

Measuring the average relative air humidity in soils over up to hundreds of square meters?



Global annual soil degradation affects about 10×10^6 ha (UBA, 2014)

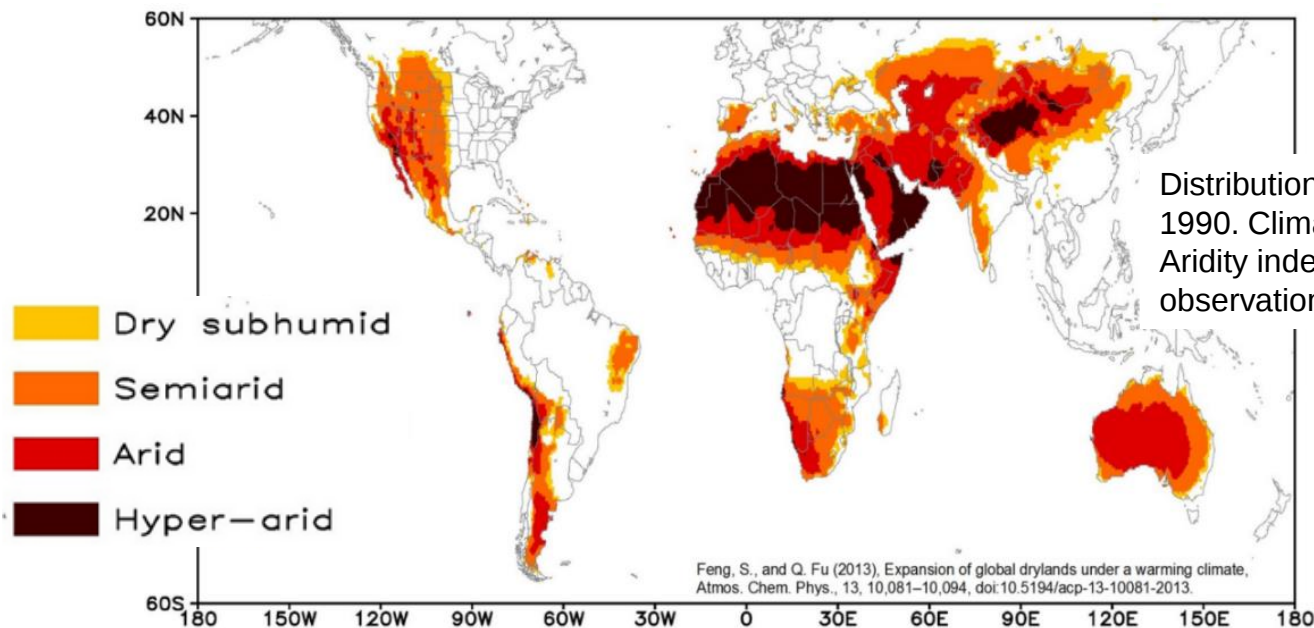
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Walter Lazik and Ralph Meissner

Increasing population size in combination with the expansion of dry areas worldwide makes it imperative to increase water use efficiency

Due to the current expansion of arid regions, the pressure on available water resources is increasing. A suitable measure for water availability and dynamics in dry soil is the relative humidity (RH) of the soil air as shown in Goss and Madliger (2007).

Monitoring of water vapor in soil, i.e. RH of soil air, can help:

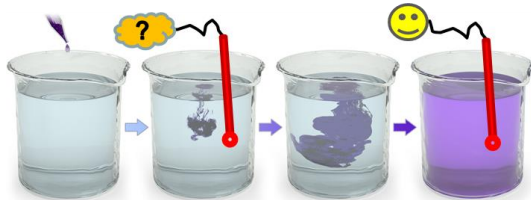
- to enhance the efficiency of water use by agriculture “More Crop Per Drop”
- to investigate liquid and vapor water movement in dry soil
- to feed remote sensing with ground-truth data



Distribution of drylands for 1961-1990. Climatology derived from Aridity index (P/PET) based on observations.

