name	Rugged Radius Dendrometer (DRW)
Suitable for plant size	Diameter > 8 cm
Range of the sensor	11 mm
Accuracy	Dendrometer: stable offset $\pm 4.5\%$ Logger dependent, e.g.: CR1000: $\pm (0.04\% + 4.4 \mu\text{m})$ DL18: $\pm 0.1\%$
Resolution	0.2 - 2.6 μm (dependent on data logger used)
Linearity	<1%
Thermal expansion coefficient of sensor	<0.2 $\mu\text{m/K}$
Operating conditions	Air temperature: -25 to 70 °C, air humidity: 0 to 100%

DD-S Diameter Dendrometer Small

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The DD-S Type dendrometers are designed specifically for agricultural plants, small trees and branches (diameter < 5 cm). Due to the optimized 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. The sensor is available in two versions: DD-S1 with standard mounting frame, DD-S2 with quick mount frame

Advantages

- Suitable for small trees and agricultural plants
- Plants do not have to bear the weight of the dendrometer (with separate support construction for very small and delicate 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

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

Limits

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

Technical specifications

Name of the Sensor	Diameter dendrometer small	
	Type DD-S1 (former name DD-S)	Type DD-S2
Scope of application	slow/normal growing, woody and herbaceous species standard mounting frame	fast, toolless installation
Suitable for plant size	Diameter 0-5 cm	
Range of the sensor	11 mm	
Resolution	The resolution of the sensor itself is infinite. Resolution of the sensor readings is determined by the connected data logger, e.g. CR1000 (differential w/i): 1.5 µm Dendrometer logger DL18: 0.2 µm	
Accuracy	Dendrometer dependent: max. ±4.5% of reading (stable offset) Logger dependent, e.g.: CR1000: ± (0.04% of reading +4.4 µm) Dendrometer logger DL18: ±0.1%	
Temperature coefficient of the sensor	< 0.2 µm / °C in the whole range	
Linearity	<1%	
Environment	Outdoor condition: -25 to 70°C air temperature, 0 to 100% relative air humidity	
Weight of the sensor	13 g without cable	15 g without cable
Power supply	Stabilized Vex of 0.5 – 10 VDC, power consumption practically zero	
Material	Stainless steel and Aluminium	
Cable length	5 m, extendable up to 100 m	

DD-L Diameter Dendrometer Large

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DD-L type dendrometers are mounted at the plant with two elastic, and uv-resistant rubber belts. With this easy and very stable fixation, the sensor remains at the desired measuring point, without exerting excessive pressure on the stem. The sensor is available in three versions: DD-L1 with standard measuring range of 11 mm for slow and normal growing species and DD-L2 and DD-L3 with increased measurement range of 25 mm and 50 mm respectively, for fast growing species. Both models are suitable for stem diameters between 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

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

Limits

- Not suitable for diameter greater than 30 cm

Technical specifications

Name of the Sensor	Diameter Dendrometer Large		
	Type DD-L1 (former name DD-L)	Type DD-L2	Type DD-L3
Scope of application	slow/normal growing species	fast growing species	
Suitable for plant diameter	stem diameter 3-30 cm		
Range of the sensor	11 mm	25.4 mm	50.8 mm
Resolution	The resolution of the sensor itself is infinite. Resolution of the sensor readings is determined by the connected data logger, e.g.		
	CR1000: 1.5 μm Logger DL18: 0.2 μm	CR1000: 3.3 μm Logger DL18: 0.5 μm	CR1000: 6.6 μm Logger DL18: 1.0 μm
Accuracy	Max. $\pm 4.5\%$ of reading (stable offset)	Dendrometer dependent: Max. $\pm 1.97\%$ of reading (stable offset)	Max. $\pm 0.98\%$ of reading (stable offset)
	CR1000: $\pm(0.04\%$ of reading + 4.4 $\mu\text{m})$ Dendrometer logger DL18: $\pm 0.1\%$	Data logger dependent, e.g.: CR1000: $\pm(0.04\%$ of reading + 10 $\mu\text{m})$ Dendrometer logger DL18: $\pm 0.1\%$	CR1000: $\pm(0.04\%$ of reading + 20 $\mu\text{m})$ Dendrometer logger DL18: $\pm 0.1\%$
Temperature coefficient of the sensor	< 0.2 $\mu\text{m} / ^\circ\text{C}$ in the whole range		
Linearity	< 1%	< 0.7%	< 0.5%
Environment	Outdoor condition: -25 to 70°C air temperature, 0 to 100% relative air humidity		
Weight of the sensor without cable	13 g	33 g	37 g
Power supply	Stabilized Vex of 0.5 – 10 VDC, power consumption practically zero		
Material	Stainless steel and Aluminium		
Cable length	5 m, extendable up to 100 m		

