A Matric Flux Potential Approach to Assess Plant Water Availability in Two Climate Zones in Brazil

Everton Alves Rodrigues Pinheiro,* Quirijn de Jong van Lier, and Klaas Metselaar

Predicting soil water availability to plants is important for agricultural and ecological models. Models that explicitly take into account root water uptake and transpiration reduction describe the ability of soil to supply water to plants based on soil hydraulic properties that depend on soil water content. The objective of this study was to further develop an existing single-layer root water uptake model based on matric flux potential to allow for multi-layer scenarios; and to illustrate its functionality using soil hydraulic properties from layered soils from two climate zones in Brazil: a semiarid zone and a humid zone. For each soil layer, the hydraulic properties were determined by inverse modeling of laboratory evaporation experiment data available for pressure heads between −165 and −1.5 m. The water supplying capacities of soils were evaluated using the newly developed multi-layer root water uptake model. Soils from the semiarid zone were able to supply water to plants over a wider range of pressure heads. Soils from the humid zone showed slightly stronger hydraulic restrictions for supplying transpirable water. For the analyzed soils, only a negligible increase in available water results from decreasing the root water potential below −150 m. Therefore, based on this analysis, it is reasonable to expect plant adaptation to move toward an increase of root length density rather than to a decrease of minimum root water potential.

The process of supplying transpirable water to plants, in which hydraulic properties are a key, is crucial in the establishment and maintenance of natural vegetation, especially when dealing with drought-prone ecosystems. In agricultural areas, a lower transpiration-limiting pressure head results in higher rainfed yields, whereas in irrigated agriculture it implies the use of less water to obtain optimized yields. Assessment of the soil-water availability to plants at depth, especially in dry regions, is necessary to evaluate the strengths and restrictions of ecosystems given the expected increase in water limitation due to environmental changes projected to occur across some large regions of the globe (Seneviratne et al., 2012; Klein et al., 2014a). For the case of the Brazilian territory, it is likely to face water availability decline due to rainfall reductions and higher temperatures in the coming years (Marengo et al., 2012). This may be a threat to natural ecosystem productivity and to rainfed crops grown in soils with limited water supplying capacity.

Soil hydraulic properties together with limiting crop (or root) water potentials can be used to characterize crop water stress by predicting the threshold value of water content or pressure head that delimits the constant and falling water uptake rate phase (de Jong van Lier et al., 2013; Raats, 2007). Soil water availability may be predicted combining a root water uptake model and soil hydraulic properties (Šimůnek et al., 1998; Durigon et al., 2011; de Jong van Lier et al., 2013; Iden et al., 2015). Such a model was developed by de Jong van Lier et al. (2006), who proposed an equation to calculate the limiting matric flux potential $M_{\text{lim}}$ (threshold value between constant and falling rate phases) for a given potential transpiration rate and root length density in a single-layer soil.

**Core Ideas**
- A multi-layer root water uptake model is developed based on matric flux potential.
- Soil hydraulic properties from two important ecological zones in Brazil are assessed.
- Water supplying capacity to plants is higher in semiarid than in humid zone soils.
- Reduction of root suction below −150 m does virtually not affect water availability.
Matric flux potential is a composite soil hydraulic property representing hydraulic conductivity integrated over a range of pressure heads. Both hydraulic properties can be determined from field and laboratory experiments using direct methods or inverse modeling techniques. Gardner and Miklich (1962) developed a laboratory method for the simultaneous measurement of retention and unsaturated hydraulic conductivity. Their method was modified by Wind (1968), who proposed an iterative graphical procedure to decrease deviations in readings. Wendroth et al. (1993) proposed the use of different evaporation rates to overcome problems of small hydraulic gradients near saturation.

The implementation of any of these methods usually relies on water-filled tensiometers with an operation range limited to the wetter soil. For the determination of hydraulic conductivity in a dry soil, at pressure heads below −10 m, special measurement devices like polymer tensiometers are an option (Bakker et al., 2007; Durigon et al., 2011).

Soil water hydraulic properties vary with depth (Domec et al., 2010; Klein et al., 2014a); therefore, the amount of transpirable water is not necessarily extracted homogeneously across the rooting zone. In this context, we aimed to further develop the single-layer equation proposed by de Jong van Lier et al. (2006), making it applicable to multilayer scenarios. To illustrate the theory, soil hydraulic properties were assessed for soils from two important ecological zones in Brazil: the Brazilian semiarid and humid subtropical zones. These zones represent part of the climate and occupation diversity of Brazil with resulting distinct patterns of water availability and use.