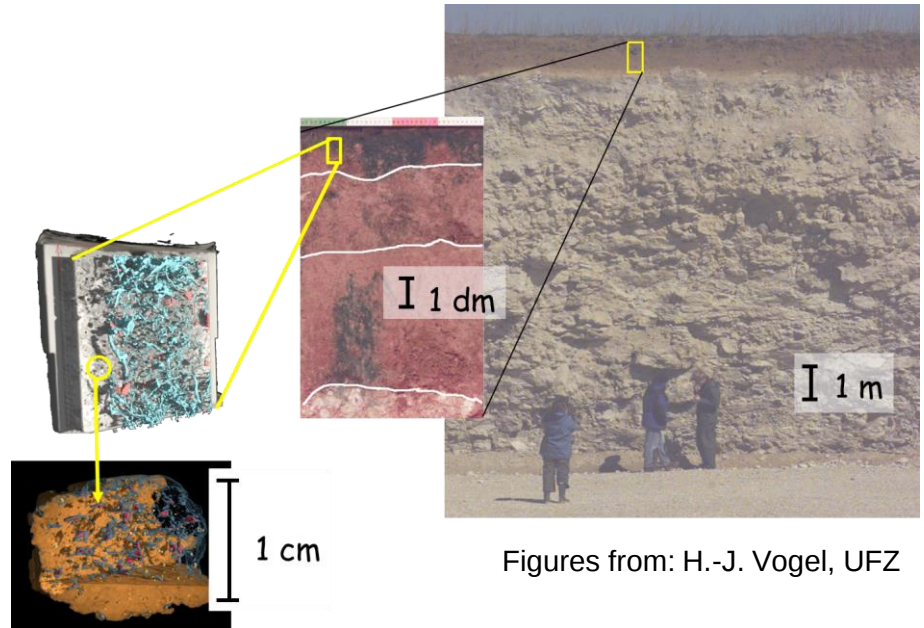
Efficient water use in (irrigated) agriculture can only be achieved if the soil water status of the heterogeneous field is known - a field-representative measure is desirable

- A homogeneous system is necessary to relate a local measure to a “mesocosm” property → beaker-glass example:



modified from BruceBlais (2013)

Due to the heterogeneity of soil, water inputs, and root water uptake, the humidity of soil air will vary in space. Therefore, area-representative measurement methods are needed to find a representative measure of the soil water status.



Figures from: H.-J. Vogel, UFZ

Soil and vadose zone are highly complex, dynamic systems with a scale-dependent heterogeneous composition

A representative measurement of a quantity in a heterogeneous system:

should integrate over:

- local processes,
- local structures,
- and phase distribution that cannot be considered explicitly

should give an integrated measurement value,

- for a well-defined volume (e.g., a depth interval in a field)
- for a suitable (process-related) time interval

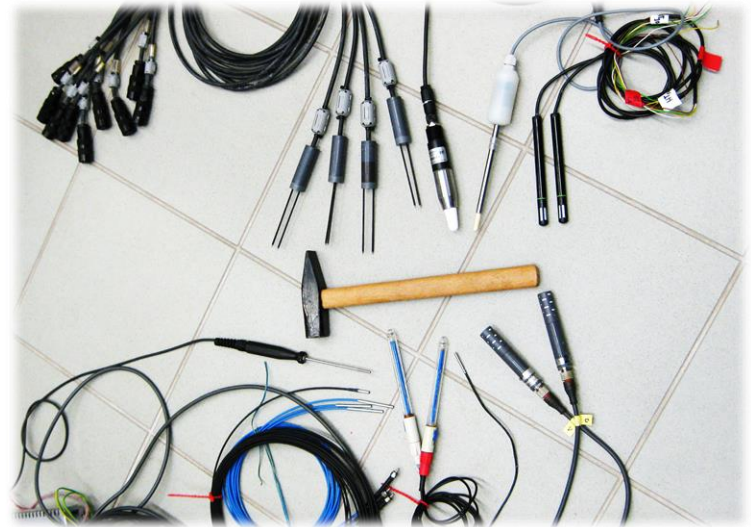
should only have an

- insignificant influence on the value of the measured quantity

But how can we obtain such a representative measure - most of sensors essentially give point measurements

Available for direct measurement in soil:

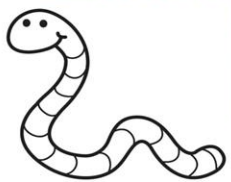
- Various sensor types for local measurement of different properties (soil liquid water content, matric potential, air humidity...)