DDW Diameter Dendrometer Rugged

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The DDW is the ruggedized version of the DD-L1 dendrometer type. In addition to the features of the DD-L1 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 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 3 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 3-20 cm (range on request extendable)
Range of the sensor	11 mm
Accuracy	Dendrometer: stable offset $\pm 4.5\%$ Logger dependent, e.g.: CR1000: $\pm (0.04\% + 4.4 \mu\text{m})$ DL18: $\pm 0.1\%$
Resolution	0.2 - 2.6 μm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	$< 0.2 \mu\text{m/K}$
Operating conditions	Air temperature: -25 to $70 \text{ }^\circ\text{C}$, 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 by means of a stem embracing cable wire. The cable wire consists of a special material (purpose specific alloy), with the lowest thermal expansion coefficient available. Slide rings reduce the friction and pressure between the wire cable and the tree bark.

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

- Elastic force of the sensor is exerted in tangential direction. The contact pressure between cable wire and stem hence depends on the curvature of the stem, i.e. the stem diameter (cf. [Young-Laplace equation](#)): -> larger the stem radius, the lower the contact pressure between cable wire and stem surface, leading to comparability problems (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	Dendrometer: stable offset $\pm 4.5\%$ Logger dependent, e.g.: CR1000: $\pm (0.04\% + 4.4 \mu\text{m})$ DL18: $\pm 0.1\%$
Resolution	0.2 - 2.6 μm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	$< 0.2 \mu\text{m/K}$
Thermal expansion coefficient of the wire cable	$< 1.4 \times 10^{-6}/\text{K}$
Operating conditions	Air temperature: -25 to $70 \text{ }^\circ\text{C}$, air humidity: 0 to 100%

DC Circumference Dendrometer

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The DC3 and DC4 are the improved versions 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 tree diameter (for further information please visit our internet page). Comparability of data from trees of different sizes is improved. The sensor is mounted by means of two elastic and uv-resistant rubber belts. The stem signal is received by a stem embracing cable wire (special alloy with very low thermal expansion).

Advantages

- Suitable for all tree sizes (> 5 cm)
- Contact pressure between wire cable and tree adjusts with tree diameter
- Sensitive measurements, even with very large trees
- No injury to plants
- Stability against wind, snow, falling small branches and small fruits
- Easy installation

Delivery

- Complete with 5 m cable
- Fixing materials and and 1 m wire cable

Options / Ordering Information

- Cable extension (please specify in meters)
- If necessary, cable wire length (please specify in meters)
- Data Logger

Limits

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

Technical specifications

Name of the Sensor	Circumference Dendrometer			
	Type DC3		Type DC4	
Scope of application	slow/normal growing species		fast growing species	
Suitable for	stem diameter > 5 cm			
Range of the sensor	25.4 mm		50.8mm	
Corresponding range for tree diameter	circumference	diameter	circumference	diameter
10 cm	50	16.2	107	34.0
50 cm	35	11.3	80	25.6
100 cm	28	9.0	65	20.6
Resolution	The resolution of the sensor itself is infinite. Resolution of the sensor readings is determined by the connected data logger, e.g.			
	CR1000: 3.3 μm Dendrometer logger DL18: 0.5 μm		CR1000: 6.6 μm Dendrometer logger DL18: 1.0 μm	
Accuracy	Dendrometer dependent: Max. $\pm 1.97\%$ of reading (stable offset) Max. $\pm 0.98\%$ of reading (stable offset)			
	Data logger dependent, e.g.:			
	CR1000: $\pm(0.04\%$ of reading + $10\mu\text{m}$) Dendrometer logger DL18: $\pm 0.1\%$		CR1000: $\pm(0.04\%$ of reading + $20\mu\text{m}$) Dendrometer logger DL18: $\pm 0.1\%$	
Temperature coefficient sensor wire	< 0.2 $\mu\text{m} / ^\circ\text{C}$ in the whole range < $1.4 \times 10^{-6}/\text{K}$			
Linearity	< 0.7%		< 0.5%	
Environment	Outdoor condition: -25 to 70°C air temperature, 0 to 100% relative air humidity			
Weight of the sensor without cable	37 g		47 g	
Power supply	Stabilized Vex of 0.5 – 10 VDC, power consumption practically zero			
Material	Stainless steel, special alloy and Aluminium			
Cable length	5 m, extendable up to 100 m			

DF Fruit and Vegetable Dendrometer

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Fruit and Vegetable Dendrometers are special dendrometers for measurements on circular fruiting bodies. The special design allows that the fruit is firmly fixed in measuring frame, without affecting its growth. Flexibly fixed on the branch, the frame sustains the weight of the fruit and relieves the peduncle. The DF series comprises three different models. The DF1 for small or slow growing fruits (e.g. cherry, grape), the DF2 for medium sized and fast growing fruits (e.g. apple, orange) and the DF3 for large and fast growing fruits (e.g. pumpkin).

