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The effect of soil stoniness on the estimation of water retention properties of soils: A case study from central France

M. Tetegan [a,b,c], A.C. Richer de Forges [c], B. Verbeque [d], B. Nicoullaud [a], C. Desbourdes [e], A. Bouthier [b], D. Arrouays [c], I. Cousin [a,*]

[a] INRA, UR0272, 2163 Avenue de la Pomme de Pin, CS40005 Ardon, F-45075 Orléans, France
[b] ARVALIS — Institut du Végétal, Domaine du Magneraud, F-17700 Saint Pierre d'Amilly, France
[c] INRA, US1106, 2163 Avenue de la Pomme de Pin, CS40005 Ardon, F-45075 Orléans, France
[d] Chambre d'Agriculture du Loiret, 13 Avenue des Droits de l'Homme, F-45921 Orléans, France
[e] ARVALIS — Institut du Végétal, 45 voie Romaine, F-41240 Ouzouer le Marché, France

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ABSTRACT

Estimation of the water retention capacity of a heterogeneous soil requires knowledge of the hydric properties of each soil phase. Nevertheless, for stony soils, the rock fragments have often been neglected. The objective of this work was then to propose a methodology to improve the calculation of the available water content (*AWC*) of stony soils at a regional scale. On a 36,200 ha surface area in Beauce located in the Region Centre of France, the *AWC* was calculated by coupling pedotransfer classes developed for fine earth and rock fragments. When calculating the *AWC* for the first 120 cm of the soil and considering the rock fragments to be inert, the *AWC* was underestimated by 15% and showed a high spatial variability. When both the volume and the hydric properties of the rock fragments were ignored, the *AWC* was underestimated by 20%. This work is then the first proposal to estimate soil water properties at a regional scale by using the water storage capacity of the main part of the stony phase, say from gravels to stones. Results of this study will improve the calculation of water deficit on a regional scale and will aid both in regional water balance modelling and in regional assessment of irrigation needs.

1. Introduction

To estimate the ability of soils to provide water to plants for their growth, soil scientists and agronomists determine the available water content (*AWC*) of the soil, which is likely to be exploited by the roots. The *AWC* is thus an important agronomic parameter for calculating soil water balance and for managing the irrigation of cultivated soils. Therefore, there is a need to explain the soil hydric characteristics to optimize crop growth and to reduce water transfer and losses deeper than the root system. As a consequence, mapping the available water content of soils at a regional scale is a key factor for evaluating land suitability and for developing models to forecast the requirements for irrigation needs and the risks to groundwater quality (Paydar et al., 2009); this mapping is especially important in the context of the climatic change that may alter water reservoir inputs and management in ways that reduce the water supply to irrigated areas (Garcia-Ruiz et al., 2011). As stated by Jensen et al. (2010), new strategies for conserving irrigation water are needed.

Nevertheless, the estimation of the soil available water content remains difficult for heterogeneous soils (Frison et al., 2009), especially stony soils, because it requires a precise knowledge of the water retention capacities of each of the main soil phases: the fine phase composed of soil particles smaller than 2 mm in diameter and the stony phase composed of rock fragments larger than 2 mm in diameter (Corti et al., 1998; Tetegan et al, 2011; Wang et al, 2013). The calculation of the available water content of the fine phase can be performed through various pedotransfer classes (tables) and pedotransfer functions based on easily accessible soil characteristics such as the bulk density, carbon content and texture of fine earth (Al Majou et al., 2007, 2008a, 2008b; Bastet et al., 1999; Wösten et al., 2001). Pedotransfer classes are tables enabling to obtain the water content of the fine earth thanks to its texture, or by combining its texture and its structure (Al Majou et al., 2005, 2008a; Baker, 2008; Bruand et al., 2002). The water retention properties of the stony phase have often been ignored when calculating the available water content of stony soils, although several studies have shown that rock fragments could be a significant water reserve for soil (Gras and Monnier, 1963; Poesen and Lavee, 1994). Tetegan et al. (2011) have also recently proposed new pedotransfer functions and pedotransfer classes to estimate the available water content of rock fragments in soils originating from sedimentary rocks. However, to our present knowledge, no attempt to map and globally assess the available water content of soils at a regional scale has been conducted using these new pedotransfer functions.

* Corresponding author.
E-mail address: Isabelle.Cousin@orleans.inra.fr (I. Cousin).

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The objective of this paper was to use these new pedotransfer functions for estimating the contribution of rock fragments to the available water content of stony soils to i) produce a more accurate map of the available soil water content at the regional scale and, ii) assess if regional estimates of the total available soil water content using the knowledge of this contribution of rock fragments lead to substantial differences from previous approaches. Conducted on several soils of variable stoniness, for each soil type, the available water content was calculated both when considering and when disregarding the volume and the water retention properties of the rock fragments.

2. Materials and methods

2.1. Study area

The study was conducted on approximately 36,200 ha located 110 km southwest of Paris in the Patay area within “Petite Beauce”. Intensive agriculture in the Petite Beauce often utilizes irrigation and 76% of the surface area is occupied by cereal crops, mainly maize and wheat (Nicoullaud et al., 2004). The climate is temperate continental with an oceanic influence and is characterized by an evapotranspiration of approximately 780 mm calculated using the Penman–Monteith formula. The average annual temperature was 11 °C from 1971 to 2000, and the average annual rainfall was 635 mm and ranged from 415 to 850 mm over the 1971–2000 period (Richer de Forges and Verbèque, 2003).