- Sensors (above) have a size on the μm to cm scale



- Macropores, e.g. shrinkage cracks, biopores (left) often have a spacing at dm-scale, and
- have a size in the dimensions of the sensors shown above



For CO₂ measurement in soil we have developed a linear sensor using a gas-selective tubular membrane

- Its measuring body is a long, flexible tube, buried in the soil, called a “line-sensor”. The tube wall is permeable to CO₂.
- Its length, material, inner construction, temporal resolution, etc., are all adaptable to the measurement object and the purpose of measurements

Would such kind of a sensor be able to analyze a measure with which the soil-water status can be determined?



- The soil water matric potential h_c and the relative humidity RH = water vapor pressure p_w / saturation vapor pressure p_s of the soil air are related to each other (Edlefsen & Anderson 1943):

$$h_c = -\frac{RT}{gM} \ln \frac{p_w}{p_s}$$

- Goss and Madliger (2007) demonstrate the conversion of RH readings to water potential for dry soil – but most of the commercially available sensors can only measure soil air RH at a single point.
- Water vapor diffuses rapidly through different kinds of membranes. Membrane-detection with line-sensors should be possible when the tube of the line-sensor consist of a material permeable to water vapor.

What happens during gas detection in the measurement chamber (the inside of the tube) of a line-sensor?

The curves in the grey area show the concentration $C_k(t)$ of gas component „k“ in the tube wall for initial equilibrium with the concentration inside the tube (yellow) and instantaneously exposure to a constant, different concentration in the soil (brown).

Diffusion through a nonporous tubular membrane described by:

$$\frac{\partial C_k(r,t)}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} r D_k \frac{\partial C_k(r,t)}{\partial r}$$

The exchange of different gases between the soil air (brown) and the air in the tube (yellow) leads to steady state gas concentration gradients in the tube wall (grey) as long as the gas inside the tube is being flushed (red line).

During this steady-state flow (dynamic equilibrium) the change of Mole number dN can be expressed by the change of gas volume dV , or by a change of pressure dp if the chamber was closed for detection:

$$dN = \frac{V_0}{RT} dp = \frac{p_0}{RT} dV$$

$$C_k^a(r = R_a) = S_k^a \cdot \frac{p_k^a}{RT}$$

But, diffusion in the tubular membrane takes place for all gas components k (partial pressure p_k) in soil:

$$p_0^{Gas} = \sum_{k=1}^n p_k$$

(p_0 – soil gas pressure). The diffusion rate of each gas component depends on the concentration difference between the inside of the tube and the soil, the solubility S_k in, and the diffusion coefficient D_k for the material of the membrane.

$$S_k^i \frac{p_k^i}{RT} = C_k^i(r = R_i)$$

R_i

R_a

r

Sensor chamber (purged, e.g. with air)

Membrane

Supporting soil area

A useful approximate solution to analyze the partial pressures of various gas components based on the pressure change dp :

$$\left. \frac{dp}{dt} \right|_{t \rightarrow t_0} = \alpha = g P_w \sum_j f_{j,w} (p_j^a - p_j^i)$$

Measurement signal $\swarrow$
 $\nwarrow$ Variable sought
 $\nearrow$ known

Geometry factor $g = 2 / (R_i^2 \cdot \ln R_a / R_i)$

Permeability $P_j = D_j \cdot S_j$

Selectivity $f_{j,w} = P_j / P_w$

2-step-measurement procedure:

1. Purging the tube with a gas of known composition, e.g. air
2. Closing the tube and recording the pressure change in the tube near the dynamic equilibrium

