

Soil Moisture as Predictor of Plant Water Status

By Johannes Hertzler and Steffen Rust

Abstract. Soil water potential can be used as a proxy for plant available water in irrigation scheduling. This study investigated the relationship between soil water potential and plant water status of pines (*Pinus sylvestris* L.) planted into two different substrates. Predawn leaf water potential as a well-established measure of the plant water status and soil water potential correlated very well. However, estimating the plant water status from individual sensor readings is subject to significant estimation errors. Furthermore, it was shown that heterogeneous soil/root ball combinations can lead to critical effects on the soil water balance, and that sensors installed outside of the root balls cannot estimate the plant water status without site-specific calibration.

Keywords. Irrigation Scheduling; Predawn Leaf Water Potential; Soil Moisture Sensor; Soil Water Potential.

INTRODUCTION

As central European trees suffer from some of the hottest and driest summers on record, efficient irrigation scheduling has emerged as critical for urban tree management. Facing increasing scarcity of water in a changing climate, landscape irrigation has to use water with care.

Irrigation scheduling can be based on meteorological data and models (Litvak et al. 2017), or on measurements of plant or soil water status (Goldhamer et al. 1999; Jones 2004).

While predawn leaf water potential (ψ_{PD}) is a generally accepted parameter that reflects the actual plant water status (Cochard et al. 2001; Larcher 2001; Williams and Araujo 2002; Matyssek et al. 2010), the time and effort required to measure leaf water potential in trees, especially at predawn, are prohibitive for its use in irrigation scheduling.

Technically sophisticated methods for measuring soil water status are available and marketed for irrigation scheduling. However, point measurements of soil water status suffer from the high spatial variability in soil properties (Feres et al. 2003). In addition, street trees are often planted with root balls, combining two often heterogeneous substrates. Thus, for placing soil water potential sensors, it is important to know

whether water potential measured in the root ball and the surrounding substrate are both equally representative of plant water status.

Besides the sensors' potential to measure soil water status accurately, it is critical that these measurements correlate with the actual plant water status if they are supposed to be used for irrigation scheduling (Feres et al. 2003). While some studies have evaluated the correlation of granular matrix sensor readings with plant water status in vineyards and orchards (Intrigliolo and Castel 2004; Intrigliolo and Castel 2006; Centeno et al. 2010), no data is yet available for trees with root balls transplanted into different substrates.

Costs for installing and maintaining soil water potential sensors are likely to limit the number of sensors per tree when they are used to manage large numbers of urban trees. Thus, this study investigated the relationship between the readings of 2 soil moisture sensors installed close to the root ball of newly transplanted trees and the predawn leaf water potential.

Four-year-old pine trees (*Pinus sylvestris* L.) were planted into containers equipped with soil moisture sensors. Two substrates were used: sandy loam and a structural soil. While the containers were left to dry out, predawn leaf water potential and soil water potential were measured to analyze their relationship.

MATERIALS AND METHODS

Experimental Set-Up

Four-year-old, container-cultivated pine trees (*Pinus sylvestris* L.) were planted in containers and placed in a greenhouse to provide protection from rainfall and to allow measurements within the whole range between saturated and dry soil. Trees were 40 cm to 60 cm tall, with shoots measuring about 15 cm to 20 cm, and terminal shoots of 20 cm to 25 cm. They had been cultivated in 1.2-L containers filled with a mixture of wood fibers, compost, peat, sand, and limestone. Evergreen conifers were chosen to avoid effects of leaf senescence when continuing the experiment until autumn.

The first treatment, hereafter referred to as the “loam treatment,” was run from 22 August 2018 to 28 September 2018. Sixteen trees were planted separately into 7.5-L containers using sandy loam as substrate.