Advantages

- Fruits do not have to bear the weight of the dendrometers
- Measures diameter changes
- Assessment of ripeness for softening fruit types
- No Injury to fruits
- Stability against wind, snow, falling small branches and small fruits

Delivery

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

Options / Ordering Information

- Cable extension (please specify in meters)
- Customized frame size (please specify in cm)
- Data Logger

Limits

- Not suitable for very soft and thin-skinned fruit types (e.g. such as ripe raspberries)

Technical specifications

Name of the Sensor	Radius dendrometer		
	Type DF1 (former name DR)	Type DF2	Type DF3
Scope of application	small or slow growing fruits	medium and fast growing fruits	large and fast growing fruits
Suitable for fruit diameter	0-11 cm (larger or smaller frame sizes on request)		
Range of the sensor	15 mm	25.4mm	50.8mm
Resolution	The resolution of the sensor itself is infinite. Resolution of the sensor readings is determined by the connected data logger, e.g.		
	CR1000: 2 µm Logger DL18: 0.3 µm	CR1000: 3.3 µm Logger DL18: 0.5 µm	CR1000: 6.6 µm Logger DL18: 1.0 µm
Accuracy	Max. ± 3.3% of reading (stable offset)	Dendrometer dependent: Max. ±1.97% of reading (stable offset)	Max. ±0.98% of reading (stable offset)
	CR1000: ±(0.04% of reading + 6 µm) Logger DL18: ±0.1%	Data logger dependent, e.g.: CR1000: ±(0.04% of reading + 10 µm) Logger DL18: ±0.1%	CR1000: ±(0.04% of reading + 20 µm) Logger DL18: ±0.1%
Temperature coefficient	< 0.2 µm / °C in the whole range		
Linearity	< 2%	< 0.7%	< 0.5%
Environment	Outdoor condition: -25 to 70°C air temperature, 0 to 100% relative air humidity		
Weight of the sensor without cable	15 g	26g	37 g
Power supply	Stabilized Vex of 0.5 – 10 VDC, power consumption practically zero		
Material	Stainless steel and Aluminium		
Cable length	5 m, extendable up to 100 m		

DRO Root and Aquatic Plant Dendrometer

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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 that of 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.

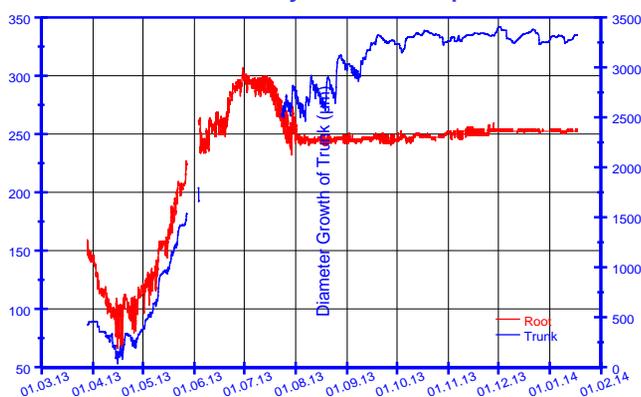
Advantages

- 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 5 cm

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.

Delivery

- Complete with 5 m cable

Options / Ordering Information

- Cable extension (please specify in meters)
- Data Logger

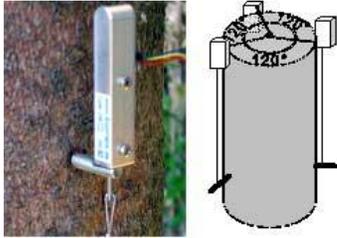
Technical specifications

Name	Root Dendrometer (DRO)
Suitable for plant size	Diameter <5 cm
Range of the sensor	11 mm
Accuracy	Dendrometer: stable offset $\pm 4.5\%$ Logger dependent, e.g.: CR1000: $\pm (0.04\% + 4.4 \mu\text{m})$ DL18: $\pm 0.1\%$
Resolution	0.2 - 2.6 μm (dependent on data logger used)
Linearity	<1%
Thermal expansion coefficient of sensor	<0.2 $\mu\text{m}/\text{K}$
Operating conditions	Temperature: -25 to 70 °C, in and on soil, under water

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 exhibited 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.

DV Vertical Dendrometer

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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 information to assess water status and static characteristics, such as mechanical stress-strain relationships and mechanical stability of trees. 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	Dendrometer: stable offset $\pm 4.5\%$ Logger dependent, e.g.: CR1000: $\pm (0.04\% + 4.4 \mu\text{m})$ DL18: $\pm 0.1\%$
Resolution	0.2 - 2.6 μm (dependent on data logger used)
Linearity	1%
Thermal expansion coefficient of sensor	< 0.2 $\mu\text{m}/\text{K}$
Thermal expansion coefficient of the wire cable	< $1.4 \times 10^{-6}/\text{K}$
Operating conditions	Air temperature: -25 to 70 °C, air humidity: 0 to 100%

Data Logging

www.ecomatik.de

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



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)

Some of the worldwide users of our dendrometers in more than 60 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 Biogeochemie, 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

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Not enough? Take a look at Google Scholar: dendrometer +Ecomatik ([GO TO SEARCH](#))

SF-L Sap Flow Sensor*

www.ecomatik.de



- 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) The Granier method arbitrarily sets the sap flow to zero 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 errors in the results (DO and Rocheteau, 2002).