Permeability P and selectivity f of gas components “ j ” and “ w ” for a silicone membrane (Lazik et al., 2019)

Gas Component j	$P_j \times 10^9 \text{ (m}^2/\text{s)}$	f_{jw}
H ₂ O	27.0	1
N ₂	0.21	0.008
O ₂	0.45	0.017
Ar	0.45	0.017
CO ₂	2.44	0.090

- Developed in Lazik & Geistlinger (2005), confirmed in Lazik (2014) by a more general solution

- Dependencies between the gas components enable the reduction of the number of gas-selective membrane tubes (Lazik et al., 2009)
- If a single gas component “ j ” changes within a given gas matrix only a single membrane is necessary

Partial pressure difference sought $\swarrow$
 Measurement signal $\nwarrow$

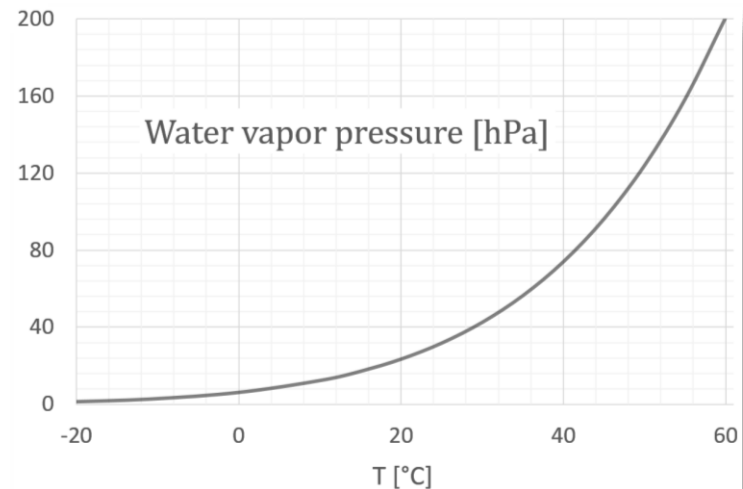
$$\Delta p_j = k_2 \alpha + k_1$$

$k_1, k_2 = \text{const}$

- Linearity between measurement signal α and concentration (partial pressure) difference
- Application needs calibration

Calibration of a line-sensor for RH

- Two parameters have to be determined by an line-sensor that is buried in a heterogeneous soil (!):
 - the water vapor pressure p_w and
 - the saturation vapor pressure p_s
- The soil temperature not too far from the surface can vary dramatically over 24 hrs, especially in warm, arid climates (e.g., Goss and Madliger, 2007)
- Saturation vapor pressure of water is highly temperature dependent (see p_s in diagram)
- For calibration exact temperature information from the sensor position in soil is possibly needed too



$$p_s = \beta_w \cdot 6.1121 \exp\left(\frac{17.502 T}{240.97 + T}\right), \quad T [^{\circ}\text{C}]$$

$$\beta_w = 1.0007 + 3.46 \cdot 10^{-6} p_{air} [hPa]$$

(Sonntag, 1990)

Long-term response behavior of a sensor must be considered

Ideally, a line sensor buried in the root zone should remain there for many months or even years