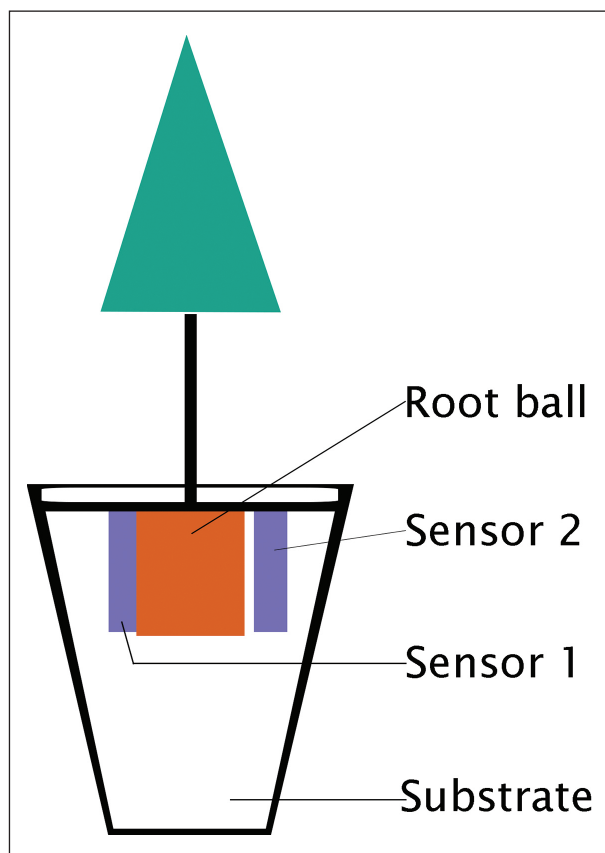


Figure 1. Experimental set-up. In the loam treatment, both sensors were placed like sensor 1 in the diagram, i.e., in contact with the root ball. In the lava treatment, sensor 1 was installed as in the loam treatment, and sensor 2 was placed 2 cm away from the root ball.

Two soil water potential sensors were installed in each container in contact with and at the same height as the root ball (Figure 1). The sensors were placed outside the small root balls (approximately 10 cm in diameter) to prevent damages during installation.

Between 02 April 2019 and 15 May 2019, the experiment was repeated using Vulkatree 0/32 mm (VulkaTec GmbH, Kretz, Germany) as substrate, a lava-based, load-bearing, compaction-resistant soil which conforms to the German FLL-guidelines (FLL 2010). One sensor was installed 2 cm apart from the root ball, while the second sensor was placed in contact with the root balls as in the first treatment. The intention of the different placements was to detect possible relationships between sensor location and variability of sensor readings. To prevent the sensor placed further away from being too close to the container wall, 13-L containers were used. This second treatment is referred to as the “lava treatment.”

Measurement of Soil Water Status

Soil water potential (ψ_s) was measured with granular matrix sensors (Watermark Model 200SS, Irrometer, Riverside, CA, USA). They consist of an encapsulated granular matrix with 2 embedded electrodes. The enclosing porous membrane allows the moisture of the surrounding soil to equilibrate with the moisture of the granular matrix inside the sensor. The electric conductivity of the granular matrix correlates with its moisture content. By applying a source of electricity to the sensor's electrodes, the electric conductivity can be measured. In combination with the separately measured soil temperature and empirically developed equations, the soil water potential can be calculated (Shock et al. 1998; Irmak et al. 2016). The sensors had been conditioned (3 cycles of watering overnight after completely drying) and were installed in a fully wet state. A hole with a smaller diameter than that of the sensor was placed into the soil, and the sensor was pushed into it. According to Irmak et al. (2016), no slurry was used for sensor installation to prevent the sensors from losing contact with the surrounding soil because of shrinking slurry. Soil water potential sensors were read with a handheld Soil Moisture Meter (Irrometer, Riverside, CA, USA, range of measurement 0 kPa to -199 kPa) at predawn right after taking the needle samples for measuring the predawn water potential.

Measurement of Plant Water Status

When stomata are closed at night, and transpiration ceases, the water potential in the leaves equilibrates with the water potential in the rhizosphere. Thus, by the end of night, leaf water potential (predawn water potential, ψ_{PD}) reflects the water potential of the soil that is accessed by the roots and serves as an indicator for the plant's water supply (Larcher 2001; Williams and Araujo 2002; Matyssek et al. 2010).

