Root Zone Plant-Available Water Holding Capacity of the Sub-Saharan Africa Soil

Gridded functional soil information (dataset RZ-PAWHC SSA version 1.0)

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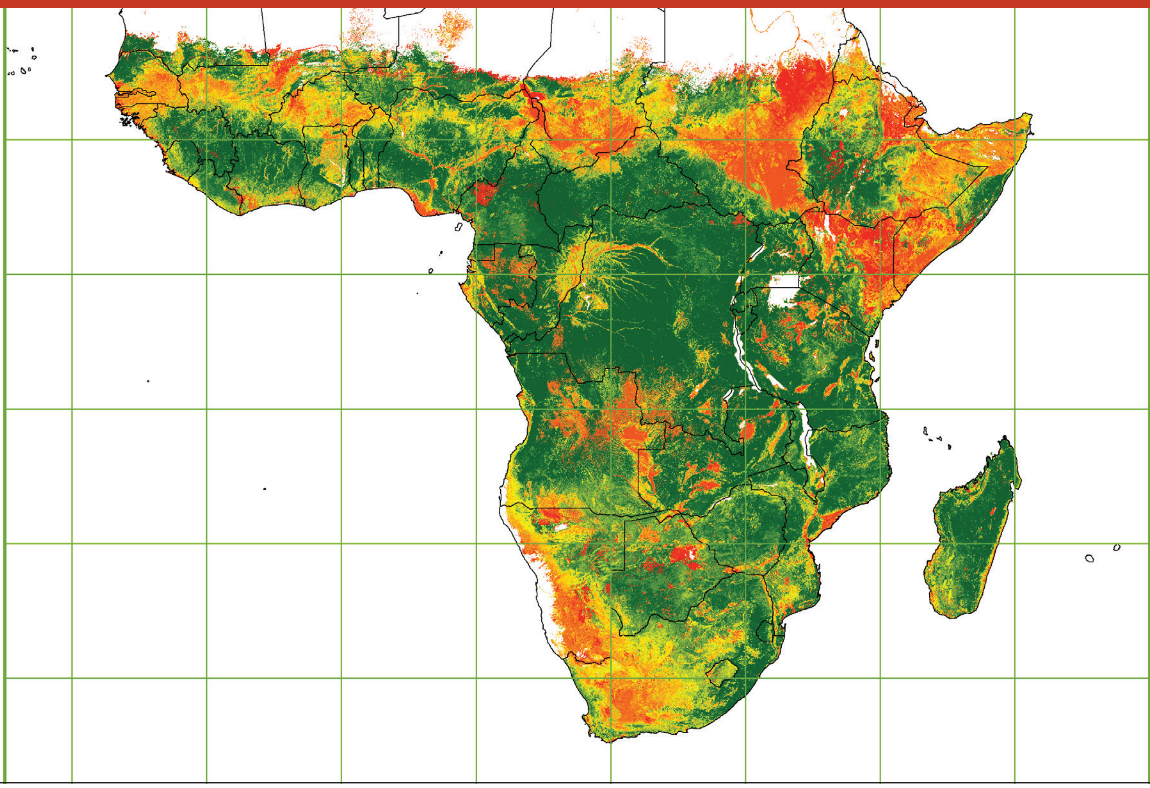

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Africa Soil Information Service AfricaSoils.net

Global Yield Gap Atlas

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Preface

Geospatially explicit data on rootable soil depth are lacking for much of Sub-Saharan Africa and yet this factor has a large influence on crop yields, especially when grown under rainfed conditions. This report attempts to fill that data gap. Production of this first version of the Root Zone Plant-Available Water Holding Capacity (RZ-PAWHC) dataset for Sub-Saharan African soils is the result of collaboration among scientists from ISRIC - World Soil Information[1] (ICSU World Data Centre for Soils), the Africa Soil Information Service[2] (AfSIS), and the Global Yield Gap and Water Productivity Atlas[3] (GYGA).

High-quality, spatially explicit soil data are required to support research and to inform discussions on the role of soil management to improve food security in Africa. For rainfed crop production, which accounts for more than 95% of existing farmland, depth of the rootable soil zone and plant-available water holding capacity in that rooted volume determines water storage capacity of the soil to support plant growth. Whether rainfall is generous or scarce, it can only be stored and used for crop uptake to the extent the rooting volume permits. Therefore, the root zone plant-available water holding capacity is a key variable affecting crop yield potential, yield stability, and response to inputs such as improved seed and fertilizers.

The RZ-PAWHC dataset builds on recent achievements and expertise of the collaborating scientists from ISRIC, AfSIS and GYGA. Soil profile data from Sub-Saharan Africa are compiled and used to produce soil property maps. Next, this soil information is interpreted by a team of soil scientists and agronomists to derive enriched maps with functional soil information used by agronomists as a base for research and development to support policy makers and land users, and especially farmers.

Funding in support of the collaborative research to produce the RZ-PAWHC dataset were provided by the Bill and Melinda Gates Foundation. The authors are grateful for this support. Others contributing in other ways are noted in the acknowledgements.

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[1] http://www.isric.org/
[2] http://africasoils.net/
[3] http://www.yieldgap.org/

Summary

The objective of this project is to produce a robust, quantitative framework, which is updateable and spatially explicit, to generate and maintain functional soil information on root zone depth and associated plant available soil water holding capacity for a major rainfed staple food crop (maize) in Sub-Saharan Africa. In most cases, the rootable soil depth is considered to be an intrinsic soil property because it is difficult to modify the soil physical and chemical traits that restrict root growth, including high acidity or alkalinity, subsoil compaction, cemented layers, abrupt textural transitions, and bedrock. To achieve the project's objective, a collaborative project was established among the Africa Soil Information Service (AfSIS) project and the Global Yield Gap and Water Productivity Atlas (GYGA) project, both funded by the Bill and Melinda Gates Foundation. Partners in the AfSIS project (www.africasoils.net) are Columbia Global Centers, ICRAF and ISRIC. Partners in the GYGA project (www.yieldgap.org) are the University of Nebraska, Wageningen University, ICRISAT, and participating institutes and universities in ten Sub-Saharan countries. The collaborative project was led by ISRIC - World Soil Information.

All soil data (field observations and laboratory measurements) and relevant covariate data (1km – 250 m resolution imagery), as generated by the AfSIS project and publicly available, are used to assess and map the plant-available water holding capacity of the effective root zone depth of maize[4]. Maps of primary soil properties are interpreted for producing maps of functional soil properties, including soil moisture retention characteristics derived by pedotransfer functions and root zone depth derived from rules and thresholds as developed for this study.

The resulting functional soil information for Sub-Saharan Africa is publicly available as a gridded dataset at 1 km resolution, referred to as version 1.0 of the Root Zone Plant-Available Water Holding Capacity dataset (RZ-PAWHC SSA v.1.0). The dataset is used by the GYGA project as input to simulation of crop yield potentials under water-limited (i.e. rainfed) production, including temporal variation, to estimate yield gaps in ten Sub-Saharan countries. Summarizing, the collaborative work developed a consistent and updateable high-resolution soil information framework for agronomic modelling in support of both long- and short-term goals of smallholder farmers in SSA.

The dataset is accessible at:
www.isric.org/content/afsis-gyga-functional-soil-information-sub-saharan-africa-RZ-PAWHC-SSA

Keywords: soil profiles, soil data, soil information, functional soil properties, rootable soil depth, effective root zone depth, rootability, plant available soil water holding capacity, pedotransfer function, digital soil mapping, regression, statistics, yield gap, yield potential, AfSoilGrids, Africa, AfSIS, GYGA, ISRIC, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central Africa Republic, Chad, Congo-Brazzaville, Congo - Democratic Republic, Cote d'Ivoire, Ethiopia, Gabon, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Lesotho, Madagascar, Malawi, Mali, Mauretania, Mozambique, Namibia, Niger, Nigeria, Rwanda, South Africa, South Sudan, Sudan, Sierra Leone, Senegal, Somalia, Swaziland, Togo, Tanzania, Uganda, Zambia, Zimbabwe

4 Although maize is the default crop for this analysis, rootable soil depth would be comparable for other major rainfed cereals and food crops.

1 Introduction

1.1 Rationale

A key challenge within risk-averse smallholder farming systems in Sub-Saharan Africa (SSA) is to improve soil health, hence crop productivity, by soil fertility management practices with unknown risk of investment. The yield response and economic return on investment from the application of nutrients, in the form of organic and inorganic fertilizers, is largely governed by the water available to support crop growth. Indeed, this water availability, and thus the yield response to fertilizer application, varies considerably in rainfed agriculture from one location to another and from one cropping season to another and is to a large extent determined by the soil water storage capacity.

The water supply to support plant growth is determined by several major factors: (1) the amount of rainfall, (2) the proportion of rainfall that infiltrates the soil and is not lost to runoff or evaporation, (3) the capillary rise of water from the groundwater, (4) the soil depth to which roots penetrate to acquire water (and nutrients), and (5) the plant-available water holding capacity of soil in the rootable soil volume. Rainfall amounts at a given location can be highly variable from year to year and season to season, and hence the storage capacity in the soil root zone has a large influence on yield and yield stability. It also influences the response stability and related risk on investments in improved seed and fertilizer. Adequate soil information in the form of maps of the root zone plant-available water holding capacity supports extrapolation of responses to nutrient application and other management practices. These practices are usually measured at a few experimental sites during one or a few seasons, and must be extrapolated to much wider environmental conditions, using validated agronomic models, to inform risk-averse small-holder farmers about the expected return on investment and associated risks.

The Africa Soil Information Service (AfSIS) project compiled georeferenced and standardised legacy soil profile observation and measurement data for over 12,500 sites (Africa Soil Profiles database; AfSP) and generated soil property maps for SSA at 1 km resolution over 2 m depth. Subsequently, and parallel with the current study, the AfSP database was expanded to 18,500 sites (Leenaars *et al.*, 2014) and combined with newly sampled topsoil data for 9,600 clustered sites (AfSIS website, Vågen *et al.*, 2010). Revised maps were derived using geostatistical methods with enhanced accuracy at 250 m resolution for soil physical (drainage, soil depth, gravel content, texture, bulk density) and biochemical (pH, CEC, exchangeable bases and acidity, organic carbon, nitrogen) properties. Next soil water retention was derived using pedotransfer functions and effective rooting zone depth, for maize, by rules and thresholds established together with GYGA agronomists based on literature review and expert knowledge.

1.2 Objective

The purpose of this study is to produce state-of-the-art gridded maps of the plant-available water holding capacity of the rootable soil depth in the Sub-Saharan Africa (SSA) soil, which can be used for estimating water-limited yield potentials, yield gaps and expected responses to improved agronomic management practices for major rainfed cereal food crops (maize, wheat, rice, sorghum, millet). While this parameter is one of the most sensitive soil profile properties influencing crop performance under rainfed conditions, it is not currently available in existing maps or georeferenced databases for SSA.