- But, the calibration may change over time

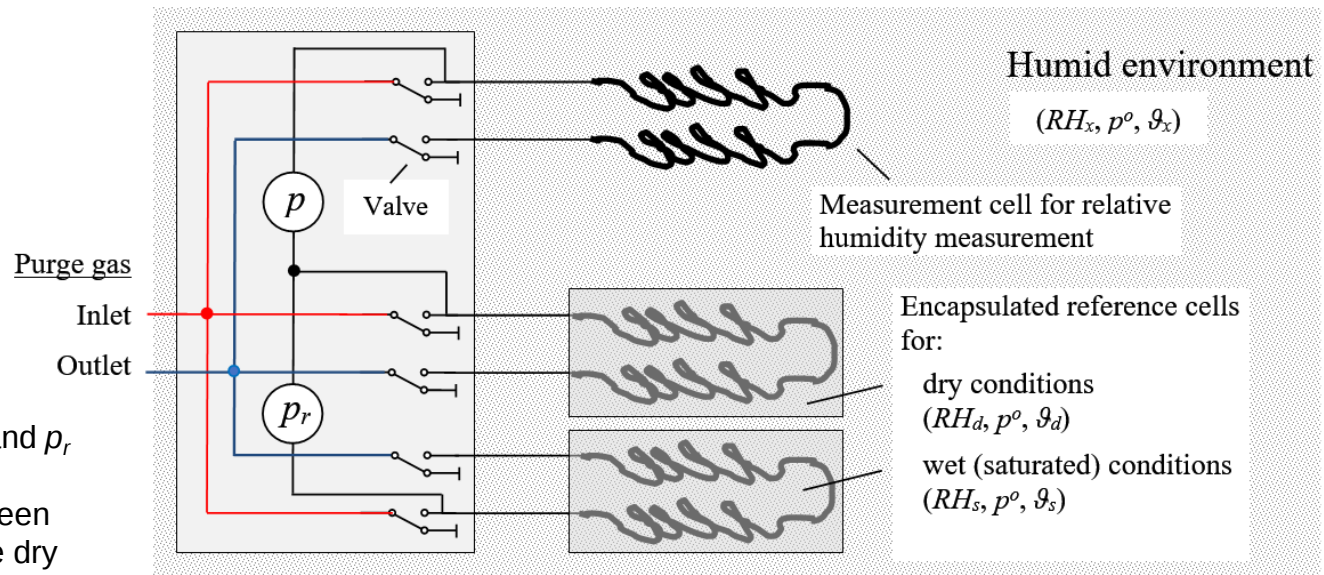


Structure of a self-calibrating, temperature-insensitive *RH* sensor based on tubular gas-selective membranes

(Lazik et al., 2019)

- Three tubular membrane cells were placed close to each other
- One is in the medium to be measured (black in the scheme), the two others are exposed to dry / wet reference conditions (gray in the scheme)
- Two pressure gauges (p and p_r in the scheme) record the pressure differences between the target medium and the dry reference $p_x - p_d$, and between both references $p_s - p_d$
- The differential pressure changes $\alpha_x - \alpha_d$ and $\alpha_s - \alpha_d$ are determined from this to calculate its ratio φ

$$\frac{\alpha_x - \alpha_d}{\alpha_s - \alpha_d} = \varphi$$



- For similar ambient temperature^(*) around the membranes this ratio φ gives:

$$RH_x = \varphi \cdot (RH_s - RH_d) + RH_d$$

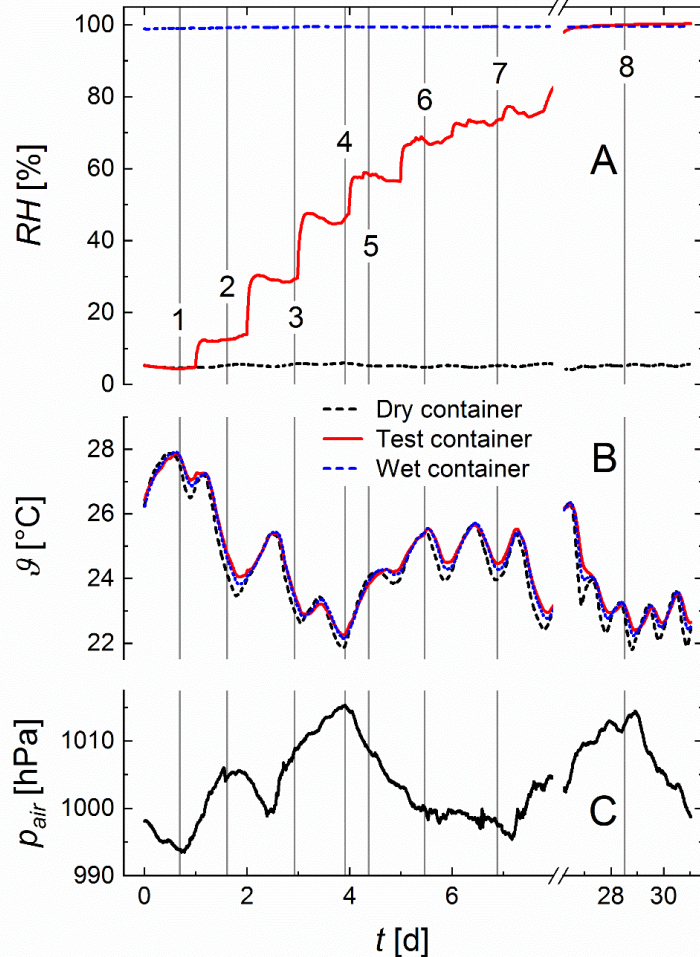
RH_x is the relative humidity to be determined

