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Research paper

Field capacity, a valid upper limit of crop available water?

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ABSTRACT

"Field capacity" (FC) is an agronomic measure with prime application in irrigation management, allowing the determination of irrigation gift without excessive leaching. FC can be determined by performing or simulating an internal drainage experiment until percolation reaches a "negligible" value. Alternatively, a static value of pressure head is often used to estimate FC, commonly −3.3 m, −1 m or −0.6 m. FC is also used in definitions regarding soil water availability to crops and has been adopted in soil water balance models to define the maximum water storage. Nevertheless, crop water uptake may occur at water contents higher than FC. This uptake may represent a significant share of total uptake, and FC would then not be a true upper limit of available water. To investigate if FC can be considered an efficient soil physical quantity to characterize soil water availability we used information of unsaturated hydraulic properties (retention and hydraulic conductivity) of 8 soil profiles in Brazil. Using the hydrological model SWAP we estimated FC based on pressure head and bottom flux criteria and evaluated water uptake by pasture and maize from the soil drier than FC (hence: from the "available water" pool between FC and permanent wilting point) as well as from the water held at tensions between saturation and FC. Results show a considerable (10–50%) fraction of transpired water is taken up from the soil at water contents above FC, making FC a questionable quantity to truly estimate crop available water and casting doubt on the reliability of bucket-type soil water balance models.

1. Introduction

"Field capacity" (FC) is an agronomic measure with prime application in irrigation management, allowing the determination of irrigation to be applied without excessive leaching. Applying the classical concept (Veihmeyer and Hendrickson, 1931), FC can be determined by performing or simulating an internal drainage experiment until percolation reaches an arbitrarily defined "negligible" value. Many experimental or modeling efforts of doing so have been reported in literature (Jabro et al., 2009; Twarakavi et al., 2009; Romano et al., 2011; Sun and Yang, 2013; De Jong van Lier and Wendroth, 2016). However, due to the complexity implicit to respective field experiments or the determination of unsaturated hydraulic properties, a static value of pressure head is most often used to estimate FC, most commonly −3.3 m, −1 m or −0.6 m. These estimates do not physically comply with a drainage criterion and may therefore be unreliable with respect to irrigation management.

Besides its use in irrigation management, FC is also used in definitions regarding soil water availability to crops and soil hydraulic status. It has been adopted in soil water balance modeling to define the maximum amount of water storage in bucket-type soil water balance models as employed in, e.g., GLEAMS (Leonard et al., 1987), DSSAT (Ritchie, 1972), HERMES (Kersebaum, 1995), and Aquacrop (Steduto et al., 2009; Raes et al., 2012). These models implicitly assume that all water stored in the soil above FC is instantaneously drained and unavailable for plants. In reality, however, this drainage takes time during which, in fact, plants do take up this water. Romano et al. (2011) investigated the effect of estimates of FC on the performance of a bucket-type model.

Irrespective of the way FC is estimated, water contents above FC may occur and water may be withdrawn from the soil by plants under these conditions. Consequently, FC may be used as a criterion for irrigation practices, but it possibly fails as a comprehensive indicator of crop available water. We aimed to evaluate to what extent water uptake from a soil wetter than FC may represent a significant share of total uptake. If this share represents a considerable amount, FC would not be a true upper limit of available water and bucket-type water balance models would underestimate available soil water.

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Table 1
Identification, classification, location, texture class and literature source for the soils used in this study.

Soil ID	WRB classification	Coordinates Latitude, Longitude	USDA Texture class	Source
A	Arenic Acrisol	−21.352, −48.166	Sandy clay loam	Brito (2006)
B	Rhodic Nitisol	−22.704, −47.623	Clay	Martins da Silva (2007)
C	Haplic Ferralsol	−22.716, −47.615	Sandy clay loam	Hurtado (2004)
D	Eutric Ferralsol	−21.252, −48.191	Clay	Angelotti Netto et al. (2007)
E	Haplic Ferralsol	−20.350, −48.300	Clay	Klein and Libardi (2002)
F	Dystric Ferralsol	−22.353, −49.835	Sandy loam	Gloaguen (2005)
G	Gleyic Arenosol	−21.751, −41.285	Sand	Bernardes (2005)
H	Fragic Acrisol	−21.757, −41.369	Clay	Bernardes (2005)

2. Materials and methods

2.1. Soil data

Data were retrieved from literature for eight Brazilian soils from the Brazilian southeast, latitudes around 21° S, covering a wide range of textures and soil classes (specific information and data sources in Table 1). In the reported soils, retention data were obtained in undisturbed samples using standard laboratory procedures (tension table and pressure chamber) for several layers (between 5 and 10 layers covering the range between the surface and 1 m depth). Unsaturated hydraulic conductivity data were obtained at the same depths from internal drainage experiments under field conditions.

Hydraulic properties were expressed using the Van Genuchten (1980) equation system:

$$S_e = \left[1 + |\alpha h|^n\right]^{\frac{1}{n}-1} \quad [1]$$

$$K = K_s {S_e}^{\lambda}\left[1 - \left(1 - {S_e}^{\frac{n}{n-1}}\right)^{1-\frac{1}{n}}\right]^2 \quad [2]$$

in which S_e is the effective saturation defined as $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$, θ, θ_r and θ_s are water content, residual water content and saturated water content ($\mathrm{m^3\,m^{-3}}$), respectively, h is pressure head (m), K and K_s are hydraulic conductivity and saturated hydraulic conductivity, respectively ($\mathrm{m\,d^{-1}}$), and α ($\mathrm{m^{-1}}$), n, and λ are empirical parameters. Parameters for Eqs. (1) and (2) were obtained for all depths by simultaneous fitting of h-θ and K-h using RETC 1.0 (Van Genuchten et al., 1991). Table 2 shows fitted parameters for all layers of the eight soils.