In the semiarid zone, an ecosystem representing 12% of the total national territory, the water-limited Caatinga biome is dominant. Besides recurrent droughts (Marengo et al., 2016), this zone faces long dry spells (e.g., dry season) with low annual rainfall amounts and high potential evapotranspiration rates throughout the year. On the other hand, the humid subtropical zone is characterized by well distributed rainfall as well as water availability. The favorable climatic conditions for crop development made this zone densely populated and its soils intensively cultivated.

**Materials and Methods**

**Development of an Expression to Calculate Limiting Hydraulic Conditions**

A convenient soil hydraulic property that is often used in soil water movement studies is the matric flux potential \( M \) (m\(^2\) d\(^{-1}\)) (Raats, 1977; Pullan, 1990; Grant and Groenevelt, 2015), which is defined as the integral of the hydraulic conductivity \( K(h) \) (m d\(^{-1}\)) over the pressure head \( h \) (m) starting at an arbitrary reference pressure head \( h_{\text{ref}} \):

\[
M = \int_{h_{\text{ref}}}^{h} K(b) \, db \tag{[1]}
\]

Using \( h_{\text{ref}} \) equal to the pressure head at the permanent wilting point \( (h_w) \), de Jong van Lier et al. (2006) proposed a linear relation between the limiting matric flux potential \( M_{\text{lim}} \) (m\(^2\) d\(^{-1}\)) and the transpiration rate \( T_p \) (m d\(^{-1}\)), with an intercept equal to zero and a slope depending on the half-distance between roots \( (r_m, m) \):

\[
M_{\text{lim}} = p r_m^g T_p \tag{[2]}
\]

where \( g \) is a fitting value \((g = 2.367)\) and \( M_{\text{lim}} \) represents the average \( M \) in the soil at the onset of transpiration reduction when \( h = h_w \) at the root surface.

The half-distance between roots, \( r_m \), is related to the root length density \( R \) (m m\(^{-3}\)) according to

\[
r_m = \sqrt{\frac{1}{\pi R}} \tag{[3]}
\]

and Eq. [2] can be written in terms of the root length density as

\[
M_{\text{lim}} = p \left( \frac{1}{\pi R} \right)^{q/2} T_p \tag{[4]}
\]

After performing a series of simulations with rooting depth \( z = 0.5 \) m (de Jong van Lier et al., 2006, Table 2), values for \( p \) and \( q \) were obtained by linear regression: \( p = 23.5 \) (m\(^{1-q}\)) and \( q = 2.367 \). It should be noted that these values were derived specifically for \( z = 0.5 \) m. In a more general form and for any rooting depth, Eq. [2] is written as

\[
M_{\text{lim}} = p^* r_m^d T_p \tag{[5]}
\]

where \( p^* \) (m\(^2\) m\(^{-q}\)) is equal to

\[
p^* = (23.5 \text{ m}\(^{1-q}\))(0.5 \text{ m}) = 11.75 \text{ m}^{2-q} \tag{[6]}
\]

Equation [5] refers to a single-layer rooted soil of depth \( z \). To adapt this equation for a scenario in which the root zone expands through \( k \) soil layers, \( T_p \) is substituted by the share of water extraction per soil layer \( (S_j, m \text{ d}^{-1}) \):

\[
M_{\text{lim}, j} = p^* r_m^d \frac{S_j}{L_j} \tag{[7]}
\]

where index \( j \) refers to the soil layer and \( L_j \) (m) is the layer thickness. A reasonable way to estimate \( S_j \) under non-limiting conditions is by weighting the potential transpiration according to \( L_j \) and root length density \( R_j \).