Known RH in the reference cell for dry (e.g. dried) air

Known RH in the vapor saturated reference cell

^(*) A compensation technique for temperature differences is demonstrated by Lazik et al. (2019)

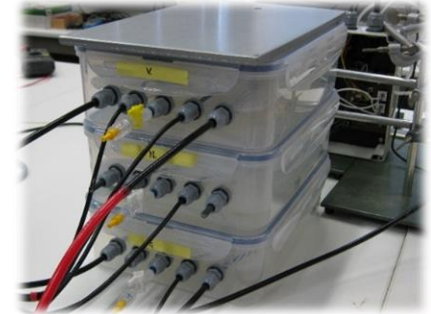
Experimental test of the sensor principle for controlled conditions in the laboratory



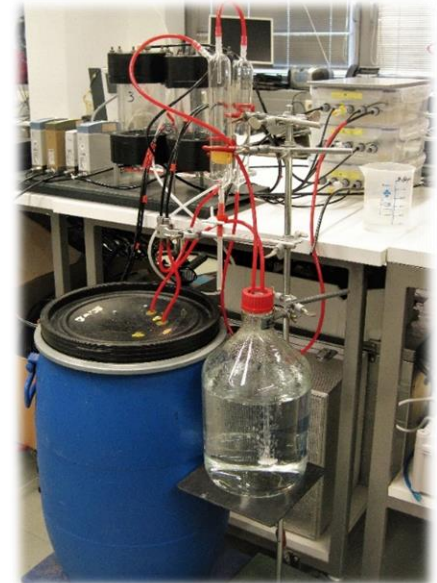
Experimental set-up:

- Silicone tubes (length 1 m) were installed in three different plastic containers.
- Shown in diagram A: Steady-state conditions for the two reference points for dried (black dotted line) and wet air (blue dotted line) are adjusted in two containers.
- RH in the third (test) container was varied (red line in A).
- RH in the wet and test container were generated using humidified air from a bubble column (right) mixed with dried air from a compressor.
- Diagrams B and C show diurnal temperature changes in the containers and the air pressure in the laboratory.