In line with the intention to use all soil data (field observations / lab measurements) and covariate data (1 km – 250 m resolution imagery) currently available for the continent, in particular those generated via the AfSIS project for developing a quantitative framework, we used specifically:

1. so-called “legacy” soil point data (Africa Soil Profiles database v1.2; www.isric.org/data/africa-soil-profiles-database-version-01-2; 18,500 points) compiled by AfSIS;
2. AfSIS sentinel site soil point data (http://africasoils.net/services/data/soil-databases/; approx. 9,600 points, including spectral data and 10% wet chemistry reference data), which were provided by AfSIS for this collaboration; and
3. SoilGrids1km layers (www.soilgrids.isric.org) produced at ISRIC using global models; updated and fine-tuned by fitting a continental model with finer resolution satellite data (http://africasoils.net/services/data/remote-sensing/) and above mentioned soil data, resulting in AfSoilGrids250m (http://www.isric.org/data/AfSoilGrids250m).

The data and methods used to produce the maps are described in Chapter 2, including: soil input data, production of the soil property maps, development of rules to estimate soil moisture retention and rootability, and production of derived functional soil property maps (i.e., maps of plant-available water holding capacity aggregated over the rootable zone depth). Chapter 3 provides a description of the resulting dataset by specifying access details and by presenting summary statistics and map visualisations of some of the key properties. Chapter 4 presents a brief discussion with conclusions.

2 Data and methods

2.1 Outline

The Root Zone Plant-Available Water Holding Capacity represents a soil quality (of quantitative nature) which reflects the adequacy of soil to support a reference crop to take up water when rainfall is limited. Maize is the reference crop used in this study.

Root zone plant-available water holding capacity is assessed by first calculating three components. The first assesses the volumetric fraction of soil fine earth, per depth interval, which determines the net volume of soil the crop can exploit within a given depth interval. The soil fine earth fraction is limited by the volumetric coarse fragments content.

The second component assesses the Plant-Available Water Holding Capacity (PAWHC), per depth interval, which is expressed as a volumetric fraction of the soil fine earth, defined as the amount of soil moisture retained over the range that the soil is neither too wet nor too dry for the crop to take up soil water. This range is better known as the range between field capacity (FC) and permanent wilting point (PWP). Thus, PAWHC equals the volumetric moisture content at FC minus that at PWP.

The third component is to assess the depth interval crops are able to explore, which is the rootable soil depth. The rootable soil depth and the coarse fragments content determine the total volume of soil fine earth crops can explore. Rootable depth is determined by factors that govern root growth and root extension and its assessment evaluates the shallowest depth at which one of the factors is completely restrictive to root development, beyond a defined threshold. Rootability is assumed optimal within the rootable soil depth.

The three components above (intermediate results) aggregated into a single value of the plant-available water holding capacity of the whole earth in the root zone depth, expressed as a relative value (volumetric fraction) and as an absolute value (mm).

The soil property data needed for the above assessment are collected by soil profile observations and measurements and compiled into soil profiles databases. Primary soil property maps (SoilGrids) are produced based on these soil profile point data using geostatistical modelling and maps of covariate data. The primary soil property maps are interpreted and functional soil information on soil water retention and rootability is derived and depicted on the final maps, per depth interval and aggregated over root zone depth. Within this workflow, the various maps were reviewed followed by a remapping or updating of few primary properties and all derived functional properties. The workflow, simplified, is visualised by Figure 1.

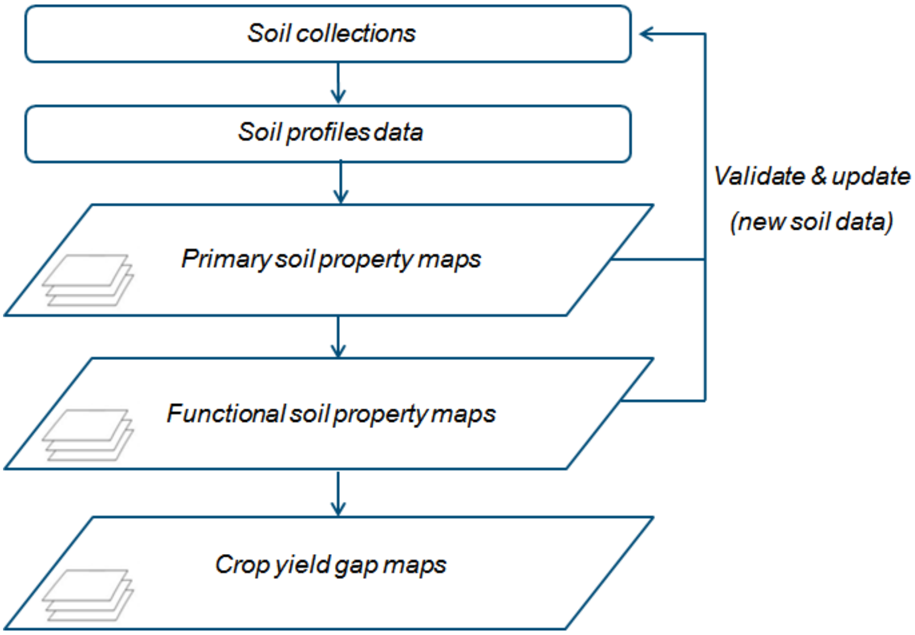

Figure 1
Workflow, simplified, to produce the functional soil property maps in support to producing crop yield gap maps.

2.2 Africa Soil Profiles data

The Africa Soil Profiles database (AfSP) is a compilation of georeferenced and standardised legacy soil profile data for Sub-Saharan Africa. Version 1.2 (Leenaars *et al.*, 2014) holds data for a current total of 18,500 profiles, including data for some 75,000 profile layers (depth intervals) up to an observed depth, on average, of 125 cm (with standard deviation 65 cm). Added to these soil profile data are the soil data (AfSS) collected from 9,600 point locations, clustered at 60 AfSIS sentinel sites, including data for 19,200 layers up to a fixed depth of only 50 cm. The AfSS data are derived from spectrally measured data, based on calibration data from 10% of the samples analysed by wet chemistry (Sila *et al.*, 2014). Note that the original AfSS data are not yet formally released or made publicly available. Additional soil data collected by the AfSIS project could not yet made available to the current project.

Queries are applied to the AfSP database to select the appropriate soil data for bulk density and electric conductivity, based on the laboratory method originally applied and reported. Included with the end product (dataset) are the data queried from the AfSP database.

2.3 Africa SoilGrids

The soil profiles data are used, together with improved geostatistical models (random forests) and fine resolution covariate data, to update the African extent of SoilGrids1km (Hengl *et al.*, 2014) to produce AfSoilGrids250m, which resulted in improved accuracy, resolution and range of predicted soil properties (Hengl *et al.*, 2015). The SoilGrids meets the GlobalSoilMap product specifications (Arrouays *et al.*, 2014), except for its spatial resolution and the soil property specifications are as described by GlobalSoilMap (2011). Soil property values, with uncertainties, are predicted for six standard depth intervals, i.e. 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm. The procedures and approaches are developed and implemented in the GSIF package for R (Global Soil Information Facilities) which is publicly accessible online

(Hengl *et al.*, 2015). The maps are produced by relating soil property values by geo-point location to spatial covariate data to build models applied to predict soil property values over a spatially continuous extent, a technique also known as digital soil mapping (McBratney *et al.*, 2003, Lagacherie *et al.* (eds.), 2006).

The primary soil property maps are next used to derive the functional soil property maps. The following sections describe how those functional soil property maps are derived.

These maps, including derived maps, at 250 m resolution are resampled to 1 km resolution and the results are subjected to in-project review. Soil scientists and agronomists indicated areas on the map with questionable results, followed by an in-team discussion of the issues raised and the identification of issues to improve. Following the review, new versions of the maps are produced at 1 km resolution for a few identified primary soil properties, using a corrected query of the input soil dataset and additional covariates, followed by the production of new versions of the derived maps with functional soil properties. The primary soil properties that are remapped after review include bulk density, exchangeable sodium and electric conductivity, for each depth interval. Additionally, drainage class and depth to bedrock are remapped. Besides the covariates used by Hengl *et al.* (2015), other covariates are added to produce these updated maps, such as maps of groundwater table depth (Fan *et al.*, 2013), surficial lithology and land surface forms (USGS Rocky Mountain Geographic Science Center, 2009), annual climatic water balance calculated from annual precipitation (AfSIS, 2013) and annual potential evapo-transpiration (Trabucco and Zomer, 2009), and the soil atlas of Africa (Jones *et al.*, 2013). Altitude grids and the AfSoilGrids250m (Hengl *et al.*, 2015) for pH, clay content and the sum of exchangeable bases, resampled to 1 km, are used as additional covariates for remapping exchangeable sodium.

Note that the production of maps at this detailed resolution, followed by production of derived outputs as described hereafter, require a large capacity in terms of computational power and handling of large data.

The results of the digital soil mapping of primary soil properties using GSIF technology are given in Section 3.3.

2.4 Volumetric Soil Fine Earth Fraction

The soil volume effectively accessible by the crop root system, for the uptake of water and nutrients, is defined as the volume of soil fine earth over a given depth interval, excluding the volume of coarse fragments (fragments of sizes exceeding 2 mm). The volumetric soil fine earth fraction (SFEF), for a given depth interval, is determined by the volumetric coarse fragments content. The AfSP database holds data for the volumetric coarse fragments content (v%) for over 40,000 layers of 10,000 soil profiles. These data are not very precise, as the majority of the numeric values are derived from descriptive class values as collected from field observations. The average value for the profile layers in the database is 9 v% (sdev = 20 v%).

Maps of the volumetric coarse fragments content are produced for six depth intervals at 250 m resolution and are resampled to 1 km resolution. Results are presented in Section 3.4. Results are also available as aggregated values (weighted averages) over the top 30 cm and over the root zone depth.

2.5 Available Water Holding Capacity

The Available Water Holding Capacity is defined as the difference between volumetric moisture content (VMC) of the soil fine earth at field capacity (VMC-FC) and volumetric moisture content of the soil fine earth at permanent wilting point (VMC-PWP). Note that this definition excludes volumetric coarse fragments content. The soil fine earth refers to soil particles < 2 mm while coarse fragments are defined as particles > 2 mm.

Permanent wilting point is commonly defined as the moisture potential of the soil equal to pF 4.2, which is equivalent to a pressure of -15 bar, -15 Atm, -1500 kPa or a suction of 15,000 cm or 1500 J/kg. Note that this is a generic soil property which is not plant specific. In reality, the moisture potential at which a crop is unable to extract water from the soil matrix and starts wilting is crop-specific. This moisture potential, also called the critical water head, is e.g. 20,000 cm for sorghum and only 7,000 cm for potato. Because this study aims to produce generic data, the common definition for moisture potential (valid for maize) has been applied.