\[
M = \int_{h_{\text{ref}}}^{h} K(b) \, db
\]

\[
M = \int_{h_{\text{ref}}}^{h} K(b) \, db
\]

\[
M_{\text{lim}} = p r_m^g T_p
\]

\[
r_m = \sqrt{\frac{1}{\pi R}}
\]

\[
M_{\text{lim}} = p \left( \frac{1}{\pi R} \right)^{q/2} T_p
\]

\[
M_{\text{lim}} = p^* r_m^d T_p
\]

\[
M_{\text{lim}, j} = p^* r_m^d \frac{S_j}{L_j}
\]
Although the assumed value \( q = 2 \) is slightly smaller than 2.367 as determined by de Jong van Lier et al. (2006), the assumption of \( q = 2 \) seems reasonable given the simplicity and physical soundness of Eq. [11] and [12]. Performing a fitting procedure for several half-distances between roots using the data obtained by de Jong van Lier et al. (2006) for \( z = 0.5 \) m and a plant surface area equal to 0.04 m², \( p^* = 5.3 \) was found to result in the best fit. Thus, the newly proposed multilayer Eq. [12] is a good alternative to the original single-layer version Eq. [2] or [5]. For a single-layer scenario, Eq. [2] or [5] could be more accurate because they include the effect of gravity.

Values of \( M_{\text{lim}} \), \( \theta_{\text{lim}} \), or \( h_{\text{lim}} \) predicted using \( T_p \) as in Eq. [2–12], can also be interpreted in the context of actual transpiration \( (T_a, \text{ m d}^{-1}) \) by substituting \( T_p \) by \( T_a \) in the respective equations. This becomes especially relevant in studies involving deficit irrigation management, or in water-limited ecosystems, as in this study.

### Evaluation of Water Availability in Some Brazilian Soils

To illustrate the use of Eq. [12], soils from two Brazilian climatic zones were studied. From the semiarid zone located in the northeastern part of Brazil, soils at three sites (Sites 1, 2, and 3) representative of an integrally preserved Caatinga watershed in Ceará State were sampled. The humid subtropical zone occurs in a vast area covering the southern, southeastern, and central parts of Brazil. To represent this region, eight sites (Sites 4–11) in São Paulo State were sampled. At each location, soil samples were collected from the surface layer and from one or more subsurface layers. Figure 1 and Table 1 show the locations and other details of the sampling locations. The ratio between annual rainfall and potential evapotranspiration shows the significant climatic difference regarding water availability among the sampling sites (Table 1). Soils from both zones show significant variation in particle size distribution with depth, and soils from the humid zone generally have a considerably higher clay content than semiarid zone soils (Table 2).

### Evaporation Experiments

To determine the unsaturated hydraulic properties for each soil layer, laboratory evaporation experiments were performed. Six rings (0.10 m high with an internal diameter of 0.145 m) were filled with air-dried and sieved soil material and then slowly saturated with water by capillarity from bottom to top. After wetting, the bottom side was sealed. Two or three days later, three polymer tensiometers were horizontally inserted in the sample through holes with centers at 25-, 50-, and 75-mm vertical distance from the sample surface. The tensiometer type used measures in the range from −165 to −1 m with an accuracy of approximately 0.2 m (Bakker et al., 2007; van der Ploeg et al., 2008). Each ring equipped with three tensiometers was placed on a precision balance (capacity 8.5 kg and resolution of 10⁻⁴ kg).

Measurements of ring sample weights and pressure heads were automatically logged every 10 min. The evaporation experiment was finished when the upper tensiometer reached a pressure head value lower than −165 m, which took on the order of 3 wk. At the end of the measurement, the final water content of the soil sample was determined by oven drying at 105°C.

### Inverse Solution

Soil hydraulic parameters were obtained from soil evaporation and pressure head measurements by an inverse one-dimensional solution using Hydrus-1D (Šimůnek et al., 2008). The unsaturated soil hydraulic properties were assumed to be defined by \( K–\theta–b \) relations described by the van Genuchten–Mualem model (van Genuchten, 1980):

\[
\Theta = \left( 1 + \alpha b^a \right)^{1-a-1}
\]

\[
K = K_s \Theta^\lambda \left( 1 - \Theta^{(a-1)} \right)^{-1/2}
\]
where \( \Theta = (\theta - \theta_r)/(\theta_s - \theta_r) \) is the effective saturation; \( \theta, \theta_r, \) and \( \theta_s \) are water content, residual water content, and saturated water content (m\(^3\) m\(^{-3}\)), respectively; \( b \) is the pressure head (m), \( K \) and \( K_s \) are hydraulic conductivity and saturated hydraulic conductivity, respectively (m d\(^{-1}\)); and \( \alpha (m^{-1}), n, \) and \( \lambda \) are fitting parameters.