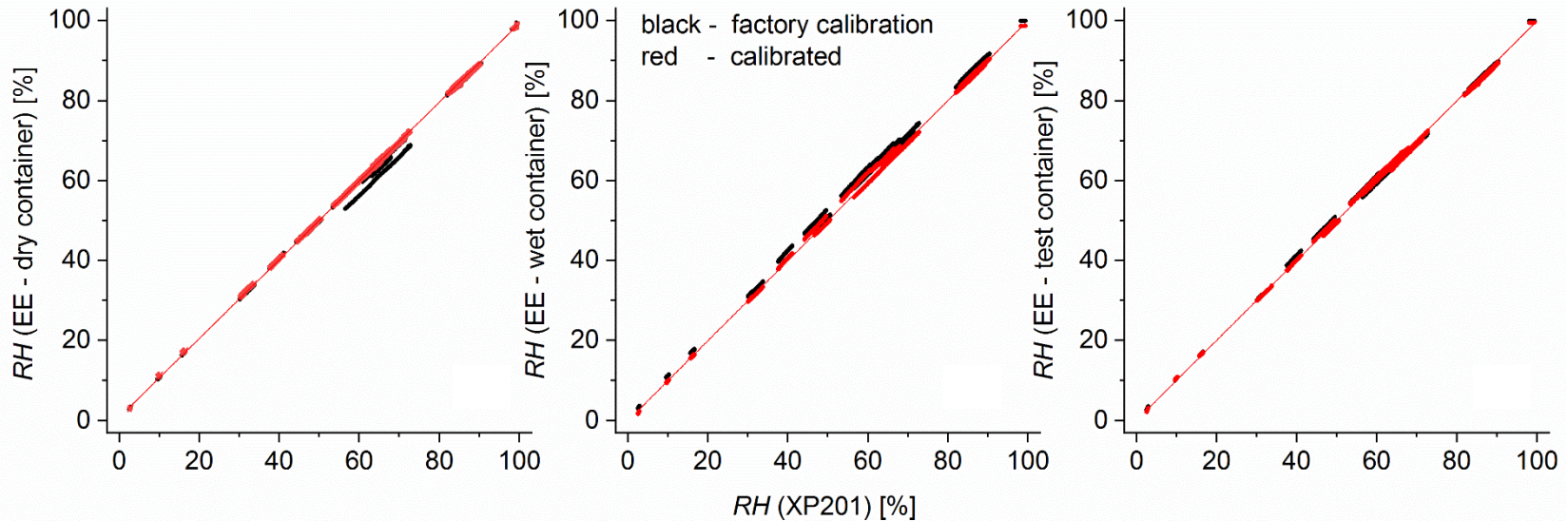
Closed containers contain the membrane tubes and reference sensors (RH + temperature ϑ)



Humidity generator



We calibrated our reference sensors (EE060) against the certified humidity sensor XP201



Reference Sensors: combined
humidity & temperature sensors
EE060

humidity range 0 – 100%,
precision 2.5%,
temperature range -40 – 60 °C,
precision 0.3 °C,

(E+E Elektronik, Engerwitzdorf,
Austria)

Calibration performed using the
certified humidity & temperature
sensor XP201

0 – 100%,
0.8%
0 – 70 °C,
0.15 °C,

(Lufft Mess- und Regeltechnik
GmbH, Fellbach, Germany)

Diagrams show the factory
calibrated (black dots) reference
sensors and the improvements
achieved by our own calibration
(red dots and red recalibration line)

Self-calibrated Membrane-based Humidity Sensor (MHS) versus intensively recalibrated reference sensor (EE)

- The setting of vapor pressure saturation in a closed chamber can be problematic - the determination of RH with a humidity sensor close to the vapor pressure saturation even more.
- To check that it is allowed to assume vapor saturation ($RH_s = 100\%$) for calculating the relative humidity RH_x in the test container two calculation schemes were compared, in which the RH_s value in the wet container was