2.2. Field capacity

To establish a value for FC, six different criteria were evaluated, three of those referring to a fixed pressure head (h_{fc}) and three to a specific bottom flow (q_{fc}). The evaluated fixed pressure heads were $h_{fc} = -0.6$ m, $h_{fc} = -1.0$ m and $h_{fc} = -3.3$ m.

FC related to specific bottom flow rates was determined by simulations of internal drainage scenarios performed with the SWAP model (Kroes et al., 2008). For modeling purposes, the 1 m deep soil profiles were subdivided in 20 layers of 0.05 m. For each soil, three depths (z_{fc}, m) were considered for FC (or bottom flow) evaluation: $z_{fc} = 0.30$ m, $z_{fc} = 0.60$ m and $z_{fc} = 0.90$ m. The initial hydraulic conditions were defined corresponding to a saturated soil profile (pressure head $h = -0.001$ m in the entire profile). Evaporation and precipitation were set to zero, and the lower boundary condition (at 1 m depth) was set to the "free drainage of soil profile" option, i.e., a gravitational flow at 1 m depth.

Simulations were run for 60-day periods with an output every simulated hour. FC was considered corresponding to the hydraulic conditions at the first occurrence of a bottom flux at z_{fc} smaller than one of three arbitrary threshold values: $q_{fc} = 0.5\ \mathrm{mm\,d^{-1}}$, $q_{fc} = 1\ \mathrm{mm\,d^{-1}}$, or $q_{fc} = 5\ \mathrm{mm\,d^{-1}}$. These values are higher than those used in several studies in temperate climate soils: Nachabe (1998), Meyer and Gee (1999), Twarakavi et al. (2009) and Sun and Yang (2013) used values of the order of $0.1\ \mathrm{mm\,d^{-1}}$, but such low values for q_{fc} result in drainage times longer than reasonable in many tropical soils (e.g. De Jong van Lier and Wendroth, 2016).

2.3. Field capacity versus crop water availability

To evaluate the validity of FC as an upper boundary of crop water availability in the eight soils from Tables 1 and 2, crop growth and root water uptake simulations were performed with the SWAP model (Kroes et al., 2008) for a 37-year period (1978–2014), using daily weather data from the University of São Paulo weather station in Piracicaba, Brazil (22.703°S; 47.624°W), representing the subtropical winter-dry climate of southeast Brazil (Köppen Cwa). For the considered period, average yearly rainfall was 1316 mm with a standard deviation of 242 mm. The driest year (1978) showed 874 mm of rainfall, the wettest year was 1983 with 2018 mm. In this region, rainfall is concentrated between October and March, whereas the dry months April - September correspond to less than 25% of annual rainfall. Fig. 1 contains information about monthly means and standard deviations for the considered range of years.

In these soils, the groundwater level is usually deep (>5 m) and does virtually not affect the surface soil water balance. Therefore, gravitational flow was considered at the profile bottom.

Three rainfed cropping scenarios were simulated on the eight soils: (1) pasture, continuously throughout the year, (2) maize sown on October, 1 and harvested on January, 31 (Summer maize), hence growing during the rainy season and (3) maize sown on February, 1 and harvested on May, 31 (Autumn maize), thus including some drier months especially at the end of the cropping cycle.

Pasture was simulated to have a constant root length density per depth, a constant rooting depth equal to the maximum rooting depth, a continuous soil cover fraction of 1.0 and a crop factor of 1.0. For maize, a fixed period of 60 days was simulated from emergence (development stage DVS = 0) to anthesis (DVS = 1), and an additional 60 days from anthesis (DVS = 1) to maturity (DVS = 2). The root length density of maize was simulated to decrease linearly from a maximum value at the surface to zero at the maximum rooting depth. Leaf area index I_{LA}, rooting depth Z_R and crop height H_c were defined as piecewise linear functions of development stage according to data points in Table 3. All crops were simulated considering three maximum rooting depths, the same depths z_{fc} used in the FC simulation scenarios: 0.3, 0.6 and 0.9 m. Maize root growth was cut of earlier at respective depths for the 0.3 m and 0.6 m scenarios (Table 3).

Root water uptake reduction due to drought stress or anoxia was estimated using the piecewise linear function proposed by Feddes et al. (1978). According to this function, a multiplicative reduction factor ε is defined by four pressure heads ($0 \geq h_1 > h_2 > h_3 > h_4$) delimiting five phases of uptake. In the permanent wilting phase, ($h < h_4$), $\varepsilon = 0$. In the falling rate phase ($h_4 < h < h_3$), $\varepsilon = (h - h_4)/(h_3 - h_4)$. In the constant (optimum) rate phase delimited by h_3 and h_2, $\varepsilon = 1$. In the wet phase ($h_2 < h < h_1$), $\varepsilon = (h - h_1)/(h_2 - h_1)$. In the anaero-