The van Genuchten–Mualem model was developed considering the theory of capillary flow. In the very dry range, film flow or even vapor flow may take over from capillary flow (Peters, 2013). This may lead to poor predictions of hydraulic conditions when only measured retention data are used to predict \( K \), or when \( K \) is predicted by the van Genuchten–Mualem model fitted to retention data combined to measurement of (near) saturated \( K \) values. In our experimental setup, however, both retention and \( K \) values were measured in the (very) dry range. These measurements implicitly include all types of flow and after fitting a mathematical model to these data it may be expected to be a good predictor of respective soil hydraulic properties.

Fig. 1. Geographical location of the sampling sites in the semiarid zone (1, 2, and 3) and humid subtropical zones (4–11).

| Table 1. General characteristics of the sampling sites. |
|-------------------|-------------------|-------------------|-------------------|
| Characteristic    | Site no.          | Site no.          | Site no.          |
| Latitude          | 1, 2, 3           | 4, 5, 6           | 7, 8, 9           | 10, 11          |
| Avg. rainfall, mm yr\(^{-1}\) | 6.7° S          | 22.7° S           | 23.1° S           | 21.2° S         |
| Avg. temperature, °C | 26.0            | 22.3             | 20.0             | 21.5            |
| Vegetation type   | Caatinga         | fallow            | orchard           | orchard         |
| Climate classification (Köppen) | BSh             | Cfa              | Cfa              | Cwa             |
| Potential evapotranspiration (ETp), mm yr\(^{-1}\) | 549             | 1300             | 1313             | 1258            |
| Rainfall/ETp      | 0.25             | 1.35             | 1.44             | 1.15            |
| Avg. temperature, °C | 28.0            | 25.3             | 22.0             | 23.8            |
| Warmest month     | 24.0             | 17.9             | 17.8             | 19.3            |
| Coldest month     | 0.25             | 1.35             | 1.44             | 1.15            |
A set of hydraulic parameters was estimated for each replicate (ring). To obtain a single set of hydraulic parameters for each soil layer, 10 pressure head values in the range of the observed readings (from −165 to −1.5 m) were selected for each replicate, calculating the respective water content and unsaturated hydraulic conductivity.

These data, for all replicates together, were then processed using RETC software (van Genuchten et al., 1991) to generate a unique averaged hydraulic parameter set for each soil layer.

### Simulation Scenarios to Estimate the Limiting Matric Flux Potential

To assess the water supply capacity of the investigated soil layers for soils from both climatic regions, we assumed the existence of vegetation with a vertical root distribution, as proposed by Schenk and Jackson (2002), of:

$$r_D = \frac{R_{\text{max}}}{1 + \left(\frac{D}{D_{50}}\right)^{50}}$$ \[15\]

where $r_D$ (m m$^{-3}$) is the cumulative amount of root length density above soil profile depth $D$ (m), $R_{\text{max}}$ is the total root length density (m m$^{-3}$) in the soil profile, $D_{50}$ is the depth (m) at which $r_D = 0.5R_{\text{max}}$, and $c$ is a dimensionless shape parameter. To calculate the vertical root distribution, we used the parameterization corresponding to a tropical semi-deciduous and deciduous forest as listed in Schenk and Jackson (2002, Table 4): $D_{50} = 0.16$ m and $c = -1.681$. To match an $R_{\text{mean}}$ of 1000 m m$^{-3}$ across a soil profile of 1-m depth, the corresponding $R_{\text{max}}$ of 4142 m m$^{-3}$ was assumed for all soils. The adopted mean root length density of a 1000 m m$^{-3}$ was based on average values across the rooted zone for different crops types reported by de Willigen and van Noordwijk (1987).

Limiting soil hydraulic conditions for plant transpiration were evaluated by calculating the value of $b_{\text{lim}}$ based on $M_{\text{lim}}$ using optimized van Genuchten–Mualem hydraulic functions and transpiration rates in the range between 0.5 and 6 mm d$^{-1}$. Two values for the limiting root water potential ($h_w$) were used: the commonly used value of $-150$ m (e.g., de Jong van Lier et al., 2006; Javaux et al., 2008; and many others), and a more negative value $h_w = -300$ m. In this way, insight was obtained into the sensitivity of the results to the value of $h_w$ and whether soil hydraulic properties allow significant water flow at soil pressure heads more negative than $-150$ m (lower values of $h_w$ will postpone the onset of the transpiration falling-rate phase).