2.2. The Patay soil map and the soil database

A soil map (scale: 1/50,000) was designed by Richer de Forges and Verbèque (2003) with a mean density of observations equal to 1 auger-hole per 17 ha. Quantitative data used to create the soil map (granulometry, carbon content, pH, etc.) were measured on approximately 100 soil profiles, using standard analyses, and stored in an associated database. Upper horizons were affected by peri-glacial winds that largely redistributed the fine material (Macaire, 1971; Bourennane et al., 1996), resulting in a rather homogeneous particle-size distribution of the fine earth (i.e., values of silt, clay, sand, etc.). Most of the soils consisted then of a silty-clay layer (approximately 60% silt and 30% clay) developed on a lacustrine limestone substrate, which was locally cryoturbated. King et al. (1999) and Bourennane et al. (1998) indicated that the soil units that formed on cryoturbated limestone deposits or on soft limestone deposits had the deepest silty-clay layer (up to 0.8 m deep), whereas the shallowest soils (approximately 0.3 m deep) were developed directly on hard calcareous bedrock. This latter bedrock is cracked (Lorain, 1973), which could allow a root proliferation of cultures. The study area was classified into 23 main map units (MUs) according to i) the spatial variability of the soil characteristics, ii) the depth and type of limestone where the soil horizons have been developed, and iii) the thickness of the silty-clay layers. Non-stony soils were mainly arenosols, cambisols, fluvisols, luvisols, haplic planosols and vertisols (IUSS Working Group WRB, 2006). Stony soils were mainly rendzic leptosols, haplic calcisols and calcaric cambisols, with various quantities of rock fragments of different sizes, from gravels to blocks (IUSS Working Group WRB, 2006).

The MUs of the soil map consisted of one or several soil units corresponding to a synthetic soil profile defined in terms of soil and agronomic characteristics observed in the field (Legros, 2006). The information on the soil units was stored in the “DoneSol” soil database (Gaultier et al., 1993; Grolleau et al., 2004). From this database, we used the following soil characteristics to estimate the available water content of both the stony and non-stony soils:

- the volume proportion and the texture of the fine phase,
- the volume proportion, the lithological class (limestone, quartz, or flint, on the studied area) and the bulk density of the whole stony phase (gravels, pebbles, stones and blocks),
- the thickness of the horizons
- the nature of the underlying parent material
- the surface proportion of each soil unit in each of the 23 MUs of the map of Patay.

To be comparable with the pedotransfer functions developed by Tetegan et al. (2011) for the estimation of the contribution of rock fragments to the available water content, the bulk density of the rock fragments located within the soil profile was used, rather than the bulk density of the bedrock, which could be slightly different.

2.3. Calculation of the available water content at different scales

2.3.1. Choice of a definition and units for the available water content

We define the available water content as the quantity of water that can be used by plants for their growth, and we assume that it is equal to the difference between the water content at field capacity, and the water content at permanent wilting point, with the units $cm^3 \cdot cm^{-3}$, as calculated in Eq. (1). Nevertheless, for practical reasons, it is also expressed as a depth (expressed in mm): it represents the available water within a soil horizon (see Eq. (2)) or within a soil profile (see Eq. (3)) and can be directly used in a water balance model.

2.3.2. Method used to calculate the available water content

The available water content for both the fine phase and the stony phase (AWC_i) was calculated using Eq. (1):

$$AWC_i = \theta_{fc,i} - \theta_{wp,i} \tag{1}$$

where AWC_i represents the available water content of the phase i in $cm \cdot cm^{-3}$, $\theta_{fc,i}$ represents the volumetric soil water content at field capacity for phase i in $cm \cdot cm^{-3}$, and $\theta_{wp,i}$ is the volumetric soil water content at the permanent wilting point for phase i in $cm \cdot cm^{-3}$. For both the fine phase and the stony phase, the volumetric soil water content at field capacity was set equal to the soil water content at a matric potential of −100 hPa, as suggested by Bruand et al. (2004) and Al Majou et al. (2008a, 2008b) for the fine earth, and by Tetegan et al. (2011) for the stony phase. For both the fine and the stony phase, the volumetric soil water content at permanent wilting point was set equal to the soil water content at a matric potential of −15,850 hPa, as typically required. For the fine phase, the volume soil water contents at −100 hPa and −15,850 hPa were calculated from the pedotransfer classes of Bruand et al. (2004). These authors used the soil texture (Baize et al., 2009) from the French texture class triangle of Jamagne (1967) and separated topsoil and subsoil horizons in the soil profile. For our study, the dominant texture of the fine phase for each horizon of each soil unit was collected from the soil database and the position of each horizon in the soil profile was simplified by distinguishing only between topsoil and subsoil horizons. Table 1 presents the AWC_i for the fine phase. For the stony phase, the volumetric soil water contents at −100 hPa and −15,850 hPa were calculated using the pedotransfer classes proposed by Tetegan et al. (2011), who used information only on the lithological class of the rock fragments and the bulk density of each rock fragment. In our study, the dominant lithological class of the rock fragments was collected from the soil database for each soil horizon. The bulk density of the rock fragments of each lithological class was taken from Tetegan et al. (2011). The AWC_i for the stony phase is presented in Table 2.

From the AWC_i of both the fine and the stony phases given by Eq. (1), the available water capacity of a horizon n (AWC_h^n) was calculated in millimetres by using Eq. (2) proposed by Cousin et al. (2003):

$$AWC_h^n = \left(\sum_{i=1}^{i=2} AWC_i \times P_i^n \right) \times T_h^n \tag{2}$$