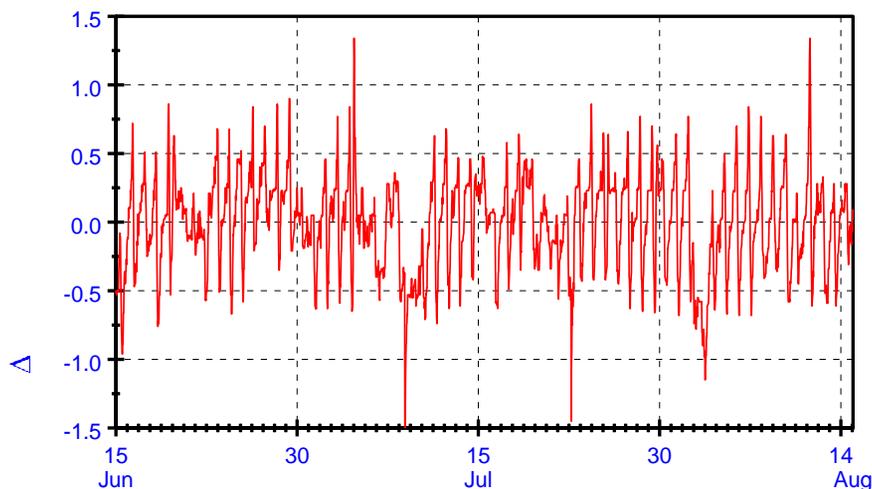


Fig.1 Vertical temperature gradients of a 40-year old spruce tree, measured with a Granier sensor with the heating turned off.

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 ($\Delta TR1$, $\Delta TR2$; 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 $\Delta TR1$, $\Delta TR2$.

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 ΔT_{max} value (temperature difference between the heated needle and the sapwood ambient temperature when sap flow=0). The ΔT_{max} value is attained under conditions of zero transpiration and zero tree body refilling. This means 100% air humidity and zero tree diameter expansion. The diameter changes are detectable with high accuracy using Ecomatik dendrometers (Fig. 3).

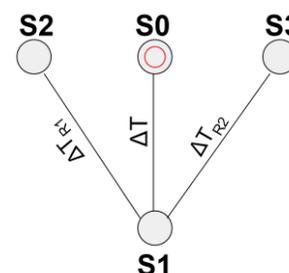


Fig. 2 Schematic diagram of the SF-L sensor

Usually there is only one universal value of ΔT_{max} in a growth period of a tree. The ΔT values in the night are dependent on the refilling state of the tree and the nocturnal transpiration demand, they rarely attain ΔT_{max} . Correct determination of ΔT_{max} enables accurate measurements of nocturnal 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.