Equation [15] was used to evaluate all soils under a similar scenario of vertical root length density distribution. For the Caatinga biome in the semiarid zone (Soils 1, 2, and 3), root length density measurements were reported by Pinheiro et al. (2016). Therefore, in addition to the root length density profiles obtained using Eq. [15], we also evaluated a scenario using the experimentally observed root length densities for the semiarid zone.

### Results and Discussion

#### Soil Hydraulic Parameter Estimation

Estimated hydraulic parameters for all analyzed soil layers are given in Table 3. Land use and vegetation type play an important role in
the formation of soil structure; they mainly affect macroporosity and soil hydraulic properties at and near saturation (Gonzalez-Sosa et al., 2010; Jarvis et al., 2013; Wang et al., 2013). In our experiment, samples were sieved and the natural macrostructure was destroyed. Therefore, the effect of land use and vegetation type on the soil hydraulic properties cannot be evaluated by our methodology. On the other hand, because our purpose was to evaluate the soil water availability determined by soil hydraulic properties for the dry water content range, these are not expected to be affected by macrostructural properties (Tuli et al., 2005; Cresswell et al., 2008; Bittelli and Flury, 2009).

The measured range of pressure heads during the evaporation experiment was different among samples. Soils from the semiarid zone were analyzed from −10 to −165 m, whereas humid zone soils allowed analysis from −1.5 to −165 m. The upper limit of these ranges matches the conditions when the flow in the sample rings was strictly upward. Dealing with sieved material, the >2-mm soil structure is disturbed, but most of the smaller structural elements, which assume a very important role in weathered tropical soils, are maintained.

As stressed by Šimůnek et al. (1998), as long as independent measured information from the analyzed range is not included in the optimization process, extrapolation beyond the range of pressure heads measured during the evaporation experiment is associated with a high level of uncertainty. Considering this, the optimized values for saturated conditions (θs and Ks) are merely fitting parameters for Eq. [13] and [14] and do not correspond to values measured at saturation.

The λ parameter from Eq. [14] is related to the tortuosity and connectivity of the pore space, but its exact physical meaning is unclear (Vogel, 2000). A higher λ leads to a faster reduction of K.
with decreasing $\Theta$ (Eq. [14]). For the analyzed soils, $\lambda$ ranged from $-1.29$ to $4.36$ (Table 3), showing the arbitrariness of the commonly used value ($\lambda = 0.5$) obtained in a fitting procedure performed by Mualem (1976) on a set of 45 soils. Predictions of $K$ are especially sensitive to $\lambda$ in the dry range, making its correct determination of utmost importance in plant water availability studies. The average $\lambda \pm$ standard deviation for the semiarid zone soils was $1.9 \pm 0.8$, for the humid zone soils the value was $0.15 \pm 1.43$.

### Limiting Pressure Head

The limiting pressure head $h_{lim}$ (the average soil pressure head at the onset of the transpiration falling-rate phase) calculated from $M_{lim}$, is lower in the semiarid zone soils (Soils 1–3) than in humid subtropical zone soils 4 to 11 (Table 4), suggesting that the hydraulic properties of soils from the semiarid ecosystem allow root water uptake at a potential rate under a wider range of soil pressure heads. Observing Eq. [13] and [14], all parameters affect unsaturated hydraulic conductivity $K$, hence matric flux potential. Generally speaking, higher values of $\lambda$, $\alpha$, and $n$ lead to a stronger decrease in $K$ in the drying soil. Comparing parameter values for the semiarid and humid soils (Table 3), in general the semiarid soils show lower values of $\alpha$, higher values of $n$, and higher values of $\lambda$. The overall effect on the hydraulic conductivity at $h_w = -150$ m ($K_{150}$) can be seen in Table 4. For the semiarid soils, $K_{150}$ is on an order of magnitude of $10^{-7}$ to $10^{-9}$ m d$^{-1}$, while for the humid soils this range is slightly lower, from $10^{-8}$ to $10^{-9}$ m d$^{-1}$.

Soils from the humid subtropical zone are more intensively weathered and, consequently, tend to show high clay contents. Semiarid zone soils usually are coarse-textured (Table 2). In addition, according to Klein et al. (2014a), coarse-textured layers are the major water source for plant water uptake during dry periods, whereas soils with higher clay content hold a large amount of non-transpirable water.