Field capacity is the situation when the soil is freely drained. The corresponding soil moisture potential is not strictly defined and varies between pF 1.7 to pF 2.5, i.e. a moisture potential of 50 to 300 cm. It was suggested to define field capacity differently for coarse, medium and fine textured soils as given by Gijsman *et al.* (2007), as respectively pF 2.0, 2.3, 2.5 (i.e., 100, 200, 300 cm). This suggestion has been adopted for preliminary analyses applied to the soil profiles data to evaluate the texture specific performance of a pedotransfer function (PTF). The results are presented in Section 3.5. The three texture groups are defined according to texture groups for unconsolidated parent material, as given by Van Engelen and Dijkshoorn (2013) and based on USDA texture classes, as respectively coarse (S, LS, SL or approximately sand > 50% and clay < 20%), medium (L, SCL, CL, Si, SiL, SiCL) and fine (SC, SiC, C or approximately clay > 40%). However, it appeared to be not recommendable to produce soil maps of available soil water capacity with field capacities that are defined differently for different textures in the 3D space (at different positions and depth intervals), as the results would become inconsistent. Instead, and based on the preliminary analyses (see Section 3.5), we used in this study field capacity at moisture potential of pF 2.3 (or 200 cm) for all texture classes.

The Africa Soil Profiles database holds measured data on water retention at various water potentials. These data can be used as input to produce maps of water retention at field capacity and at permanent wilting point and hence also of available water holding capacity. The amount of data is too limited, though, to produce such maps for the whole of Sub-Saharan Africa. An indication of data availability is given in Table 1, which summarises the measured data on volumetric moisture content at pF 0.0 (saturation), 2.0, 2.5 (field capacity) and 4.2 (wilting point). AWHC = FC – PWP can be assessed for maximally 1572 profiles only. The Table also shows that AWHC is, on average, 8 v% - 16 v%, using FC given at respectively pF 2.5 and pF 2.0.

Table 1
Summary of measured data on water retention (v%) held by the Africa Soil Profiles database, v. 1.2.

	VMC at pF 0.0	VMC at pF 2.0	VMC at pF 2.5	VMC at pF 4.2
Profiles	194	335	1572	1723
Layers	551	1157	5279	5878
Min	5.0	3.7	1.0	0.0
Max	85.0	98.0	98.0	83.3
Ave	42.0	30.9	22.9	14.9
SDev	14.9	16.0	15.1	10.7

Water retention characteristics have not been measured from the soil samples taken from the AfSIS sentinel sites. Instead, a pedotransfer function (PTF) of Brooks and Corey (1964, 1966) has been applied to calculate or estimate those characteristics. Wösten *et al.* (2013) validated a PTF for tropical soils as suggested by Hodnett and Tomasella (2002), which parameterises (Table 2) equations of Van Genuchten (1980), on the basis of data from the first version of the Africa Soil Profiles database (Leenaars, 2012). This PTF is applied to version 1.2 of the Africa Soil Profiles database to assess if and how the water retention characteristics, especially at field capacity, change between textural classes.

The PTF requires data for sand, silt, clay content, organic carbon content, bulk density, cation exchange capacity and pH (H_2O). These data are all held by the AfSP database. However, the PTF can only be applied directly to a selection of the profile layers with data available for each of the required properties. Measured data for bulk density are available only for 9,600 layers, out of the 75,000, and therefore simple PTFs (including both texture and organic carbon content) are used to estimate bulk density. Applied are the PTFs and rules of Kaur *et al.* (2002), Tomasella and Hodnett (1998), Bernoux (1998), Rawls (1983) and FAO (2006) and those outcomes are simply averaged to produce an estimated value for bulk density for 48,000 profile layers, subsequently used as input in the PTF to estimate AWHC for these layers. Similarly, data gaps for pH (H_2O) for these 48,000 layers were filled by applying simple conversion rules from data available for pH (KCl) and pH ($CaCl_2$). These rules were derived from data in the AfSP database itself, with pH (H_2O) = 0.99 * pH (KCl) + 1.16 (R^2=0.83) and pH (H_2O) = 0.93 * pH ($CaCl_2$) + 1.08 (R^2=0.92). Note that this gap filling exercise has been applied only in the AfSP database to enable the use of the PTF to assess retention curves and AWHC for coarse, medium and fine texture classes. The results are summarised in Section 3.5.1.

Table 2

Parameters used in the PTF of Hodnett and Tomasella (2002) as copied from Wösten et al. (2013).

Predictor variable	$\ln(\alpha)$ (100 kPa^{-1})	$\ln(n)*100$ (−)	θ_s (100 cm^3/cm^3)	Θ_r (100 cm^3/cm^3)
$a_{i,1}$	−2.294	62.986	81.799	22.733
Sand (%)				−0.164
Silt (%)	−3.526			
Clay (%)		−0.833	0.099	
Organic carbon (%)	2.440	−0.529		
Bulk density (kg/dm^3)			−31.420	
CEC (cmol/kg)	−0.076		0.018	0.235
pH	−11.331	0.593	0.451	−0.831
$Silt^2$	0.019			
$Clay^2$		0.0070		0.0018
Sand*silt		−0.014		
Sand*clay			−0.0005	0.0026

The soil properties required by the PTF are all included in the soilgrids for Africa (ISRIC, 2013). The water retention maps were computed by running the PTFs with the basic soil property maps of soilgrids. This procedure implies that the water retention maps are coherent with the underlying soil property maps.

Following the update to AfrSoilGrids250m (Hengl *et al.*, 2015), the PTF has been applied and maps are produced for each of the standard depth intervals of the VMC at saturation (pF 0) and at permanent wilting point (pF 4.2) as well as of the AWHC (with field capacity defined at pF 2.3 and also with field capacity defined at pF 2.0 and 2.5). Annex 1a provides the metadata and the scripts applied to assess soil water retention (AWHC) with the GSIF package.

The maps at 250 m resolution are resampled to 1 km resolution and are subjected to in-project review. Following a corrected query of the input soil dataset, a new version of the map for bulk density was produced (at 1km resolution) and a new version of the maps for water retention was derived, resulting in the final (version 1.0) maps of AWHC (with field capacity defined at pF 2.3) for the six depth intervals. The results are described in Section 3.5.

As mentioned, the maps for AWHC with field capacity defined at pF2.3 are produced and available for six depth intervals at 1km resolution, together with maps for VMC at PWP and at saturation. These intermediate results per depth interval are in the next sections aggregated (weighted averages) to maps applicable over the root zone depth, and over the top 30 cm, both including and excluding the volume occupied by coarse fragments. To assist analysis, a map of the particle size fractions classified to textural classes and aggregated over depth is produced as well.

2.6 Root Zone Depth (i.e. rootable soil depth)

The depth interval defining the soil volume accessible to plants is determined by the root zone depth (RZD). Root zone depth is also commonly referred to as the rootable soil depth or plant exploitable (effective) soil depth, as described in the GlobalSoilMap specifications (2011). The root restricting (i.e. plant accessible) depth is the depth at which root penetration is strongly inhibited because of physical, chemical or hydrological characteristics (Soil Survey Division staff, 1993). A restriction means the inability to support more than a very few fine or a few very fine roots. Note that the root zone depth is not necessarily similar to the effective soil depth.

The root zone depth is crop specific and its assessment is basically a land evaluation procedure (FAO, 1976), in which soil factors (land qualities, of quantitative nature) are compared, over depth, with the requirements of the crop (land-use requirements), which is maize in this study. This results in an estimate of the relative adequacy of the soil to meet these requirements. This estimate is compared to a threshold to evaluate whether the soil, over depth, is either adequate (optimal) or inadequate (restrictive) for rooting. The shallowest depth at which the soil is evaluated as inadequate for rooting is the maximal root zone depth (in cm) for a given location.

The maximal rooting depth of maize, attained near anthesis under optimal conditions, is assumed to be 150 cm. The crop requires a soil adequate for rooting over that depth or, in other words, without root restrictive soil factors within 150 cm. The root zone depth is the shallowest of the depths assessed for:
(1) maximal rooting depth of maize,
(2) depth of soil,
(3) depth of aerated soil, or
(4) depth to a soil profile layer with a root restricting soil factor.

The depth of soil is evaluated based on the presence, over depth, of bedrock or any other physically impermeable material, such as an iron pan. The presence serves as a threshold for rootability and the depth to presence of bedrock defines the depth of soil. Please note that this soil factor is evaluated based on one value mapped for (the centre point of) the map pixel, or soil profile, as a whole.

The depth of aerated soil is evaluated based on the presence of oxygen shortage as determined by excessive water content. The presence serves as a threshold for rootability and the depth to presence of oxygen shortage defines the depth of aerated soil. Note that this soil factor is evaluated based on one figure mapped for the map pixel, or soil profile, as a whole as derived from the drainage class.

The depth to a soil profile layer, or map voxel, with a root restricting soil factor is evaluated based on a number of soil factors that are interpreted from soil properties mapped for six depth intervals. The adequacy of the soil for rooting is estimated for each depth interval considering each soil factor and compared to threshold values for rootability. The shallowest depth interval at which one of the soil factors is evaluated as inadequate for rooting, beyond the rootability threshold, defines the depth to a soil profile layer with a root restricting soil factor

The following sections describe in more detail how each soil factor is estimated from soil property values and how the soil factors determine rootability and the rootable depth of soil. Annex 1b provides the R script, with metadata, implemented to assess root zone depth using the GSIF package.

2.6.1 Depth of soil

The depth of soil is limited by the depth to bedrock, or the depth to iron pan, which is a soil profile property included in the Africa Soil Profiles database (AfSP). It is not included in the AfSIS sentinel sites soil database (AfSS), which only considers the upper 50 cm of soil. Data on the observed depth to a physical root restriction, as collected from augering at the sentinel sites according to the field protocol of the Land Degradation Surveillance Framework (Vågen *et al.*, 2015) are not yet available. The Africa Soil Profiles database (AfSP) gives a value for the depth to bedrock for just over 3,400 profiles only. The deepest depth to bedrock reported is 17 m. For 600 profiles, the occurrence of bedrock or an iron pan is indicated by a horizon designation R or, not according to designation standards, R/C, respectively. A content of coarse fragments exceeding 90% is in this study also considered as bedrock and determines the depth to bedrock for 770 profiles. The depth of observation, reported for all profiles, is not indicative for the depth to bedrock but indicates the minimum depth at which bedrock does not occur. These so-called 'censored observations' are still useful data for mapping the depth to bedrock.