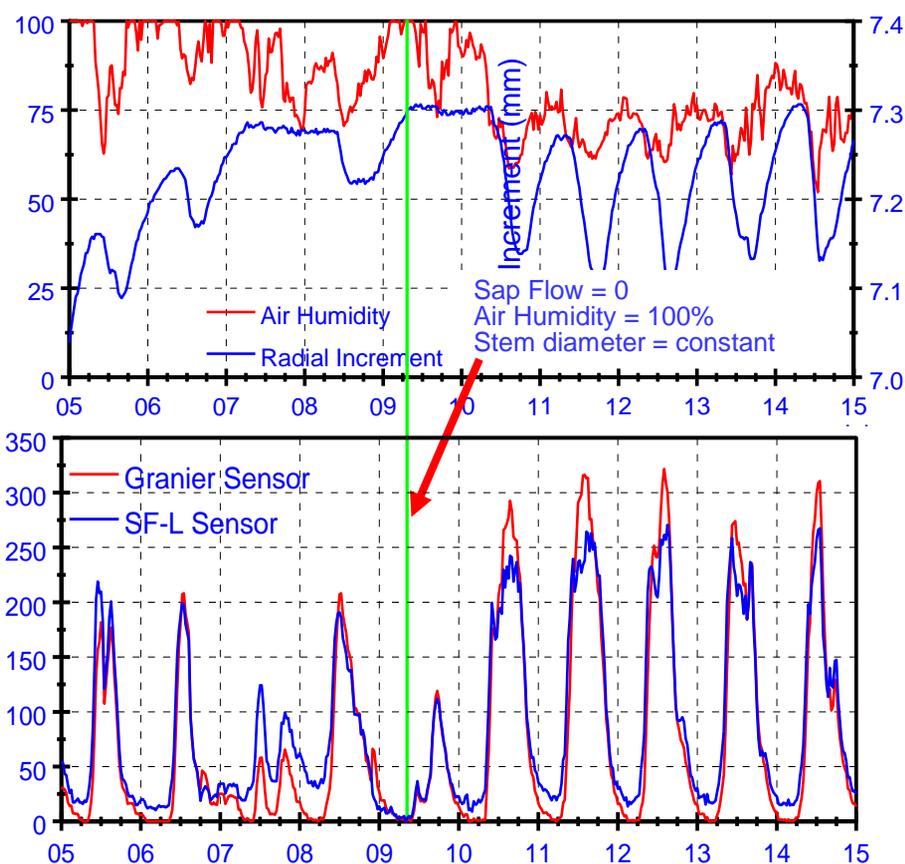


Fig. 3

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 $\mu\text{l cm}^{-2} \text{min}^{-1}$ 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

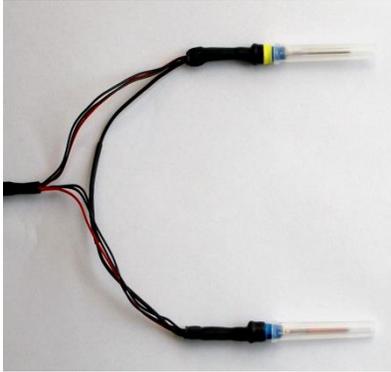
Sensor	
Sensor composition	4 needles
Needle size	33 mm length, 1.5 mm diameter
Heating zone	20 mm from top of the needle
Cable length	5 m, extendable to 20 m
Tree size	Diameter > 8 cm
Power consumption	0.2 W +/-5%, 84 mA DC, stabilized
Output	-100 μV to 1000 μV DC
Data Recording	3 differential channels required
Power supply	
Input	12 V DC
Output	84 mA stabilized, suitable for 1 to 3 SF-L sensors

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SF-G Sap Flow Sensor

www.ecomatik.de



Introduction

The SF-G is the well-known thermal dissipation probe (TDP) developed by André 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 >2 cm
Power consumption	0.2 W +/-5%, 84 mA DC, stabilized
Output	100 μ V to 800 μ V DC
Logger requirement	1 differential channel

Scientific publications related to Ecomatik sap flow sensors www.ecomatik.de

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Not enough? Take a look at Google Scholar: “sap flow” +Ecomatik ([GO TO SEARCH](#))

Leaf Temperature Sensor (NEW) *

www.ecomatik.de



Type LAT-B2: Broad leaf version of the LAT-Sensor (Leaf-&-Air-Temperature)

- Direct, continuous and highly accurate, measurements of leaf (T_{leaf}) and air temperature (T_{air}).
- Dual-probe matching for highest precision of leaf-to-air temperature difference ($\Delta T_{leaf-air}$)
- Small and light-weight sensor with minimal load on the leaf
- Sensor signal in mV, recordable with most common data loggers
- Suitable for measurements under field conditions
- Extremely low power consumption
- Easy installation

Why we 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 ($\Delta T_{leaf-air}$). Simplified, the phenomenon can be reduced to three main components:

1. Different energy influx:

Exposed to solar radiation, differing optical properties (absorptivity, reflectivity and transmissivity) of the regarded object and the air result in different magnitudes of energy input, which is converted into thermal energy.

2. Different thermic capacity:

The specific capacity of a substance to store thermal 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 $\epsilon = 1$ 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 size of the surface as well as wind speed.

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

Why do we need to know leaf temperature?

- Physiological and ecological temperature limits (stress monitoring):

At both ends of the species specific temperature range we observe lethal temperature limits (chilling, heat stress). The only reliable parameter to identify leaf temperature stress (for monitoring as well as early-warning systems in smart farming) is the actual leaf surface temperature.

- Leaf functioning:

Due to their central function as photosynthesis organs, 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, whereas all chemical reactions and hence whole leaf physiology depends on leaf temperature.

- Plant ecological, physiological as well as agricultural modelling (yield, pest and pathogen) :

Actual leaf temperature is decisive for physiological functioning, at the leaf as well as the whole plant level and therefore a key input parameter in modelling (i.a. species distribution, assimilation, transpiration, pathogen and herbivore development, stomatal conductance, microclimate effect of the canopy, O₃-uptake, 13C and 18O of assimilates). Continuous and precise measurements of the actual leaf temperature can substantially improve model reliability in plant research as well as in smart agriculture.

The LAT sensor as solution and its principle of measurement

Air temperature measurements are reliable and affordable. Notwithstanding, the parameter cannot be readily employed as surrogate for leaf temperature (cf. explanation above). Additionally to local air temperature (T_{air}), actual leaf temperature (T_{leaf}) and the temperature difference between ambient air and the leaf surface ($\Delta T_{\text{leaf-air}}$) are most important.