#### Table 4. Hydraulic conductivities $K_{150}$ at limiting root water potentials $h_w = -150$ m and $K_{300}$ at $h_w = -300$ m together with hydraulic conditions (limiting pressure head $h_{lim}$ [m] and effective saturation $\Theta_{lim}$ [m$^3$ m$^{-3}$]) at the onset of the falling-rate phase calculated for a total root length density of 4142 m m$^{-3}$ and transpiration rate of 6 mm d$^{-1}$ and for $h_w$ of $-150$ and $-300$ m for all layers of the evaluated soils.

<table>
<thead>
<tr>
<th>Site</th>
<th>Great Soil Group†</th>
<th>Depth</th>
<th>$M_{lim}$ m$^2$ d$^{-1}$</th>
<th>$K_{150}$ m s$^{-1}$</th>
<th>$K_{300}$ m s$^{-1}$</th>
<th>$h_{lim150}$ m</th>
<th>$h_{lim300}$ m</th>
<th>$\Theta_{lim150}$ m$^3$ m$^{-3}$</th>
<th>$\Theta_{lim300}$ m$^3$ m$^{-3}$</th>
</tr>
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<tbody>
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<td>1</td>
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<td>0.00–0.20</td>
<td>1.30 x 10$^{-5}$</td>
<td>3.8 x 10$^{-8}$</td>
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<td>-81</td>
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<td>0.12</td>
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<td></td>
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<td>-77</td>
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<td>6.5 x 10$^{-9}$</td>
<td>1.4 x 10$^{-9}$</td>
<td>-10</td>
<td>-10</td>
<td>0.72</td>
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<td>0.15–0.30</td>
<td>3.9 x 10$^{-9}$</td>
<td>9.3 x 10$^{-10}$</td>
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<td></td>
<td>0.30–0.50</td>
<td>1.10 x 10$^{-5}$</td>
<td>1.3 x 10$^{-8}$</td>
<td>-35</td>
<td>-35</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Acrisol</td>
<td>0.00–0.30</td>
<td>1.10 x 10$^{-5}$</td>
<td>1.3 x 10$^{-8}$</td>
<td>-35</td>
<td>-35</td>
<td>0.60</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.51–0.68</td>
<td>2.9 x 10$^{-8}$</td>
<td>4.6 x 10$^{-9}$</td>
<td>-36</td>
<td>-38</td>
<td>0.63</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Leptosol</td>
<td>0.40–0.60</td>
<td>1.55 x 10$^{-4}$</td>
<td>1.6 x 10$^{-8}$</td>
<td>3.1 x 10$^{-9}$</td>
<td>-7.0</td>
<td>-7.0</td>
<td>0.76</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.56–0.72</td>
<td>4.42 x 10$^{-4}$</td>
<td>5.3 x 10$^{-9}$</td>
<td>-7.0</td>
<td>-7.0</td>
<td>0.76</td>
<td>0.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.10–0.15</td>
<td>2.57 x 10$^{-5}$</td>
<td>5.3 x 10$^{-10}$</td>
<td>-1.5‡</td>
<td>-1.5‡</td>
<td>&gt;0.99</td>
<td>&gt;0.99</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Cambisol</td>
<td>0.45–0.75</td>
<td>1.9 x 10$^{-9}$</td>
<td>4.0 x 10$^{-10}$</td>
<td>-3</td>
<td>-3</td>
<td>0.85</td>
<td>0.85</td>
<td></td>
</tr>
</tbody>
</table>

† IUSS Working Group WRB (2015).
‡ $h_{lim} > -1.5$ is out of the range of pressure head measurements used in the parameter optimization (−165 to −1.5 m).
To what extent plants are able to sustain the water demand of their shoot depends on the hydraulic properties of the soil–root system. As long as the root system conductance is large enough, root system geometry and root hydraulic properties have a low impact on water uptake. The ability of the soil to keep water flowing toward the roots is then predominantly determined by the soil hydraulic properties (de Jong van Lier et al., 2013; Lobet et al., 2014). Because the rhizosphere is highly susceptible to a local drop in hydraulic conductivity (Lobet et al., 2014), a lower limiting soil pressure head \( h_{lim} \) will allow plants to withstand a wider range of water content with a lower risk of hydraulic failure due to embolism or cavitation triggered by a soil water potential below a species-specific threshold (Choat et al., 2012; Klein et al., 2014b). This would allow plants to withstand adverse scenarios of soil drought.