A pressure chamber (SKPM 1400, Skye Instruments Ltd., Llandrindod Wells, UK) was used to measure ψ_{PD} . Out of the upper third of the crowns, 2 or 3 short-shoots (needle pairs) per tree were sampled approximately 30 minutes before dawn. Together with moist paper tissue, they were put into small plastic bags. These plastic bags were then stored in plastic bags clad with aluminum foil and stored in a cooling box. Measurement of ψ_{PD} started approximately 45 minutes after needle collection.

Statistical Analysis

Statistical analysis was done using additive mixed models, allowing for autocorrelation within data from each sensor and heterogeneity of variance in treatments (Zuur et al. 2009; R Core Team 2018).

RESULTS AND DISCUSSION

The soil water and predawn leaf water potentials were closely correlated in both soil types, and fitted models show very narrow confidence intervals (Figure 2). Adjusted R^2 for the full model was 0.8. Thus, for each treatment, the measured ψ_s allows for the estimation of the mean ψ_{PD} and therefore the mean plant water status. There was a highly significant interaction effect of $\psi_s \times \text{treatment}$ ($p < 2e - 16$).

Similar to Intrigliolo and Castel (2004), who reported a remarkable variance of the soil sensor readings, results for the same container varied between sensors

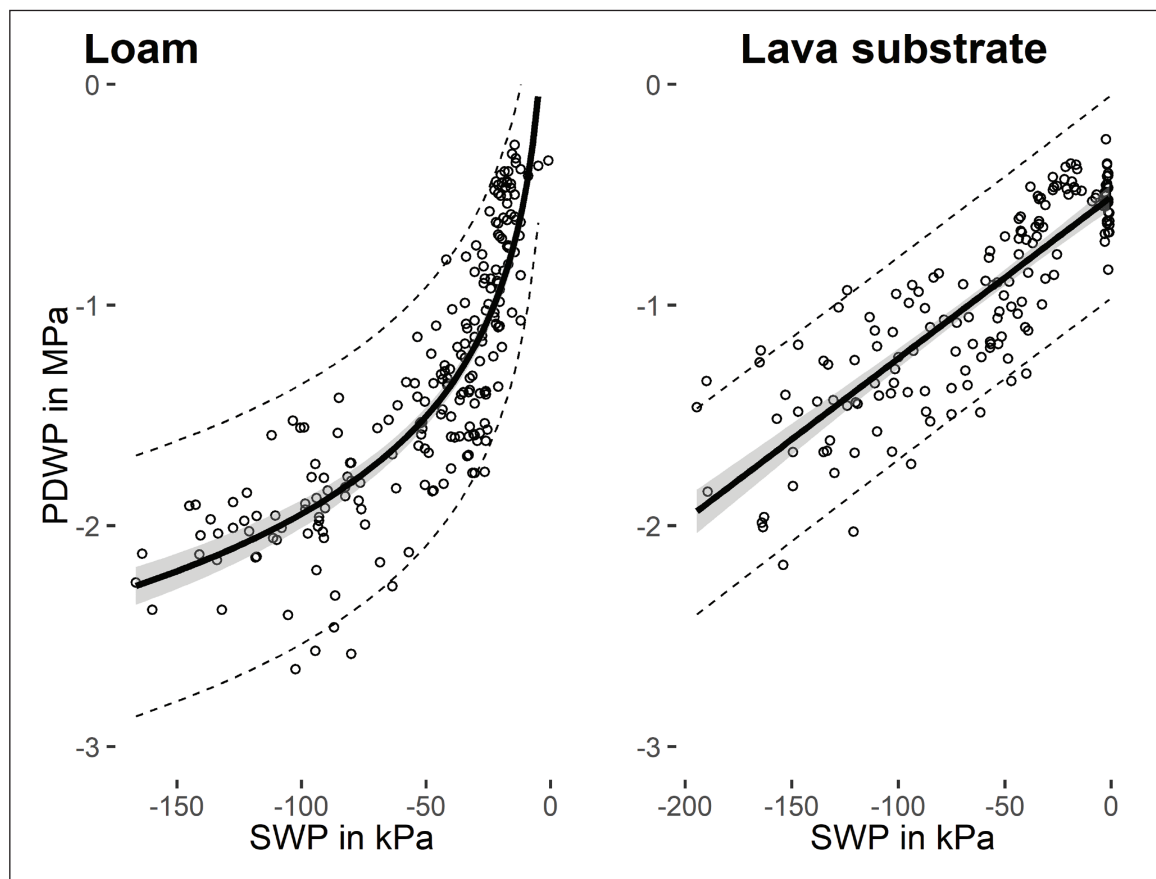


Figure 2. Predawn leaf water potential (PDWP) as a function of soil water potential (SWP) for the loam treatment (left; adjusted $R^2 = 0.73$, $p < 2e - 16$, $DF = 214$) and the lava treatment (right; adjusted $R^2 = 0.73$, $p < 2.2e - 16$, $DF = 164$). Points are daily means of PDWP and SWP measurements per pot. Continuous line: line of best fit; gray area: confidence interval (95% confidence level). The dashed lines confine the 95% prediction interval.