A map of the depth to bedrock, of maximally 200 cm, is produced at 250 m resolution and resampled to 1 km. The results are described in Section 3.6. The map is used in the evaluation to assess the root zone depth.

2.6.2 Depth of aeration

Aeration in the soil is limited by the rate of soil drainage and the depth, during rainy periods, to saturated or wet soil. Quoting FAO (1976), the availability of oxygen is most closely estimated by the period when the redox potential (Eh) is less than +200 millivolts. Such information is generally not available. Another criterion could be the time periods when a part of the root zone is situated below the groundwater table. If such information is also missing, soil mottling, soil drainage class or natural vegetation could be used as diagnostic criteria for assessing oxygen availability. Also relevant is the depth to the groundwater table or phreatic level. Such data are not included in the AfSP or AfSS soil profiles databases, except for data on soil drainage included in the AfSP database. Drainage classes, as defined by the Soil Survey Division Staff (1951, 1993) and adopted by the guidelines for soil description (FAO, 1977), are commonly reported during soil survey and reflect the rate of water being removed from the soil and the associated depth of the water table during given (rainy) periods in the year. Drainage classes are interpreted and translated into a 'depth to oxygen shortage during a large part of the rainy season', as given in Table 3.

The drainage classes range from very poorly drained to excessively drained. According to definitions of the Soil Survey Division Staff (1993), in poorly drained soils the water table is at or on the surface during a considerable part of the year. In imperfectly drained soils the soil remains wet for significant periods. These soils commonly have a high water table, a slowly permeable layer within the profile and/or additions through seepage. Oxygen availability is limited in such wet soils. Moderately well drained soils have similar conditions, where the periods of wetness are also significant but smaller and the slowly permeable layer is deeper. Water availability in well drained soils is commonly optimal after rain events, which means that the soil is readily drained to field capacity, implying a moist and not wet soil without oxygen shortage.

Table 3 gives indicative figures for the depth to saturated soil as suggested in the literature. FAO (1976) refers to drainage classes which reflect the severity of oxygen shortages in the root zone of oil palm. Landon (1991) suggests a rough guide for interpreting drainage class and water regime related to soil morphology, which includes indicative figures for depths to the saturated soil for specific periods of the year. These figures require interpretation, though. The figures suggested by Sys *et al.* (1993) are more concrete as well as those suggested by NRCCA (Cornell University, 2010). The descriptions given above and the figures summarised in Table 3 are subjected to further interpretation and expert judgement to derive applicable estimates. The team of soil scientists and agronomists agreed to define strict figures for the very poor and poor drainage classes, whereas increasingly less strict figures were derived for the other drainage classes. The resulting draft estimates as given in Table 3 proved to have a large impact on the final estimate of the root zone depth over Africa. Because interpretation of this soil factor is largely based on expert judgement, it appeared to be justifiable to apply less strict final estimates for depth to oxygen shortage (Table 3, see column to the right). The function applied to derive the final estimates for the depth of aerated soil, is as follows: Depth = $2.5\ x^2 + 27.5\ x + 10$, with x = the ordinal drainage class (0-6).

The drainage class is specified for 13,700 profiles in the Africa Soil Profiles database. It is not included in the AfSS dataset. A drainage class map is produced at 250 m resolution, resampled to 1 km, depicting the seven discrete drainage classes derived from interpolated ordinal class values. Note that the current version of the map depicts classes 1-7 rather than the ordinal classes 0-6 as given in Table 3. The drainage class map is reproduced at 1km resolution, using additional covariates including the groundwater table depth (Fan *et al.*, 2013), and the results are described in Section 3.6. The map is used in the evaluation of the root zone depth.

Table 3
Drainage classes interpreted to derive a depth (cm) to the layer with oxygen shortage during a large part of the rainy season.

Drainage	Ordinal class	FAO	Landon	Sys	NRCCA	Depth (draft)	Depth (final)
V -very poor	0	<50	0-25 (0)	0-20 (10)	0-10 (5)	(5)	10
P -poor	1	<50	25-50 (25)	20-50 (35)	15-40 (25)	(30)	40
I -imperfect	2	>50	30-60 (45)	50-75 (60)	40-60 (50)	(60)	75
M -moderate	3	>120	50-90 (80)	75-100 (85)	50-90 (70)	(100)	115
W -well	4	>120	>90 (120)	>100 (130)	65- >100 (90)	(150)	160
S -somewhat excessive	5		(150)	(160)	(120)	(200)	210
E -excessive	6					(250)	265

From the drainage classes, classes of the depth to oxygen shortage are derived. For a follow-up study it is recommended to use a semi-numeric drainage map rather than a categorical drainage class map. A semi-numeric drainage map maintains the originally predicted interpolations of the ordinal class values (as 1.1, 1.2, etc.) which, fed into the function above, produces a map of more precise depths to oxygen shortage (i.e., with 61 values instead of 7 for these depths as distinguished now).

2.6.3 Depth to a soil layer with a root restricting soil factor

Depth to a soil layer with a root restricting soil factor is assessed from rootability indices evaluated per soil depth interval and for each of the soil factors considered. These soil factors are characterised by primary soil properties of morphological, chemical and physical nature as observed and measured over a sequence of soil depth intervals, such as horizons, layers or samples and as mapped by the AfSoilGrids to a total depth of 200 cm. For each soil factor a threshold value for the rootability index is defined beyond which the soil is considered inadequate to support root growth and beyond which root growth no longer occurs. Alternatively, where the threshold value (threshold index) is not met, the adequacy for root growth is assumed optimal. Note that this approach is not scalable and evaluates each identified soil factor separately. The depth to the shallowest soil layer with one or more soil factors evaluated beyond the threshold for root restriction, is assumed to be the depth where rooting is unlimited (100%).

The rootability indices express the relative adequacy of the soil factors to meet the crop requirements at a scale of 0 - 100%. This approach is scalable. The definition of a threshold index makes the approach not-scaled, as described above, resulting in a final rootability score, for a given soil layer, of either 0% or 100% (inadequate or adequate) based on the most limiting rootability index evaluated per soil factor.

The concept is visualised for three soil factors in Figure 2. The Limiting Rootability Index (LRI) expresses the relative adequacy (in %) of the soil factor to support rooting of maize as a function of the underlying soil property value. By setting a threshold on the index the associated threshold value for the underlying soil property is known.

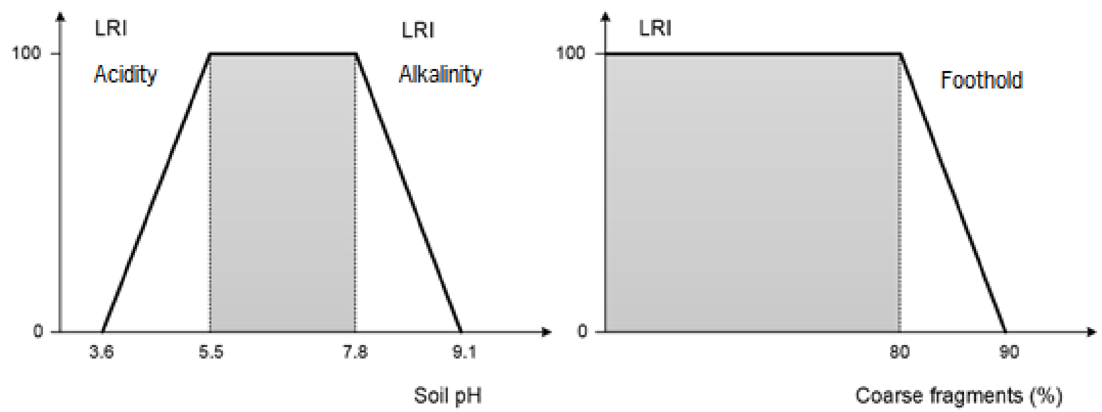

Figure 2
Rules illustrated to assess the Limiting Rootability Index associated with the soil factors acidity, alkalinity and soil volume (foothold)

The threshold index is set at 20% for all soil factors. Choosing a threshold of 20% is arbitrary to an extent, but based on the study of Jones (1983), who distinguishes soil conditions with optimal root growth (100%) and with 20% of optimal root growth. The latter is fit to a threshold beyond which, in his study, 10% of observed soil layers with 'no roots' occur. A threshold index of 20% is thus rather strict, beyond which the soil layer is considered root restrictive, meaning the inability to support more than few very fine or very few fine roots.

The development of rules to evaluate the soil factors identified, including parameterisation of the underlying soil property values relative to rootability indices and threshold values, is based on literature review. Note that the evaluation assumes adequate supply of water and nutrients. These soil factors are thus not limiting to rootability and not considered.

The preliminary rules derived from the literature review, for evaluating descriptive as well as numeric soil properties, are applied first to the AfSP database for testing purposes. Both the complexity and number of preliminary rules that have been applied to the AfSP database largely exceed that of the rules, after testing, applied to the SoilGrids maps. This is because of the inherently heterogeneous nature of the legacy data compiled by the soil profiles database for many soil properties, compared to the standardised nature of the data mapped by the SoilGrids for only few soil properties. The results of the preliminary analyses applied to the AfSP database are not reported here.

Rootability is a soil factor (soil quality) which is rarely observed or measured during soil surveys or soil studies. No soil property directly reflects rootability either, if not actual rooting density itself. The actually rooted depth, excluding layers with only few very fine or very few fine roots, is given for about 3,950 soil profiles in the AfSP database. The average is 99 cm (sdev = 51 cm). Presence of roots is also given by profile layer (8,500) for a total of only 2,500 profiles. These data are too few to produce maps of rooted depth but may be used, despite its heterogeneous nature, for validation purposes.

Rootability is highly determined by soil morphology. Related soil factors are commonly characterised by soil morphologic observations, such as on soil structure and consistency, porosity, compaction and cementation, colour and mottling (aeration) and specific features such as slickensides (verticity), which are expressed by descriptive values. Some of these soil factors could also be interpreted from qualitative information such as horizon designation, diagnostic horizon, -material or -property and soil type (Baruth *et al.*, 2006). Soil rooting conditions can be evaluated from these descriptive data and qualitative information as shown by Driessen *et al.* (1997). However, rules and thresholds are hard to define and parameterise consistently, as tested by preliminary analyses applied to the AfSP database (not reported). Moreover, the availability as well as the degree of harmonisation of these morphologic data are not yet sufficient to produce maps and derived rootability maps. Consequently, these descriptive qualitative data and information are excluded from this first approximation of assessing root zone depth.

Soil factors relevant for evaluating root zone restriction and can be parameterised robustly are the adequacies of foothold (soil volume), porosity, texture, induration (cementation), acidity, alkalinity, salinity, sodicity and toxicity. These factors are characterised by numerical soil properties and for which sufficient data are available to produce maps. Although cementation is identified, the associated properties that include contents of calcium carbonates and gypsum are not mapped and thus, cementation cannot be evaluated.

