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Mapping rootable depth and root zone plant-available water holding capacity of the soil of sub-Saharan Africa

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ABSTRACT

In rainfed crop production, root zone plant-available water holding capacity (RZ-PAWHC) of the soil has a large influence on crop growth and the yield response to management inputs such as improved seeds and fertilisers. However, data are lacking for this parameter in sub-Saharan Africa (SSA). This study produced the first spatially explicit, coherent and complete maps of the rootable depth and RZ-PAWHC of soil in SSA. We compiled geo-referenced data from 28,000 soil profiles from SSA, which were used as input for digital soil mapping (DSM) techniques to produce soil property maps of SSA. Based on these soil properties, we developed and parameterised (pedotransfer) functions, rules and criteria to evaluate soil water retention at field capacity and wilting point, the soil fine earth fraction from coarse fragments content and, for maize, the soil rootability (relative to threshold values) and rootable depth. Maps of these secondary soil properties were derived using the primary soil property maps as input for the evaluation rules and the results were aggregated over the rootable depth to obtain a map of RZ-PAWHC, with a spatial resolution of 1 km^2. The mean RZ-PAWHC for SSA is 74 mm and the associated average root zone depth is 96 cm. Pearson correlation between the two is 0.95. RZ-PAWHC proves most limited by the rootable depth but is also highly sensitive to the definition of field capacity. The total soil volume of SSA potentially rootable by maize is reduced by one third (over 10,500 km^3) due to soil conditions restricting root zone depth. Of these, 4800 km^3 are due to limited depth of aeration, which is the factor most severely limiting in terms of extent (km^2), and 2500 km^3 due to sodicity which is most severely limiting in terms of degree (depth in cm). Depth of soil to bedrock reduces the rootable soil volume by 2500 km^3, aluminium toxicity by 600 km^3, porosity by 120 km^3 and alkalinity by 20 km^3. The accuracy of the map of rootable depth and thus of RZ-PAWHC could not be validated quantitatively due to absent data on rootability and rootable depth but is limited by the accuracy of the primary soil property maps. The methodological framework is robust and has been operationalised such that the maps can easily be updated as additional data become available.

1. Introduction

Substantial and sustainable increases in crop yields are needed in sub-Saharan Africa (SSA) to help meet food demand due to population and income growth (Jayne et al., 2010; Pretty et al., 2011; Garnett and Godfray, 2012; van Ittersum et al., 2016). Yield increases require

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Abbreviations: AfSP, Africa Soil Profiles database; AfSS, Africa Sentinel Sites database; BD, bulk density; CEC, cation exchange capacity; DSM, digital soil mapping; EC, electrical conductivity; FC, field capacity; ISFM, Integrated Soil Fertility Management; PAWHC, plant-available water holding capacity; pF, logarithm of the negative hydrostatic head or matrix potential; PWP, permanent wilting point; PTF, pedotransfer function; RI, rootability index; RZD, root zone depth (rootable depth); RZ-PAWHC, root zone plant-available water holding capacity; SFEF, soil fine earth fraction; SSA, sub-Saharan Africa; VMC, volumetric moisture content

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improved crop and soil management practices, including improved seeds and cost-effective application of nutrients in the form of organic and/or inorganic fertilisers according to the principles of Integrated Soil Fertility Management (ISFM) (Vanlauwe et al., 2010). However, ISFM will only be adopted by smallholder farmers, which make up 65–80% of the population in SSA, if the return on investment is appreciable and without too much risk. Indeed, farmer's motivation and decision making relies heavily on the perceived likeliness of obtaining a profitable return at minimized risk. This likeliness largely depends on the yield response to inputs, both in terms of magnitude and stability (i.e. temporal variation), which depends to a large extent on site-specific soil properties and year-to-year variation in weather. Hence quantitative estimates of the yield response to inputs at a given location, and especially its temporal variation, are essential for estimating the risks associated with these investments and such information may well be key to achieving higher rates of adoption of ISFM practices and especially fertiliser application (Marenya and Barrett, 2007; Dercon and Christiaensen, 2007; Rötter and van Keulen, 1997; Hiebert, 1974).

Rainfed crop production is practiced on > 95% of existing farmland in SSA (Alexandratos and Bruinsma, 2012) where current average farm yields for the major cereal crops are only about 20% of the potential rainfed yields without limitations from nutrients or pests and diseases (van Ittersum et al., 2016). This potential yield represents the crop demand for nutrients and sets a reference for determining the degree that soil supply of nutrients is deficient. The amount of water available to support crop growth in these rainfed systems is largely determined by rainfall amount and timing, and the amount of water that can be stored in the soil profile and that is available for uptake by crop roots -hereafter called the root zone plant-available water holding capacity (RZ-PAWHC). The RZ-PAWHC represents a reservoir from which crops can take up water and which buffers against water deficits in periods when rainfall does not meet crop water demand and also determines the length of the growing period at the end of the rainy season in monsoonal tropical climates, and thus the appropriate cultivar to use (e.g. FAO, 1978; Zingore et al., 2007). Therefore a larger RZ-PAWHC reduces risk of drought stress and contributes to higher yields and yield stability, and thus increases the resource use efficiency (de Wit, 1992) and the probability of obtaining a profitable response to ISFM.