in some cases (e.g., container 6 in the lava treatment, Figure 3), resulting in different relationships between ψ_S and ψ_{PD} per sensor. However, within many containers of both treatments, the fitted lines for ψ_{PD} and ψ_S were almost identical. Between pots, there were highly significant differences in the correlation between ψ_S and ψ_{PD} .

In both treatments, however, the fitted models had very broad prediction intervals, which describe the range of values where, for a given ψ_S , the corresponding ψ_{PD} can be expected. Thus, estimating ψ_{PD} from individual measurements of ψ_S is prone to significant estimation errors. For that reason, efficient irrigation scheduling based on given threshold values for ψ_{PD} is not possible with the derived models. The variance of the sensor readings is likely to be just one cause among other factors for the resulting estimation error. Despite the different sensor positions in the lava treatment, the variance of sensor readings was very similar in both treatments (data not shown).

In the loam treatment, the variance of sensor readings might have been caused by rapid drying of the soil, with shrinking processes impairing contact between sensor and soil, essentially the effect that was meant to be prevented by dry sensor installation. It remains unclear if that effect would have been more severe with slurry used for installation. However, in the lava treatment, it would have not been feasible to create slurry with the coarse-grained substrate. Drying and shrinking are unlikely to have occurred in the lava substrate. It is supposed that the coarseness itself led to impaired contact between sensor and substrate. These effects may have led to variance in sensor readings, and thus varying model functions as shown in Figure 3. In some cases, the model functions vary notably, both within an individual container (e.g., container 6 in the lava treatment) and between the containers (e.g., containers 4 and 15 in the loam treatment). At the same time, some functions match very closely (e.g., container 2 in the lava treatment).