Note that data availability is not sufficient to map and evaluate all numeric properties such as the contents of extractable aluminium, iron, manganese, zinc, copper, boron and sulphur (being relevant to assess toxicity), although rules are established. For other relevant properties, such as soil strength, rules could also be developed (see Hazelton and Murphy, 2007), but the data are not available.

The rules and threshold values developed for each soil factor are given in Table 4 and are described in detail in the following sections.

2.6.3.1 Foothold (soil volume)

The volumetric coarse fragments content limits the volumetric foothold for crops to establish a stable rooted stand. No references are found which quantify this effect of coarse fragments. Driessen and Konijn (1992) refer to Rijsberman and Wolman (1985), describing the quantification of the effect of coarse fragments on a productivity-index (decreasing from 100 to 0% at gravel contents of 10 to 70%), but that effect is due to reduced plant available water rather than reduced rooting depth. Sanchez's (1982, 2007) capability classification identifies soils with gravel content in the top 50 cm exceeding 35 v%.

Table 4

Soil factors, with associated soil properties, rules and threshold values, to evaluate the soil adequacy (Limiting Rootability Index) for rooting of maize.

Soil factor	Soil property	Soil variable	Unit	LRI 100%	LRI 100%	LRI[1] y%	LRI 0%	LRI 0%	Trend	a	b	threshold[2] value	
Foothold (soil volume)	Coarse fragments content	CfPc	v%	0	80	-	90	100	-1	-10	900	>	88
Porosity	Pore volume	TetaS (PTF)	v%	100	40	-	27.5	0	1	8	-220	<	30
Porosity	Bulk density fine earth	BD -(1.6 -(0.0035*Clay))	kg/dm³	<0	0	-	0.3	>0.3	-1	-333.33	100	>	0.24
Texture adequacy	Sand fraction	Sand*100/(Sa+Si+Cl)	w%	0	95	-	100		-1	-20	2000	>	99
Texture adequacy	Abrupt clay increase	Clay, n - clay, n-1	w%	0	30	-	55	100	-1	-4	220	>	50
Texture adequacy	Abrupt sand increase	Sand, n - sand, n-1	w%	0	30	-	55	100	-1	-4	220	>	50
Induration (cement.)	Carbonate content	CaCO3	g/kg	0	150	-	750	1000	-1	-17	125	>	630
Induration (cement.)	Gypsum content	CaSO4	g/kg	0	150	-	750	1000	-1	-17	125	>	630
Acidity	pH H_2O, low	pH-H_2O	-	12	5.5	-	3.625	1	1	53.33	-193.33	<	4
Alkalinity	pH H_2O, high	pH-H_2O	-	1	7.8	-	9.05	12	-1	-80	724	>	8.8
Salinity	Electric conductivity, unsaturated	EC	dS/m	0	1.5	-	6.75	>6.75	-1	-19.05	128.57	>	5.7
Sodicity	Exchangeable sodium percentage	ExNa*100/CEC	%	0	10	-	25	> 25	-1	-6.667	166.667	>	20
Sodicity	Exchangeable sodium (+)	ExNa	cmolc/kg	0	1	-	5	> 5	-1	-25	125	>	4.2
Toxicity	Exchangeable acidity saturation	ExAcid*100/eCEC	%	0	35	-	85	100	-1	-2	170	>	75
Toxicity	Exchangeable acidity	ExAcid	cmolc/kg	0	2.5	-	6.5	>6.5	-1	-25	162.5	>	5.7

[1] The Limiting Rooting Index is scaled from 0% to 100% (see Figure 1) and is, for a soil property value between an upper and lower boundary as defined by LRI = 0% or 100%, LRI = a * soil property value + b.

[2] The soil property threshold value at a threshold for LRI defined at 20%.

Note that the decision rules, including the factors and properties considered and the thresholds defined, are always open for improvement.

It seems justifiable to consider a soil volume which is dominated by coarse fragments as a volume which is too limited to support root development. According to FAO (2006) a soil is dominated by coarse fragments if the content exceeds 80 v%. The rule therefore assumes suboptimal rooting conditions (LRI<100%) beyond a coarse fragments content of 80 v%. The rooting conditions are assumed fully restrictive (LRI=0%) beyond a coarse fragments content of 90 v%. This limit corresponds to the limit applied to define depth to bedrock (which is also evaluated to assess the depth of soil or foothold).

The threshold value for coarse fragments content (CfPc) is 88 v% at a threshold index of LRI=20%. The suboptimal LRI at 80 < [CfPc] < 90 is given by 900 – 10 * [CfPc].

2.6.3.2 Porosity

Porosity determines the volume available for storing water and air and for roots to elongate. Compacted soil is restrictive to rooting because of the reduced pore volume causing physical resistance and loss of air. According to Landon (1991) pore size should exceed 250 μm and pore volume should be more than half (50 v%) of the soil volume (40 v% in sandy soils). Though porosity is a parameter observed in the field, few data are available. Instead, two properties are considered that serve as a proxy, i.e. the volumetric water content at saturation (TetaS) which represents the pore volume, and bulk density, which reflects pore volume. TetaS maps are calculated from primary soil property maps, using the PTF described in Section 2.5 for assessing water retention, while maps for bulk density are produced based on measured data.

The critical TetaS is defined according to the critical porosity suggested in the paragraph above. That threshold proved too strict, resulting in preliminary results with rooting limited by TetaS over vast areas in the continent. Instead, a critical value for TetaS optimal for rooting (LRI=100%) was defined as 40 v%. This value corresponds to the porosity associated with the critical value for bulk density defined below. Rootability (LRI) is suboptimal (<100%) beyond this critical value for TetaS and is 0% for TetaS, rather arbitrarily, set at 27.5 v%. The associated threshold value for TetaS is 30 v% at a threshold index of LRI = 20%.

The suboptimal LRI at 40 > [TetaS] > 27.5 is 8 * [TetaS] – 220.

Kiniry *et al.* (1983) predict sufficiency of bulk density as a parameter most closely related to mechanical impedance of root growth. The sufficiency is comparable to LRI expressed from 0-100%. The sufficiency is optimal (100%) for a bulk density of maximally 1.3 kg/dm^3. It decreases from 80 to 0% with bulk density increasing from 1.55 to 1.8 kg/dm^3. The GlobalSoilMap specifications (2011) refer to bulk density above 1.85 as root restrictive.

Landon (1991) suggests values for bulk density that are limiting for rooting and that are texture group specific. Rooting is limited at bulk density values exceeding 1.6-1.8 kg/dm^3 in loamy and sandy soil and 1.45-1.65 kg/dm^3 in silty and clayey soil. The value for bulk density for a soil with adequate porosity is derived from Porosity = (1 – (BDsoil / BDparticle)). This would imply that a soil composed of 100% sand, with a particle density of 2.65 (quartz), has a threshold BD = (1 – 0.4) * 2.65 = 1.6 kg/dm^3.

Hazelton and Murphy (2007) give particle densities for various rock materials. They suggest a bulk density of 1.4 kg/dm^3, typical for an agricultural soil with an associated porosity of 47 v%, and 1.8 kg/dm^3 for a dense pan with a porosity of 32 v%, and consider root penetration likely to be severely restricted at bulk density values of 1.8, 1.7, 1.6 and 1.4 kg/dm^3 for sandy loam, fine sandy loam, loam and clay loam, and clay, respectively.

Rijsberman and Wolman (1985) give for different soils values for bulk density which are a) non-limiting, b) critical and c) root-limiting:

	a)	b)	c)
Corn Belt Sandy	1.60	1.69	1.85
Corn Belt Clay (45%)	1.30	1.39	1.47
Hawaii Chromustert (vertisol)	1.31	1.44	1.76
Hawaii Hydrandept (andosol)	0.79	0.85	0.96

FAO (2006) gives clay content dependent bulk density values for different consistencies. Bulk density of a friable soil BD = 1.6 – 0.009 * [Clay]. The soil is firm, and thus restrictive for rooting, beyond BD = 1.8 – 0.009 * [Clay], which corresponds with a restrictive bulk density of 1.8 kg/dm^3 for a fully sandy soil, 1.35 kg/dm^3 for a clayey soil (50 % clay) and only 0.9 kg/dm^3 for a full clay soil.

Referring to Jones (1983), the slope of bulk density over clay content is less steep, as illustrated in graphs of clay content dependent bulk density, where rooting behaviour is optimal (BD = 1.52 – 0.0065 * [Clay]) and 20% of optimal (BD = 1.77 – 0.0063 * [Clay]). Note that the two lines are 0.25 kg/dm^3 apart. Plotted around those lines are the actually measured values for clay content and bulk density, where measured rooting behaviour is optimal and suboptimal, and a careful look shows that the plotted data show an asymptotic rather than a straight line pattern. The critical bulk densities of a fully sandy soil (0% clay) are approximately 1.6 and 1.85 kg/dm^3 for optimal and 20% of optimal rooting conditions, respectively, rather than the given 1.52 and 1.77 kg/dm^3. The critical bulk densities for clayey soils need to be even more increased. Note that Jones (1983) also gives data for critical bulk densities depending on silt+clay contents, which seem even more appropriate. A fully sandy soil supports optimal rooting at a bulk density of 1.6 kg/dm^3 and 20% of optimal rooting at 1.83 kg/dm^3 with a slope of bulk density over silt+clay content of – 0.0045.

Combining the above information resulted in defining a critical bulk density optimal for rooting (LRI =100%) as f.BD = 1.6 – 0.0035 * [Clay], corresponding to 1.6 kg/dm^3 for a 0% clay soil and 1.25 kg/dm^3 for a 100% clay soil. Rooting is limited beyond this value and is assumed to stop beyond the threshold score of LRI = 20%, corresponding to bulk density values that exceed the critical ones with 0.24 kg/dm^3 (1.84 kg/dm^3 for a 0% clay soil and 1.49 kg/dm^3 for a 100% clay soil). Note that a slope of only –0.0035 is defined, instead of the steeper slopes suggested in the paragraph above, to more or less fit to the figures as suggested by Landon (1991) avoiding a too strict threshold for clay soils.

The suboptimal LRI at 0 < [f.BD] < 0.3 is given by 100 – 333 * [f.BD].

2.6.3.3 Induration (cementation)

Cementation and induration of the soil can be caused by various reasons. Commonly, the accumulation, either relative or absolute, of minerals that precipitate, and harden upon drying causes the soil pores to fill and the soil to cement. Iron oxides and aluminium oxides may cause induration by the formation of petro-plinthite (laterite) and bauxite. Note that this phenomenon is included implicitly by the depth to bedrock and is not considered here any further. Also SiO2 is known to cause soil cementation and induration, forming a petroduric horizon (duripan) but associated data required for mapping are lacking. Data availability permits to map and evaluate the contents of carbonates and sulphates in soil, which also may cause the soil to cement and root restrictive induration to occur. Most common on-land carbonates and sulphates are associated with calcium (lime and gypsum or CaCO3 and CaSO4) and magnesium (dolomites), and are associated with alkalinity.