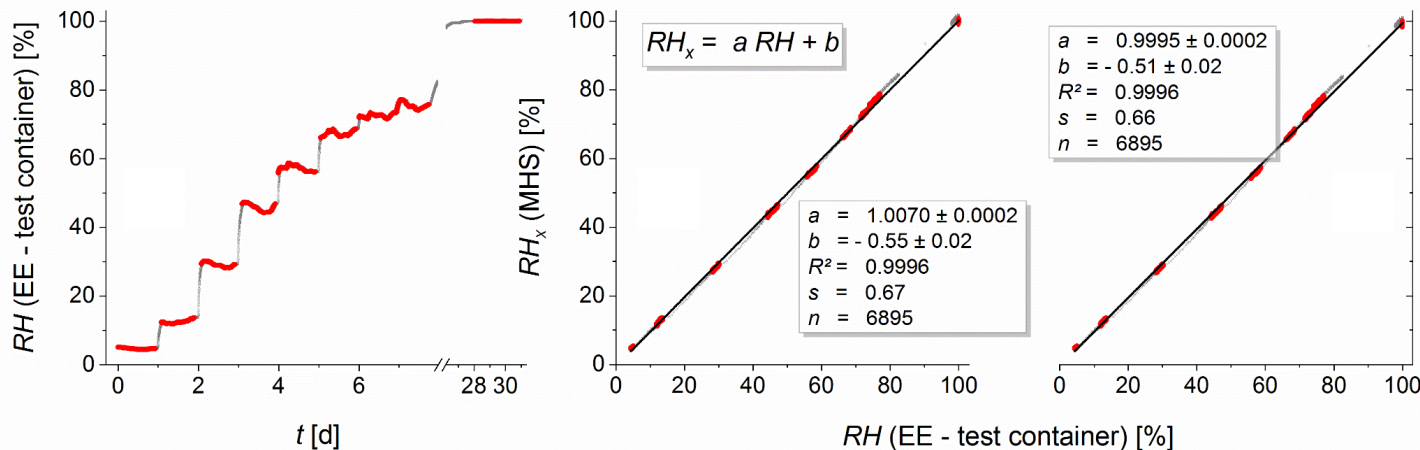
assumed to be
100 %, i.e.:

$$RH_x = \varphi(100 - RH_d) + RH_d$$

measured with EE
sensors, i.e.:

$$RH_x = \varphi(RH_s - RH_d) + RH_d$$

Experimental data



To guarantee thermal adjustment of all sensors, only slowly changing experimental data (red dots) were considered in calculating the regression lines for RH_x .

- It is desirable to have a stand-alone set-up that does not rely on external sensors for calibration. The RH values of the non-calibrated MHS show a perfect match with those of the elaborately recalibrated reference sensors (EE)
- The comparison of both calculation variants shows no significant difference, consequently:
- Only the single reference point for RH_d (the RH of the dried air) must be known.
- This internal reference point can be determined during monitoring much simpler and more precisely than an RH value close to 100%.

Conclusion

The experimental comparison of the responses of the membrane based MHS and the EE reference sensors demonstrates:

- self-calibrating *RH* measurement is feasible, and
- highly accurate measurement results can be obtained.

Importantly, the measurement is

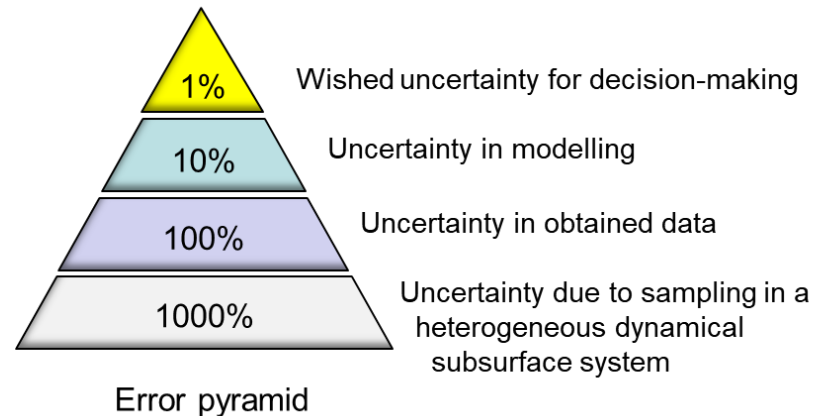
- independent of varying temperature,
- i.e. no additional temperature measurement is needed to determine *RH* provided all tubes of the MHS are exposed to similar, possibly non-constant, temperatures during measurement.

- **Therefore the MHS seems to be highly qualified for monitoring of *RH* in hot dry soil**

Due to its tube-based, length-adjustable structure an MHS

- can enable us to reduce the uncertainties associated with local subsurface humidity measurements, e.g., at the Pedon scale, Ecosystem scale ...
- our sensor development is at an early point, but we believe that a single MHS could provide a valuable average *RH* value over an area of order of 10^0 to 10^3 m²
- such a sensor could replace a huge number of *RH* point sensors

For further Information
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Thank you
very much!



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