Comparing the calculated values of \( h_{lim} \) for \( h_w = -150 \) and \( h_w = -300 \) m, differences were small and did not represent a significant increase in soil water availability. These values show the low sensitivity of available water to the lower limiting pressure head, analogous to the low sensitivity of the permanent wilting point to the corresponding pressure head (e.g., Savage et al., 1996). Based on soil hydraulic properties, it is therefore suggested that, in order for vegetation to adapt to dry soils without capillary rise from a water table, natural vegetation is more likely to evolve toward shallower and denser root systems and toward an efficient stomata closure but not in structures that allow a decrease in the minimum root water potential (Castellanos et al., 1991; de Jong van Lier et al., 2006; Klein et al., 2014a; Pinheiro et al., 2016).

### Limiting Pressure Head in Semiarid Zone Soils Using Measurements of Root Length Density

Although the bulk root length density (RLD) measurements made in this research for the Caatinga biome do not exclusively represent active fine roots (roots able to conduct water), the measured values were higher (Table 5) than those used in the previous scenario calculated using Eq. [15].

For the semiarid climate zone, actual transpiration rates below \( T_p \) are the rule. In Fig. 2 we show the values of \( h_{lim} \) for a wide range of transpiration rates. Analyzing these values, we see that \( h_{lim} \) ranges from \(-36\) to \(-148\) m (Fig. 2).

As observed by de Jong van Lier et al. (2006), in the case of a high RLD, the root pressure head remains similar to the average pressure head in the surrounding soil because the flux density toward the root surface to meet the transpiration rate is small compared with a scenario with low RLD. Therefore, hydraulic gradients to meet water demand will be smaller and \( h_{lim} \) corresponds to a drier condition. The semiarid Leptosol, with the lowest RLD and the shallowest rooting depth of the Caatinga samples (Pinheiro et al., 2013), has the highest \( h_{lim} \), making the vegetation on this soil more susceptible to drought stress. In addition to high RLD (Table 5), the Caatinga biome typically develops shallow roots (Pinheiro et al., 2013), which may maximize uptake of ephemeral pulses of available water in the upper soil layers (Pinheiro et al., 2016). The concept of pulse water availability of short duration for water-limited ecosystems has been reported, e.g., by Sala and Lauenroth (1982), Reynolds et al. (2000), Williams et al. (2009), and Lauenroth et al. (2014).

Klein et al. (2014a) found that the variability in hydraulic properties with soil depth plays an important role in water availability for plants, particularly in water-limited ecosystems. For the Caatinga biome, Table 5 and Fig. 2 suggest that the surface layer allows root water uptake to occur at lower (more negative) water potentials than in deeper layers. This supports the premise that the surface layer is the most important layer regarding water availability in the Caatinga biome for several reasons: it receives ephemeral pulses of rainfall; it contains the highest root length density; and it shows

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### Table 5: Hydraulic conditions (limiting pressure head \( h_{lim150} \) and \( h_{lim300} \) and effective saturation \( \Theta_{lim150} \) and \( \Theta_{lim300} \)) at the respective limiting root water potentials \( h_w = -150 \) m and \( h_w = -300 \) m for soils from the Caatinga biome with measured root length densities (RLDs) associated with a transpiration rate of \( 6 \) mm d\(^{-1}\).