Landon (1991) refers to soil with a CaCO3 content of over 400 g/kg as being extremely calcareous. Contents of 700 g/kg or more occur in arid zones. A content of calcium carbonate equivalents exceeding 150 g/kg is used as a criterion to identify a calcic horizon, which becomes petrocalcic when hardened (IUSS, 2006). Physical and chemical properties are negatively affected. Sys *et al.* (1993) rate CaCO3 contents in relation to maize yield levels relative to unrestricted maize yield, with contents of 0, 60, 150, 250, 350 and >350 g/kg CaCO3 corresponding to relative yield levels of 100, 95, 85, 60, 40 and 0%, respectively.

A CaSO4 content exceeding 50 g/kg is used as a criterion to identify a gypsic horizon, which becomes petrogypsic when hardened (IUSS, 2006). Landon refers to gypsum contents of 140 to 800 g/kg at which cemented and indurated layers can occur and usually impede root growth. Also, crop yields are reduced at gypsum contents exceeding 250 g/kg. Sys *et al.* (1993) rate CaSO4 contents in relation to maize yield levels relative to unrestricted maize yield, with contents of 0, 20, 40, 100, 200 and >200 g/kg CaSO4 corresponding to relative yield levels of 100, 95, 85, 60, 40 and 0%, respectively.

In this study we adopted the figures reported to cause cementation and induration impeding root growth. The parameters used for CaCO3 and CaSO4 are similar.

The threshold value for CaCO3 content, at LRI = 20%, is 630 g/kg with the suboptimal LRI at 150 < [CaCO3] < 750 given by 125 – 17 * [CaCO3].

The threshold value for CaSO4 content, at LRI = 20%, is 630 g/kg. The suboptimal LRI at 150 < [CaSO4] < 750 is given by 125 – 17 * [CaSO4].

2.6.3.4 Textural adequacy

Soil texture can be root restrictive. For example, heavy clay showing verticity causes roots to break. Heavy clay within a well-structured soil (e.g. a nitisol) is very adequate for rooting though. Near pure sand is inhibitive to root development (GlobalSoilMap, 2011). An abrupt textural change over depth is also restrictive for root elongation. Literature review did not result in clear suggestions for rules to parameterise and therefore rules are estimated.

Near pure sand soil is defined as a sand content between 95 and 100%. The resulting threshold value for the sand fraction, at LRI = 20%, is very strict with 99 %. The suboptimal LRI at 95 < Sand < 100 is given by 2000 – 20 * [Sand].

Abrupt textural change is a diagnostic property in the World Reference Base (IUSS, 2006). It refers to a sharp increase of clay content, within a depth-distance of 7.5 cm, and implies, freely translated, a doubling of clay content if the clay content of the lower layer is below 20% and an (absolute) increase of 20% if the clay content of the lower layer is above 20%.

The size of the depth intervals mapped by SoilGrids increases with depth and the sharpness of any increase is consequently hard to assess. With any abrupt change not anticipated very near to the surface, the grid intervals all exceed the 7.5 cm used by WRB. Rather arbitrary, we define a textural change greater than 30% as indicative for an abrupt textural change suboptimal for root growth. The lower limit, still adequate for rooting, is defined as an absolute increase with 30%, of either sand or clay content. The upper limit, at which root growth is stopped, is set at an absolute increase with 55%.

The threshold value for an abrupt sand increase, at LRI = 20%, is 50% with the suboptimal LRI at 30 < [delta Sand] < 55 given by 220 – 4 * [delta Sand]. (Delta = content layer n – content layer n–1).

The threshold value for an abrupt clay increase, at LRI = 20%, is 50%. The suboptimal LRI at 30 < [delta Clay] < 55) is given by 220 – 4 * [delta Clay].

2.6.3.5 Acidity

Acidity restricts root development for a number of reasons, including restrictions due to the acidity itself as well as due to associated imbalances in the soil solution with both insufficient and excessive element (including nutrient) contents. Excessive element contents can be toxic, which is dealt with separately in Section 2.6.3.8.

Acidity is commonly measured and expressed by soil pH. Considered here is the pH-H_2O, as measured in a soil-water suspension, corresponding to the soil pH as mapped. Little disagreement exists about the critical value for pH-H_2O (LRI=100%) beyond which rootability gets restricted. The lower limit (LRI=0%) is less well defined.

Landon (1991) mentions a value of 5.5 for pH-H_2O (measured in a 1:2.5 soil: water suspension) below which the soil is seen as strongly acid. Optimum is above 6 and considered suitable between 5 and 6. Hazelton and Murphy (2007) refer to a value between 4.9 and 5.3 (derived from values of 4.1 - 4.5 for pH-$CaCl_2$) below which cereal yield decline and consider a pH-H_2O of minimally 5.5 as optimal for cereal crops (rice minimally pH 5). Liming is recommended below a pH-H_2O of 4.0. Sys *et al.* (1993) refer to an optimum pH for maize of minimally 5.8 and a suitable pH of minimally 5.2. Sanchez (1982) identifies soil acidity at pH-H_2O 1: 1 between 5.0 and 6.0 and Al toxicity (caused by acidity) happening below pH 5.0. Later, the latter critical value for pH-H_2O is adjusted to 5.5 (Sanchez, 2003). Brenes and Pearson (1972) also indicate pH 5.5 as the point where Al saturation, relative to CEC at pH 7, starts building up. It is unclear though whether they refer to pH-H20 or pH-$CaCl_2$. Measured root yield of maize (relative to 100%) decreases from 100% at pH 4.7 to 0% at pH 3.8.

Kiniry *et al.* (1983) predict sufficiency of pH (1: 1 soil: 0.01M $CaCl_2$ suspension), with the sufficiency comparable to the LRI expressed 0-100%. They state to have subtracted 0.4 units from the reported values of pH and it is unclear to which reported pH values is referred to; presumably the studies from which the sufficiency rules are developed, including Woodruff (1967), Adams and Lund (1966). That may imply that the reported original values apply to pH-H20. Sufficiency for rooting is optimal (100%) at pH 5.5 and near optimal (0%) at pH 5.0 beyond which the sufficiency drops in a straight line to 0% at pH 2.9 (extrapolated from pH 4.4-2.9). If indeed the subtracted 0.4 units can be re-added, the sufficiency decreases from 90 to 0 % from pH-H_2O 5.4 to 3.4

Combining the above resulted in the following rule, with a pH-H_2O of 4.0 as the threshold value at the threshold index of LRI = 20%.

The suboptimal LRI at 5.5 > [pH-H_2O] > 3.625 is given by = 53.33 * [pH-H2O] – 193.33.

2.6.3.6 Alkalinity

Alkalinity is commonly measured and expressed by soil pH. Considered here is the pH-H_2O, as measured in a soil-water suspension, corresponding to the soil pH as mapped. Little disagreement exists about the critical value for pH-H_2O (LRI=100%) above which rootability gets restricted. The lower limit (LRI=0%) is less well defined.

Landon (1991) mentions a value of 8.5 for pH-H_2O (measured in a 1:2.5 soil: water suspension) above which the soil is considered strongly alkaline corresponding with a high likeliness of sodicity, salinity, nutrient shortages and boron toxicity. Optimum is below 7 and suitable below 8. Hazelton and Murphy (2007) consider a pH-H_2O of maximally 7.0 optimal for cereal crops (barley maximally pH 7.8). Sys *et al.* (1993) refer to an optimum pH for maize of maximally 7.8 and a suitable pH of maximally 8.5. Sanchez (1982, 2003) identifies soil alkalinity at pH-H_2O 1: 1 above 7.3.

Adopted are the ratings for pH-H_2O, as earlier adopted by Mulders *et al.* (2001) to assess land suitability in Sahelian land-use systems, with pH-H_2O > 7.8 rated as unsuitable under current conditions and > 9 rated as permanently unsuitable.

The above combined resulted in the following rule, with a pH-H_2O of 8.8 as the threshold value, at the threshold index of LRI = 20%, and the suboptimal LRI (at 7.8 < [pH-H_2O] < 9.05) = 724 – 80 * [pH-H_2O].

2.6.3.7 Salinity

Salinity can be characterised by electric conductivity, indicating the total quantities of soluble salts. Excessive salinity hinders root and crop growth, not only by toxicity effects or unbalanced nutrient uptake but also by increasing the osmotic pressure with negative impact on soil water availability. Conventionally, soils are seen as saline at an electric conductivity of the saturation extract (ECe) exceeding 4 dS/m.

FAO (1998) lists the salt tolerance of common agricultural crops expressed as ECe. For maize, crop performance is unlimited up to a maximum ECe value of 1.7 dS/m. Beyond this point, maize yield reduces by 12% per 1 dS/m, which implies a yield reduced to 0% of the full yield potential at ECe = 10 dS/m. Maize is seen as moderately sensitive.

Landon (1991) sees maize as moderately tolerant to salinity. He gives crop specific values for ECe with associated relative yield potentials decreasing from 100 to 0%. Maize yield potential is 100, 90, 75, 50 and 0% at ECe values of 1.7, 2.5, 3.8, 5.9 and 10 dS/m, respectively, and ECw values of 1.1, 1.7, 2.5, 3.9 and 6.7 dS/m. Landon (1991) also refers to the function given by FAO above.

Sys *et al.* (1993) refer to maize yield potentials of 100, 95, 85, 60, 40, 25 and 0% at ECe values of 0, 2, 4, 6, 8, 12 and >12 dS/m, respectively. Sanchez (2003) considers soil salinity significantly limiting for most crops at ECe > 4 dS/m. Kiniry *et al.* (1983) define the sufficiency of ECe for maize, comparable to the LRI (0-100%), by 114 – 7 * [ECe] beyond the limit of an ECe of 2 dS/m. The sufficiency is 0% at an ECe of 16 dS/m.

The above combined results in the following rule, with an ECe of 8.3 dS/m as the threshold value at the threshold index of LRI = 20% and the suboptimal LRI at 1.7 < [ECe] < 10 given by 120 – 12.05 * [ECe].

However, while mapping electric conductivity, it was decided to map electric conductivity of the unsaturated extract (EC) rather than the saturated extract or any combination of both. The values for ECe were queried and excluded. Consequently, the rules and thresholds are adapted to lower values than those reported above. Few data are reported on the effect of EC on root and crop performance. Hazelton and Murphy (2007) elaborate on the relationship between ECe and EC 1: 5. Landon (1991) suggests approximate and tentative rules to convert ECe values to EC values (EC1: 1 = ECe /2.2, EC1: 5 = ECe /6.4). The rules adopted are based on the ECw values given by Landon (1991).