In case of the LAT-C for coniferous species, local absolute air temperature is measured by means of a highly precise micro thermistor. Additionally multiple thin thermocouples (10-fold) are employed to measure $\Delta T_{\text{leaf-air}}$, in order to enable representative (integrating temperature signal of 10 needle leaves) and high resolution measurements.

In case of the LAT-B2, both T_{air} and T_{leaf} are measured by means of two highly precise micro thermistors. Individual matching of the thermistor couple ensures maximum accuracy of $\Delta T_{\text{leaf-air}}$.

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 a very high signal-to-noise ratio.
2. Multiple, spatially distributed measurement points in direct contact with a sample of 10 needles, provide an integrative temperature signal of the needle 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 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 LAT sensors 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 ($\Delta T_{\text{leaf-air}}$) were measured with a LAT-B2 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 $\Delta T_{\text{leaf-air}}$ 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 $\Delta T_{\text{leaf-air}}$, air temperature (T_{air}) and solar radiation (PPFD), it becomes evident that, $\Delta T_{\text{leaf-air}}$ depended mainly on solar radiation but not on T_{air} . Additionally to often unknown leaf transpiration rates (i.e. latent heat flux), this aspect illustrates another potential source of error, when mere T_{air} is employed in plant ecological modelling instead of T_{leaf} .

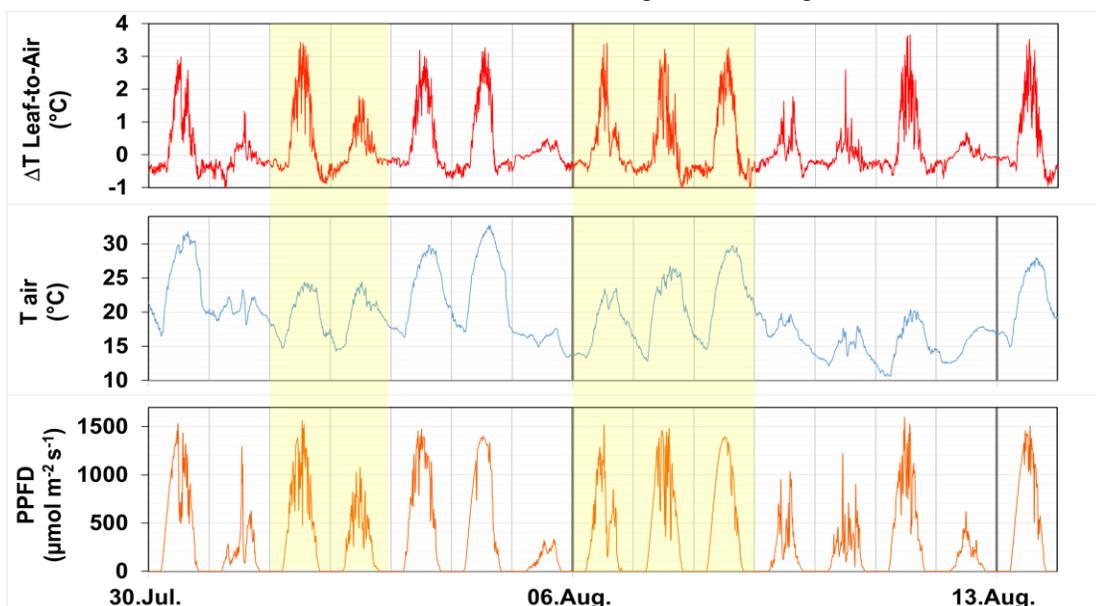


Fig. 1: Comparison of temperature difference between leaf surface and ambient air ($\Delta T_{\text{leaf-air}}$), air temperature (T_{air}) and solar radiation (PPFD).

Upper: Diurnal variations in temperature difference between upper leaf surface and ambient air ($\Delta T_{\text{leaf-air}}$, measured via LAT-B2 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 (T_{air} , measured via LAT-B2 sensor), at canopy height (27m above ground)

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

LAT Leaf-&-Air-Temperature Sensor

www.ecomatik.de



Advantages

- Precise and continuous measurement of leaf-to-air temperature difference and local absolute air temperature
- Multiple measurement points distributed over leaf/needle surface, spatially integrative sensor signal
- Minimal load on the target, no injury to plants
- Installation resistant against wind and rain
- Leaf/needle size and shape specific ordering possible

Limits

- Not suitable for sizes smaller than 3 cm (leaf) and 3mm (needle)

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

The LAT-C is a highly precise sensors for continuous measurements of temperature differences between needle surface and air ($\Delta T_{\text{leaf-air}}$) as well as local absolute air temperature (T_{air}). Temperature signals are captured by means of a very thin chain (10-fold) of thermocouples and a air-sided, highly precise micro thermistor. Distributed over the leaf or needle surface, multiple measurement points are in direct contact with the leaf or needle surface, providing a spatially integrative and hence representative temperature signal. LAT-C sensors are very light-weight and either mounted on the leaf blade with a carbon frame, or directly attached to the needles themselves.