Data on RZ-PAWHC are thus key input to soil moisture models such as GLEAMS (Martens et al., 2017), crop growth models such as WOFOST (van Diepen et al., 1989), LINTUL (Spitters and Schapendonk, 1990), DSSAT (Jones et al., 2003), Hybrid-Maize (Yang et al., 2004) and data mining (Jeong et al., 2016; You et al., 2017) and therewith to yield gap analysis for performing *ex ante* assessments of yield responses to inputs across a wide range of environmental conditions (Grassini et al., 2015; van Ittersum et al., 2013). While recent initiatives, e.g. the Africa Soil Information Service (AfSIS) project (http://africasoils.net), have improved the availability, accuracy and resolution of spatially explicit and coherent data on soil fertility parameters in SSA (ISRIC, 2013; Hengl et al., 2015b, 2017b), there are few data on RZ-PAWHC or root zone depth. This study, which is a collaborative initiative of the Global Yield Gap and water productivity Atlas (GYGA) project (www.yieldgap.org) and the AfSIS project, attempts to fill this "data gap" by developing the first spatially explicit soil maps for SSA of root zone depth and RZ-PAWHC. In this study we derive maps for maize as a reference crop because maize is an important cereal in SSA and to a large extent representative for other major cereals.

2. Materials and methods

2.1. Definitions and methodological framework

The RZ-PAWHC reflects the adequacy (capacity) of soil to store water and support crop growth when rainfall is insufficient to meet crop water requirements. RZ-PAWHC (expressed by an absolute value (mm)) is composed of three components which are aggregated to a single parameter. The first component is the plant-available water holding capacity (PAWHC) of the soil fine earth and is defined as the amount of soil moisture retained over the range in which the soil is neither too wet nor too dry for crop roots to take up soil water. The PAWHC is assessed per depth interval and expressed as a volumetric fraction. The second component is the soil fine earth fraction (SFEF) which is the volume of soil fine earth (particle size < 2 mm) as a fraction of the volume of soil whole earth. The SFEF determines the net volume of soil, per depth interval, that can retain soil moisture and that crop roots can effectively exploit. The third component is the total depth interval from which the crop can extract water, which is the rootable soil depth or root zone depth (RZD). This study derives maps of the RZ-PAWHC for maize which has a genetically defined potential root zone depth, attained near anthesis, between 100 and 170 cm (van Keulen and Wolf, 1986). In this study, a maximum potential root zone depth of 150 cm is used.

There are three main ways to map each of the three components defining RZ-PAWHC. The first is to collect sufficient direct observations of the three soil properties, and use these primary soil profile data for producing interpolated maps, either representing individual soil profile layers or the soil profile as a whole. This direct approach can make use of digital soil mapping (DSM) techniques such as regression kriging and machine-learning (McBratney et al., 2003; Hengl et al., 2004, 2015b; Lagacherie et al., 2006) and requires sufficient data well distributed over geographic- and feature space. The second way is to infer secondary soil profile data for the three targeted soil properties from primary soil profile data readily available for other soil properties, e.g. by existing or yet to be established pedotransfer functions (PTF; Bouma, 1989), and to use the derived data and DSM techniques to produce interpolated maps of each of the three target soil properties (first calculate, then interpolate; Heuvelink and Pebesma, 1999). This approach requires the available soil profile data to be sufficiently coherent in terms of scope, homogeneity and completeness, without important data gaps, to consistently derive the secondary data. The third way is to first create interpolated soil property maps, using DSM and primary soil profile data which are available in sufficient quantities and of sufficient coherence, and then use these interpolated coherent maps as input for (pedotransfer) functions, rules and criteria to calculate derived, inferred, maps of the targeted secondary soil properties (first interpolate, then calculate). For each of the three ways, the results for different depth intervals for water retention and the soil fine earth fraction can be aggregated into a single value over the rootable soil depth to produce the RZ-PAWHC map. Because the soil profile data available for this study were not complete for all required variables, and the soil depths sampled were not consistent and often did not include soil layers below 50 cm depth, this third approach was used in this study. Basically, this approach is a digital soil assessment (Minasny et al., 2012). An overview of the methodological framework to map RZ-PAWHC is given in Fig. 1. The steps in the workflow are explained in detail in the next sections.

2.2. Data preparation

2.2.1. Soil profiles data

Soil profiles data used for mapping and validation, and for the development and testing of pedotransfer functions and rules to produce derived data and maps, came from two soil profile datasets generated by the AfSIS project. First, the Africa Soil Profiles database (AfSP) which is a compilation of georeferenced and standardised legacy soil profile data for SSA (Leenaars et al., 2014a) and is available at www.isric.org/projects/africa-soil-profiles-database-afsp. The AfSP version 1.2 consists of soil data taken at 18500 profile point locations which are described and sampled on average at 4.1 (± 1.6) depth intervals to an average soil depth of 125 (± 65) cm. The second soil dataset was collected more recently from 60 sentinel sites of 10 × 10 km (AfSS) and is available at afsisdb.qed.ai with data for 9600 point locations sampled at the 0–20 and 20–50 cm depth intervals. Ten percent of the AfSS data