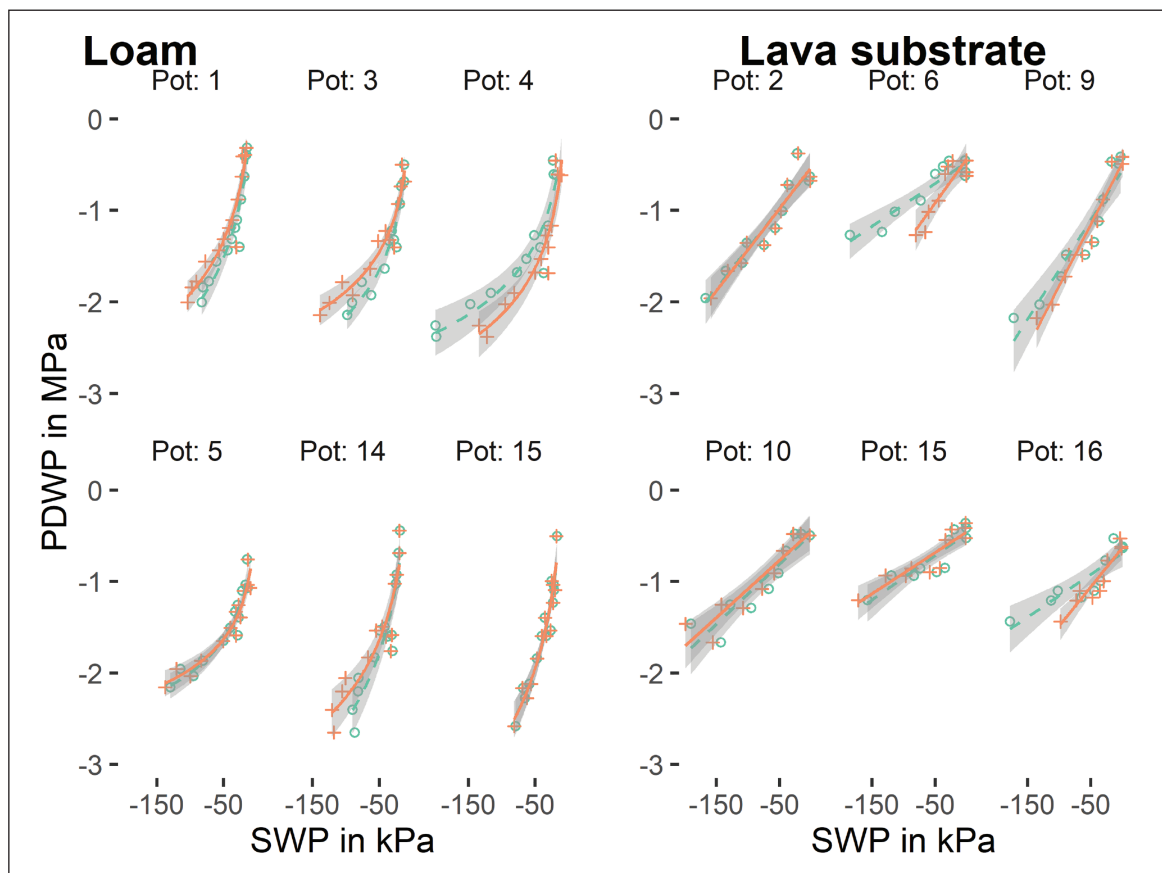


Figure 3. Correlations between soil and leaf water potential for individual containers in the loam treatment (left) and the lava treatment (right). Circles and dashed line: sensor 1; crosses and solid line: sensor 2. Gray area: 95% confidence interval. Selected pots.

Furthermore, there was a highly significant difference in the form of the relationship between ψ_s and ψ_{PD} : in sandy loam, an exponential model function gave a good fit, while in the lava substrate, the correlation was almost linear. Soil hydraulic phenomena are more likely to explain the differing model functions than the different seasons. The soil sensors were placed outside the root ball, thus measuring the water potential of the surrounding soil, while ψ_{PD} reflected the water potential within the rhizosphere, i.e., mainly the root ball. So, the linear model function for the lava treatment implies that the soil water potential of the surrounding substrate and that of the root ball both changed in an equal manner. The exponential model function for the loam treatment on the other hand suggests that the soil water potential of the root ball decreased more rapidly than that of the surrounding soil. Additionally, ψ_{PD} in the loam treatment generally reached lower values than in the lava treatment. This means that for the same range of ψ_s measured within the planting substrate, the root ball dried out faster and more severely when it was surrounded by loamy soil than by lava substrate.