Technical specifications

Name	Leaf-&-Air Temperature Sensor LAT-C (conifer needle type)
Application position, Suitable for needle size	Conifer needle surface, needle length > 3mm
Range of the sensor - thermopile ($\Delta T_{\text{leaf-to-air}}$) - thermistor (T_{air})	$\Delta T = \pm 20^\circ \text{ C}$ $T_{\text{air}} = -40 \text{ to } 125^\circ \text{ C}$
Accuracy - thermopile ($\Delta T_{\text{leaf-to-air}}$) - thermistor (T_{air})	CR1000: $\pm (0.06\% \cdot \text{reading} + 0.01^\circ \text{ C})$ CR1000: $\pm 0.2^\circ \text{ C}$
Resolution - thermopile ($\Delta T_{\text{leaf-to-air}}$) - thermistor (T_{air})	- Theoretically infinite, depends on data logger. (e.g. CR1000-Logger with 1 μV resolution within a Signal range of $\pm 7.5 \text{ mV}$: 0.0025° C) - Theoretically infinite, depends on data logger (e.g. CR1000-Logger with 667 μV resolution within a Signal range of $\pm 2500 \text{ mV}$: 0.1° C)
Size and weight	2 cm x 2 cm x 0.1 cm, ca. 2 g
Output signal type - thermopile ($\Delta T_{\text{leaf-to-air}}$) - thermistor (T_{air})	- At a ΔT range of $\pm 20^\circ \text{ C}$ signal ranges within $\pm 8.5 \text{ mV}$ - Supplied with 2500 mV, output signal is 0 to 2500mV
Power supply - thermopile ($\Delta T_{\text{leaf-to-air}}$) - thermistor (T_{air})	- Not required - Excitation voltage Vex usually switched 2500 mV, power up 100ms max. power consumption negligible.
Operating conditions	Air temperature: $-25 \text{ to } 70^\circ \text{ C}$, air humidity: 0 to 100%

LAT-B2 Leaf-to-Air Sensor



The LAT-B2 (Leaf-&Air-Temperature Broadleaf type) is a highly precise sensor for continuous measurements of leaf surface and ambient air temperatures. Absolute air temperature (T_{air}) and leaf temperature (T_{leaf}) are measured via two highly precise micro thermistor probes. Sensor-individual matching of the two probes, ensures high precision of leaf-to-air temperature difference ($\Delta T_{leaf-air}$). Designed for broad leaves, the sensor is mounted at the leaf by means of a ultra-light-weight carbon frame.

Advantages

- Precise and continuous measurement of leaf-to-air temperature difference
- 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 3 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	LAT-B2 : Leaf-&Air Temperature Sensor, broadleaf type
Application position, suitable for leaf size	Leaf surface, standard size for leaves between > 3 to 20 cm length
Range of the sensor	-40 to 125° C
Accuracy	Sensor dependent: Absolute accuracy of T_{air} & T_{leaf} : +/- 0.2 ° C $\Delta T_{leaf-air}$: +/- 0.1 ° C (sensor-individual dual-probe matching!) Logger dependent: e.g. CR1000: +/- 0.2 ° C
Resolution	Theoretically infinite, depends on data logger (e.g.: 0.1° C)
Size and weight	2 cm x 2 cm x 0.1 cm, ca. 2 g
Output signal type	Supplied with 2500 mV, output signal is 0 to 2500mV
Power supply	Excitation voltage Vex usually switched 2500 mV, power up 100ms max. Power consumption negligible.
Operating conditions	Air temperature: -25 to 70 ° C, air humidity: 0 to 100%

Equitensiometer*

www.ecomatik.de



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 (ψ_s). Soil water content describes the amount of water in a given amount of soil relative to the mass of oven-dried soil. Matric potential (ψ_m), 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 (ψ_o) of total soil water potential (ψ_s) 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 (ψ_s), and not water content (swc). The two are however, related parameters:

$$\begin{aligned} \text{Soil Water Availability} &= \text{Water Potential} \\ &= f(\text{Water Content, Soil Properties}) \end{aligned}$$

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 led 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.

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 (Ψ_s). 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.