<table>
<thead>
<tr>
<th>Site</th>
<th>Great Soil Group</th>
<th>Depth</th>
<th>RLD</th>
<th>( M_{lim} )</th>
<th>( h_{lim150} ) m</th>
<th>( h_{lim300} ) m</th>
<th>( \Theta_{lim150} ) m (^3) m (^{-3})</th>
<th>( \Theta_{lim300} ) m (^3) m (^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lixisol</td>
<td>0.00–0.20</td>
<td>( 3.7 \times 10^3 )</td>
<td>( 5.01 \times 10^{-6} )</td>
<td>(-99)</td>
<td>(-108)</td>
<td>(0.11)</td>
<td>(0.10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.20–0.40</td>
<td>( 2.8 \times 10^3 )</td>
<td></td>
<td>(-95)</td>
<td>(-101)</td>
<td>(0.17)</td>
<td>(0.16)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.40–0.60</td>
<td>( 2.0 \times 10^3 )</td>
<td></td>
<td>(-91)</td>
<td>(-92)</td>
<td>(0.12)</td>
<td>(0.12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.60–0.80</td>
<td>( 1.6 \times 10^3 )</td>
<td></td>
<td>(-133)</td>
<td>(-171)</td>
<td>(0.25)</td>
<td>(0.20)</td>
</tr>
<tr>
<td>2</td>
<td>Luvisol</td>
<td>0.00–0.20</td>
<td>( 4.1 \times 10^3 )</td>
<td>( 8.58 \times 10^{-6} )</td>
<td>(-97)</td>
<td>(-109)</td>
<td>(0.29)</td>
<td>(0.27)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.20–0.40</td>
<td>( 1.8 \times 10^3 )</td>
<td></td>
<td>(-55)</td>
<td>(-56)</td>
<td>(0.12)</td>
<td>(0.12)</td>
</tr>
<tr>
<td>3</td>
<td>Leptosol</td>
<td>0.00–0.20</td>
<td>( 2.8 \times 10^3 )</td>
<td>( 1.10 \times 10^{-5} )</td>
<td>(-53)</td>
<td>(-53)</td>
<td>(0.36)</td>
<td>(0.36)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.20–0.40</td>
<td>( 1.8 \times 10^3 )</td>
<td></td>
<td>(-36)</td>
<td>(-37)</td>
<td>(0.25)</td>
<td>(0.25)</td>
</tr>
</tbody>
</table>

† IUSS Working Group WRB (2015).
the most favorable hydraulic properties for water flow to plant roots. These results corroborate an earlier study performed for the same Caatinga forest, where the upper layer supplied up to 90% of the total water requirement (Pinheiro et al., 2016). Other researchers have also found transpiration to be controlled by the soil water content of the surface layer (Liu et al., 2011; Raz-Yaseef et al., 2012; Klein et al., 2014a; Gaines et al., 2015).

Similar to the results discussed above, when considering \( b_{\text{lim}} = -300 \) m instead of \(-150 \) m, only a slight decrease in \( h_{\text{lim}} \) is observed, corresponding to a minimal increase in transpirable water for forest survival. According to Klein et al. (2014b), the remarkable changes in hydraulic properties among soil types that are mostly independent of the forest biome type introduce additional variation among forests in terms of their susceptibility to soil drought. Many plant strategies can be recognized in the Caatinga biome that allow the vegetation to cope with low soil-water ranges, e.g., spreading of shallow roots, reduced leaf area, and shedding of leaves (Pinheiro et al., 2013, 2016). There are indications that the ability of woody plants to survive and recover from periods of sustained drought is strongly related to their resistance to embolism (Choat et al., 2012). Possibly, some strategy regarding hydraulic failure, i.e., protection of the xylem from extensive embolism, may be part of Caatinga species strategy. However, our results suggest that soil hydraulic properties allowing maintenance of a water supply to plants under low soil pressure heads is another very important feature in determining the establishment and survival of plants in the Caatinga biome.

**Conclusions**

Using hydraulic properties measured under unsaturated conditions in samples of Brazilian soils from two different climate zones to determine crop water availability using a matric flux potential approach, we conclude that:

1. Given characteristic root density patterns, the matric flux potential approach extended to multilayer scenarios allows identification of soil hydraulic limitations regarding crop water supply for different ecosystems.

2. Soils from the Brazilian semiarid zone are able to deliver water to plants under a wider range of pressure head than soils from the humid zone. Considering \( h_{w} = -150 \) m, limiting pressure heads for semiarid soils ranged from \(-118 \) to \(-33 \) m; soils from the humid zone showed slightly stronger hydraulic restrictions, with limiting pressure heads ranging from \(-36 \) to \(-3 \) m.

3. For the analyzed soils from semiarid and humid climate zones, a negligible increase in available water results from decreasing the root water potential \( (b_{w}) \) below \(-150 \) m. It has been generally suggested that species in semiarid ecosystems are adapted to lower root water potentials. Our results, however, indicate that it is more reasonable to expect plant adaptation under dry climate conditions to evolve toward other strategies, e.g., development of a higher root length density (i.e., more lateral roots), especially in the surface layer.

**Acknowledgments**

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**References**


Fig. 2. Limiting soil pressure head estimated from the limiting matric flux potential \( M_{\text{lim}} \) across a range of transpiration for soils from the semiarid zone. LX = Lixisol (Soil 1), LV = Luvisol (Soil 2), and LP = Leptosol (Soil 3).