In a hydraulic continuum, the total potential drop equals the sum of all partial potential drops along all corresponding partial flux resistances (van den Honert 1948; Richter 1973; Matyssek et al. 2010). The water potential drop between the root ball and its surrounding loamy soil can therefore be explained by a corresponding partial flux resistance within the hydraulic soil-plant-atmosphere continuum. In general, the hydraulic conductivity of soils decreases with their saturation. Its magnitude and dynamics of change are determined by the soil's pore size distribution. Soils high in clay, as the one used in the loam treatment, are dominated by fine pores and therefore have a lower hydraulic conductivity than the root ball substrate (Matyssek et al. 2010; Amelung et al. 2018). This may have constrained water flux towards the root ball. This hypothesis is in line with reports of unfavorable hydraulic effects when combining different soil types and root ball substrates (Balder and Strauch 2000).

Results indicate that with sensors installed in contact with but outside the root ball, a site-specific calibration is necessary to estimate the plant water status. However, even with calibrated model functions, users are faced with significant estimation errors. Furthermore, combinations of different soil types or substrates can in general lead to adverse hydraulic effects impairing the water supply.

Further studies should investigate if sensors installed in root balls both bypass the necessity of site-specific calibration and reduce the estimation error. If so, roots growing out of the root ball into the surrounding soil raise further questions of how long the sensors installed in the root ball remain representative for the plant water status.

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Conflicts of Interest:

The authors reported no conflicts of interest.

Résumé. Le potentiel hydrique du sol peut être utilisé comme indicateur de la disponibilité de l'eau pour la programmation d'arrosage des plantes. Cette recherche a examiné la relation entre le potentiel hydrique du sol et l'état hydrique de pins (*Pinus sylvestris* L.) plantés dans deux substrats différents. Le potentiel hydrique des feuilles avant l'aube, en tant que mesure bien établie de l'état hydrique de la plante, et le potentiel hydrique du sol sont très bien corrélés. Cependant, l'estimation de l'état hydrique des plantes à partir de relevés des capteurs individuels est sujette à d'importantes erreurs d'estimation. En outre, il a été démontré que les combinaisons hétérogènes sol/racines peuvent avoir des effets critiques sur l'équilibre hydrique du sol et que les capteurs installés à l'extérieur des mottes de racines ne peuvent estimer l'état hydrique des plantes sans un calibrage spécifique au site.

Zusammenfassung. Das Bodenwasserpotenzial kann bei der Bewässerungsplanung als Stellvertreter für das für die Pflanze verfügbare Wasser verwendet werden. Diese Studie untersuchte die Beziehung zwischen dem Bodenwasserpotenzial und dem Wasserstatus der Pflanzen von Kiefern (*Pinus sylvestris* L.), die in zwei verschiedene Substrate gepflanzt wurden. Das Blattwasserpotenzial in der Morgendämmerung als etabliertes Maß für den Wasserstatus der Pflanze und das Bodenwasserpotenzial korrelierten sehr gut. Die Schätzung des Pflanzenwasserstatus aus einzelnen Sensorwerten ist jedoch mit erheblichen Schätzfehlern behaftet. Darüber hinaus wurde gezeigt, dass heterogene Boden/Wurzelballenkombinationen zu kritischen Effekten auf den Bodenwasserhaushalt führen können und dass Sensoren, die außerhalb der Wurzelballen installiert sind, den Wasserstatus der Pflanze nicht ohne standortspezifische Kalibrierung einschätzen können.

Resumen. El potencial de agua del suelo se puede utilizar como una aproximación del agua disponible de la planta en la programación de riego. Este estudio investigó la relación entre el potencial de agua del suelo y el estado de agua de la planta de pinos (*Pinus sylvestris* L.) plantados en dos sustratos diferentes. El potencial de agua de la hoja antes del amanecer como una medida bien establecida del estado del agua de la planta y el potencial de agua del suelo se correlacionaron muy bien. Sin embargo, la estimación del estado del agua de la planta a partir de lecturas individuales del sensor está sujeta a errores de estimación significativos. Además, se demostró que las combinaciones heterogéneas de suelo/bola de raíz pueden conducir a efectos críticos en el balance hídrico del suelo y que los sensores instalados fuera de las bolas de raíz no pueden estimar el estado del agua de la planta sin calibración específica del sitio.