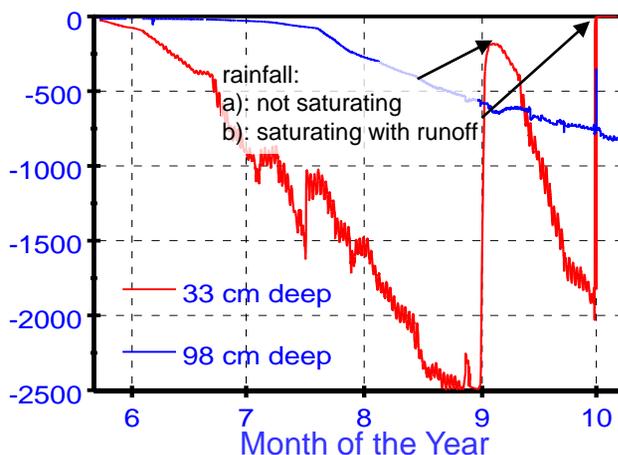


Fig.1 Course of matric potential in a Quercus suber Stand Very dry soil conditions in the upper soil (low matric potential, red line), relatively moist soil conditions in the lower soil (higher matric potential, blue line). Rainfall events: a, not saturating; b, saturating with runoff (peak of the blue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

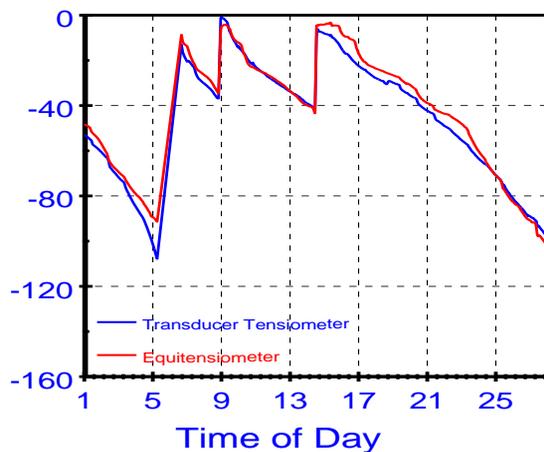


Fig. 2: Comparing the sensitivity of the EQ15 (red line) with transducer tensiometer (blue line). The soil was periodically irrigated. Either during the wetting or drying phases there were no significant differences between both sensors.

• 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.

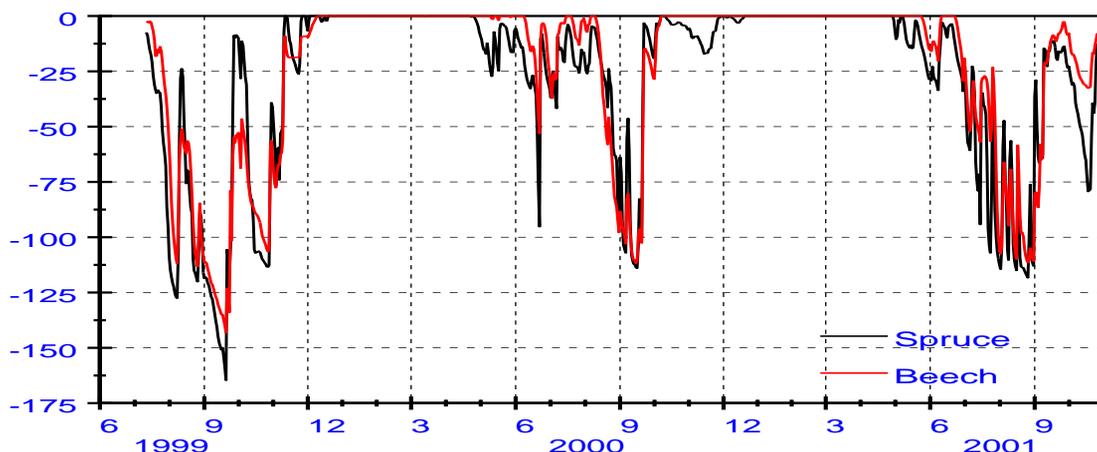


Fig. 4 Matric water potential in two neighbouring spruce and beech stands in Bavaria continuously measured with Equitensiometers. Corresponding to the transpiration characteristics the soil under spruce stand in Spring and in late Autumn is dryer than under beech stand (Unpublished data of Technical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

• 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 contact between the equilibrium body and soil. For installation in deep soil the use of the type EQ15/Adapter with an extension tube is recommended. 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.

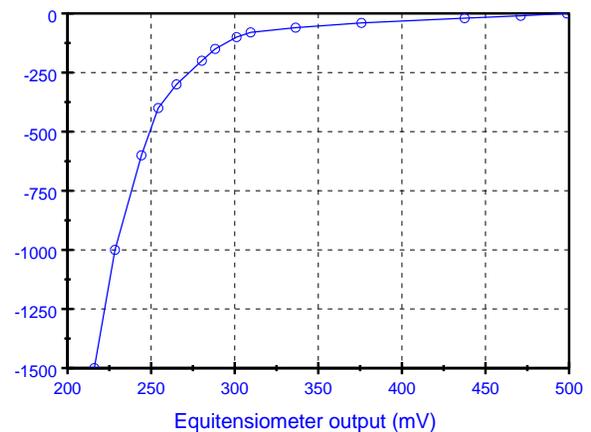


Fig. 3 Typical Calibration data of Equitensiometer

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

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