The above resulted in the following rule, with an EC of 5.7 dS/m as the threshold value at the threshold index of LRI = 20% and the suboptimal LRI at 1.5 < [EC] < 6.75 given by 128.57 – 19.05 * [EC].

2.6.3.8 Sodicity

Sodicity is comparable to salinity except for the fact that sodium dominates the salts. The electric conductivity is often low. Sodicity correlates with very high alkalinity. Sodic soils are those which have an exchangeable sodium percentage (ESP) of more than 15. Excessive sodium content strongly affects the physical conditions of the soil, and particularly of clay soil which tends to disperse resulting in low porosity. It also causes nutritional imbalances and toxicity.

FAO (1988) refers to maize as sensitive to exchangeable sodium with yields being affected if the ESP exceeds 10%. The relationship between ESP and crop yield, or relative crop yield, is given for wheat which would be semi-tolerant and which is affected beyond ESP values of 35%. The relationships suggest wheat yields being affected beyond an ESP of 10-20% with yield reduced to 50% at an ESP of 55% and to 0% when ESP reaches 60%.

Landon (1991) mentions the performance of sensitive crops affected by ESP values of 10-20%, while physical soil conditions may be good. Those crops, including maize, have yields reduced to 50% at ESP values below 15%. Wheat is classified as a tolerant crop which shows stunted growth at an ESP of 40-60% due to adverse physical soil conditions. In the same manual of Landon, wheat is considered semi-tolerant with yield reduced to 50% at ESP values of 15-25%.

Sanchez (2003) refers to sodicity as an indicator for alkalinity affecting most crops, incipient at ESP values of 6-15% and a full modifier above 15% (relative to ECEC). Also Sys *et al.* (1993) refer to ESP as an indicator for alkalinity and rate ESP values relative to maize yield potential, with a relative yield of 100, 95, 85, 60, 40 and 25-0% at ESP values of 0, 8, 15, 20, 25 and >25%, respectively.

Combining the data suggested by Landon (1991) and Sys *et al.* (1993) resulted in the following rule, with an ESP of 22% as the threshold value at the threshold index of LRI = 20% and the suboptimal LRI at 10 < ESP < 25 given by 166.67 – 6.67 * [ESP]. Note that this rule and threshold have not been applied during the second run assessing LRI and derived root zone depth (following the suggestion to only use one parameter related to a given soil property). Instead the exchangeable sodium content has been evaluated in absolute terms and not relative to CEC.

The following rule is used with an Exchangeable sodium content of 4.2 cmolc/kg as the threshold value at the threshold index of LRI = 20% and with the suboptimal LRI at 1 < [ExNa] < 5 given by 125 – 25 * [ExNa].

2.6.3.9 Toxicity

Rules for evaluating toxicity are developed related to the contents (ppm) of extractable aluminium, iron, manganese, zinc, copper, boron and sulphur. Toxic contents of these elements are commonly induced by very high acidity or alkalinity. The primary data for these elements are available in the AfSP database, though at limited numbers only, and are also measured at the sentinel sites but not included in the available AfSS dataset. Consequently, these elements have not been mapped, except for extractable aluminium content, and the associated rules for evaluating toxicity have not been applied.

Instead, rules are developed related to exchangeable aluminium (cmolc/kg). Sanchez *et al.* (2003) define 60% exchangeable aluminium saturation, relative to ECEC at pH 7, as a threshold for toxicity for common crops. The associated threshold pH-H_2O is 5.5. Chemical limitation would occur at aluminium saturations from 10-60% for sensitive crops only.

Landon (1991) refers to absolute levels of exchangeable aluminium of 2-3 cmolc/kg as excessive for some crops. Sensitive crops are affected by an aluminium saturation of 30%, relative to CEC, and common crops by a saturation of 60% due to toxicity. Tolerant crops are affected only at a saturation of 85%.

Brenes and Pearson (1972) measure root response to aluminium saturation, and relate aluminium saturation to Al content in solution and to the soil pH. They indicate pH 5.5 as a threshold where Al saturation, relative to

CEC at pH 7, starts building up. Measured root yield of maize (relative to 100%) is optimal at Al saturations of up to 50 % beyond which the root yield decreases to 0% at an Al saturation of 90%. They also report about the relation between measured root growth, of maize and sorghum, and the aluminium concentration in solution. Sorghum is less tolerant to Al toxicity.

Hazelton and Murphy (2007) refer to much lower values for exchangeable aluminium saturation, relative to CEC, as critical for very sensitive to very tolerant plants, ranging from 9 to 43%.

Exchangeable acidity is the sum of exchangeable aluminium and hydrogen and the relative portion of hydrogen generally decreases with decreasing levels of pH (< 5.5). The rules and thresholds defined are based on this property, both in absolute terms and relative to ECEC.

The following rules are applied, with exchangeable acidity of 5.7 cmolc/kg as the threshold value at the threshold index of LRI = 20% and the suboptimal LRI at 2.5 < ExAcid < 6.5 given by 1625 – 25 * [ExAcid], and with exchangeable acidity saturation of 75% as the threshold value, at LRI = 20%, and the suboptimal LRI at 35 < [ExAcid*100/ECEC] < 85 given by 170 – 2 * [ExAcid*100/ECEC].

Note that the indices are scalable while the approach used is made not-scalable, as intended, by introducing a threshold for the index. At some point, an approach including scalable indices can be applied. The approach can be further fine-tuned to provide a scalable composite index (0 - 100%) in line with the soil productivity index (Kiniry *et al.*, 1983; Rijsberman and Wolman, 1984; Driessen and Konijn, 1992) where the various limiting factors have a combined impact instead of only the impact of the most limiting factor. Even though such approach is simple by itself and also applicable to datasets of heterogeneous nature, such as the legacy data compiled in the Africa Soil Profiles database, parameterising such composite index, reflecting the combined impact on rootability of multiple soil factors, may require considerable additional work beyond the scope of the current work.

Maps of the limiting rootability index (LRI) together with the associated most limiting factor (LRF) are produced for six depth intervals at 1 km resolution, together with the map of the root zone depth to maximally 150 cm. See Annex 1c for the R script, with metadata, implemented to assess RZD using the GSIF package. The results are described in Section 3.6 and used in section 2.7 to assess the root zone depth plant-available water holding capacity.

2.7 Root Zone Plant-Available Water Holding Capacity

The root zone plant-available water holding capacity of a soil profile aggregates the layer specific (or depth interval specific) values for plant-available water holding capacity of the whole soil (thus including coarse fragments) to a (weighted average) single value valid for the entire root zone, expressed as a relative value (volumetric fraction of the effective soil volume) and expressed as an absolute value (mm).

Similarly, maps are produced by aggregating the depth interval specific values for other soil properties to a single (weighted average) value valid for the root zone depth, including texture class, coarse fragments content, volumetric moisture content at permanent wilting point and at saturation and available water holding capacity.

The results are described in Section 3.7.

3 Results

3.1 Data access

The final results, together with the intermediate results and the input data, are publicly accessible and available for use according to the data policy of ISRIC. The ISRIC data policy is established in line with its role as World Data Centre for Soils and is available at www.isric.org/data/data-policy. Not yet publicly accessible and available though are the AfSS input data (AfSIS sentinel sites soil data).

The data products (gridded maps), together with associated metadata files, are accessible and available at www.isric.org/content/afsis-gyga-functional-soil-information-sub-saharan-africa-rz-pawhc-ssa (giving access to the ISRIC ftp-server[5]). The available data are described here as GYGA inputs, intermediate results and final results. The data products (file names) are also listed and described by metadata in Annex 2a & b.

Note that the data (input data, intermediate results and final results) are also made available through the SoilGrids project as accessible through the ISRIC ftp-server[6]. Annex 2c provides a conversion table giving the file names and file locations as applied and reported (here) by the AfSIS-GYGA project and as applied by the SoilGrids project. Additional data sources are available as specified.

Summary statistics are given in Annex 3a, per depth interval and also as weighted averages up to 150 cm depth. Annex 3b gives the histograms for the data aggregated over 150 cm and over the root zone depth.

GYGA inputs
The Africa Soil Profiles database compiled by AfSIS is available at: www.isric.org/data/africa-soil-profiles-database-version-01-2. A selection queried for use to produce the SoilGrids is included with the GYGA input data as dbf tables named AfSP012Qry. The AfSS data will become publicly available at a later instance.

SoilGrids, or the soil maps of the primary soil properties produced at 250 m spatial resolution, are available at www.isric.org/data/afsoilgrids250m.

SoilGrids resampled to 1 km resolution, serving as input to producing the derived products, are available as tif files with the GYGA input data. Also included are the most recent versions for those primary soil properties that, following review, were remapped using selected input soil data and additional covariates (bulk density, exchangeable sodium, electric conductivity, all for six standard depths, and drainage class).

GYGA intermediate results
Derived from the above input data are the gridded functional soil property maps, available as intermediate results for the six standard depth intervals, including maps related to soil moisture retention and to soil rootability.

5 ftp://gyga:gygagyga@ftp.isric.org (with user=gyga and password=gygagyga)
6 ftp://soilgrids:soilgrids@ftp.isric.org/data/AF/ (with user=soilgrids and password=soilgrids)

The preliminary versions of the intermediate results, produced at 250 m before correction, are available with the SoilGrids data on the ISRIC ftp-server.

GYGA results
Available as final results are the gridded maps of the (effective) root zone depth (ERZD or RZD) and the associated root-limiting factor, and maps of derived soil properties aggregated over the RZD (and also over the top 30 cm), including coarse fragments content, texture class, AWC (PAWHC), VMC at PWP, VMC at TetaS and the Total AWC (PAWHC) of the whole earth. The final map is the plant-available water holding capacity of the root zone depth, expressed in mm.

Geoserver
All gridded data products are also available as Web Mapping Services and as Web Coverage Services, at: http://wms4.isric.org/geoserver/afsis_gyga/ows. This URL can be used within a GIS environment, as QGIS, ArcGIS or otherwise, for direct access to the online data. These web services also feed directly into the GYGA atlas. The services including metadata are made accessible through GeoNetwork.

The following URL is an example which directs to a viewer (showing VMC at PWP aggregated over RZD): http://wms4.isric.org/geoserver/afsis_gyga/wms?service=WMS&version=1.1.0&request=GetMap&layers=afsis_gyga:af_agg_ERZD_PWP__M_1km&styles=&bbox=-2583464,-4142767,6333146,4514575&width=512&height=497&srs=EPSG:3857&format=application/openlayers. Another example is the same grid available as KML file for use in Google Earth: http://wms4.isric.org/geoserver/afsis_gyga/wms/kml?layers=afsis_gyga:af_agg_ERZD_PWP__M_1km.

Note that it requires important technical capacity, in terms of computational power and large data handling, to produce the soil maps and derived outputs, at increasingly high resolution, and to make those data available through web services.

3.2 Africa Soil Profiles data

Soil profile observations and measurements are combined from the Africa Soil Profiles (AfSP) database and the Africa sentinel sites (AfSS) database, providing soil data under a common standard for a total of approximately 28,000 point locations and 94,000 soil profile layers. Figure 11 illustrates the spatial distribution over Sub-Saharan Africa, representing for a total area of some 18 M km^2 an average density of 1 profile per 650 km^2. In general, the AfSP data explain relatively large distance variability, whereas the AfSS data, clustered over 60 sites of 10*10 km, provide information about short distance variability.

The nature of the soil data has some degree of heterogeneity, due to the heterogeneity inherent to legacy data as described by Leenaars *et al.* (2014) and because legacy data (AfSP) are combined with new data (AfSS). Soil depth (depth to bedrock or to iron pan) is a soil property which is not recorded in the AfSS database and is also frequently not recorded in the AfSP database, while the property is highly significant to explain and map the root zone depth, and associated plant-available water holding capacity. Similarly, the coarse fragments content is only recorded by the AfSP database, while this property is highly significant to explain the effective soil volume and plant-available water holding capacity. Both relevant properties are relatively very cost-efficiently observed in the field, but nonetheless data availability is still limited.

As yet, no soil data are available within AfSIS for Djibouti, Equatorial Guinea, Eritrea, Gambia and the island-countries off the main land (Cape Verde, Comoros, Mauritius, Mayotte (France), Reunion, Saint Helena, Sao Tome and Principe and the Seychelles). The AfSP database is described by Leenaars (2014), including lineage, content and statistics. The dataset and associated metadata is listed in Annex 2.

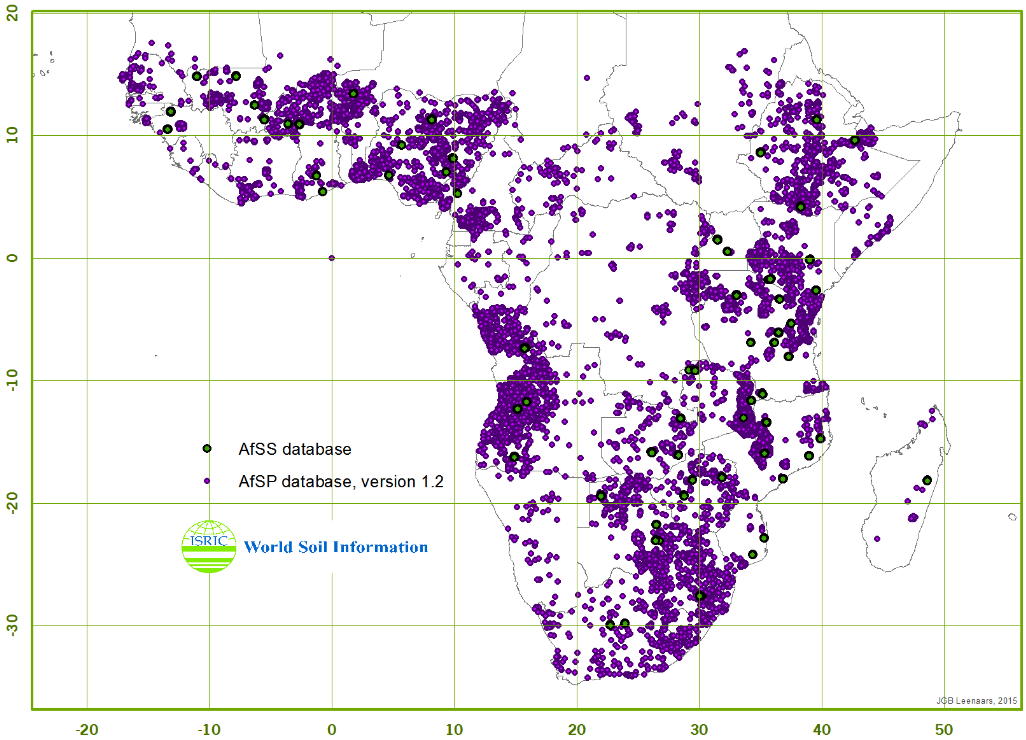

Figure 3
Spatial distribution of the soil data included in the Africa Soil Profiles (AfSP) database version 1.2 and the AfSIS sentinel sites (AfSS) database.

3.3 Africa SoilGrids

Available through the AfSoilGrids250m maps are soil property values predicted for six standard depth intervals including coarse fragments content, sand, silt and clay fractions, bulk density of the fine earth, pH (H_2O), electric conductivity, sum of exchangeable bases, exchangeable acidity, cation-exchange capacity and organic carbon content. Predicted for only two, not standard, depth intervals are the individual exchangeable bases (Ca, Mg, Na) except K, total nitrogen content and extractable aluminium. Moreover, predicted soil property values are available considering the entire soil profile including depth to bedrock and drainage class. The data are available at www.isric.org/data/afsoilgrids250m, together with a brief description, metadata and the mapping accuracy as assessed by cross validation. Omitted are predictions for carbonates and gypsum.

The data (grids) are resampled from 250 m to 1 km resolution. This step generally increases the accuracy. Remapped are the predictions for bulk density, exchangeable sodium and electrical conductivity at 1km resolution and for six standard depth intervals. Additionally, also remapped are the depth to bedrock and the drainage class. The list of outputs including metadata is given in Annex 2. Summary statistics are given in Annex 3a per depth interval and for profiles up to 150 cm. Annex 3b gives histograms showing the frequency distributions.

Figure 4 shows the result of remapping of the drainage class map. Predicted are ordinal drainage classes, while interpolated values are re-aggregated to discrete drainage classes. For relating drainage classes to depths to undrained soil (Table 3) it is recommended, in future, to maintain the interpolated values rather than the discrete drainage classes.

The prediction pattern seems very reasonable except for the extensive areas in the humid tropics mapped as well-drained, where (somewhat) excessively drained soils are common. Note, though, that data availability is particularly limited for these areas.

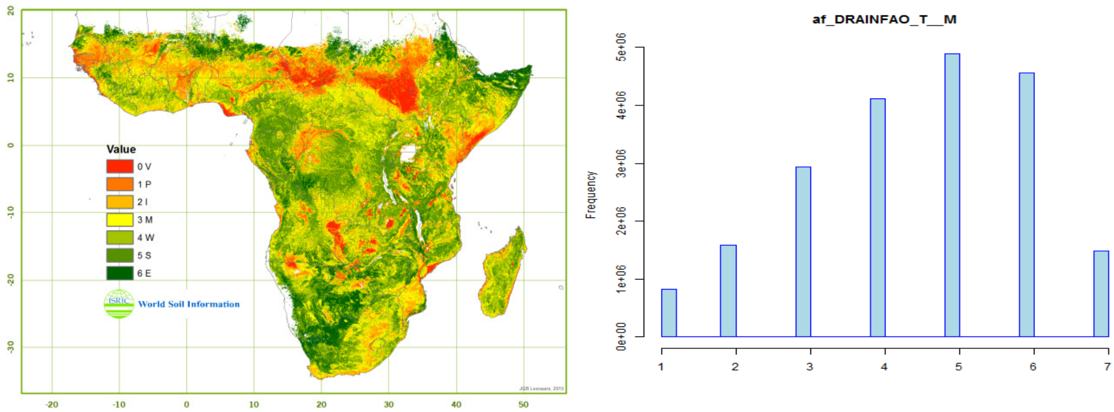

Figure 4
Predicted drainage classes (0-6 for very poorly to excessively drained) and associated histogram (1-7) with y-axis 0-6 M km².

The preliminary maps (AfSoilGrids250m) for bulk density showed patterns which suggest incorrect predictions in particular areas. Particularly in South Ghana and Ivory Coast, values appeared much too high, which could be explained by the fact that the AfSP database holds very high values for bulk density, originating from a soil survey study conducted in South West Ivory Coast (DRC, 1967) and a few other studies elsewhere. These studies report values for bulk density measured for the whole earth (including ironstone) instead of the fine earth, resulting in very high bulk densities (> 2.0 kg/dm³). The AfSP data were queried for those data that are measured by laboratory methods applied to the whole earth. These queried data were excluded in cases that the coarse fragments content is unknown. In case of known content of coarse fragments, the value for bulk density was corrected for the volume occupied by coarse fragments, while assuming a bulk density of 2.65 kg/dm³ (quartz) for coarse fragments (a reasonable estimate knowing that both metamorphic rocks, which are heavier, and iron stone gravel, which is lighter, occur). To avoid this procedure having undesired impact on the resulting values, extreme values (below 1.1 and above 1.8 kg/dm³) were excluded rigidly. Further, all other values for bulk density exceeding 1.85 within a depth of 1 m were excluded. The selected data are given in a separate dbf table (AfSP012Qry) together with the input data as available through the link given in section 3.1 and were used to remap bulk density at 1km.

The preliminary maps for electric conductivity (AfSoilGrids250m) are produced using soil profile data for both EC and ECe (measured on unsaturated and saturated paste). The AfSP database was queried for the EC data, excluding the ECe data, and electric conductivity is remapped at 1km. The selected soil profile data are given in a separate table together with the resulting grids.

Very high values were predicted by the preliminary maps (AfSoilGrids250m) for exchangeable sodium in all depressions, including in humid climates such as the gleysol area along the Congo river. Remapping exchangeable sodium proved to require additional covariates to 'force' sodium out of the low pH - low CEC soils of the humid tropics. Consequently, relatively high values for exchangeable sodium are predicted for high pH - high CEC soils in particularly arid regions.

Figure 5 shows maps of pH, bulk density, electrical conductivity and exchangeable sodium for standard depth interval 4 (30-60 cm). The overall (0-150 cm) weighted mean value predicted for pH (H_2O) is 6.4, with a standard deviation of 1.1 over a min-max range from 4.2 to 10.6 (see Annex 3a). Near all predictions are within a range of 4.5 - 9.0 though (Annex 3b). In the AfSP database these values are 6.2 (±1.2), 2.7 - 10.3. The overall mean, and median, values are nearly similar but, apparently, the extreme values are not captured and represented by the prediction modelling. This phenomenon of smoothening is inherent to the geostatistical approach of soil mapping. Something similar occurs for bulk density, with an overall (0-150 cm) weighted mean value predicted at 1.45 kg/dm³, a standard deviation of 0.12 and a min-max range from 0.74 to 1.99. Annex 3b shows that near all values are within a range of 1.15 - 1.80 kg/dm³. In the AfSP database these values are 1.40 (±0.12), 0.16 - 2.60, respectively. The mean values, and the median, are near similar but the extreme values, both minimum and maximum, are not predicted.

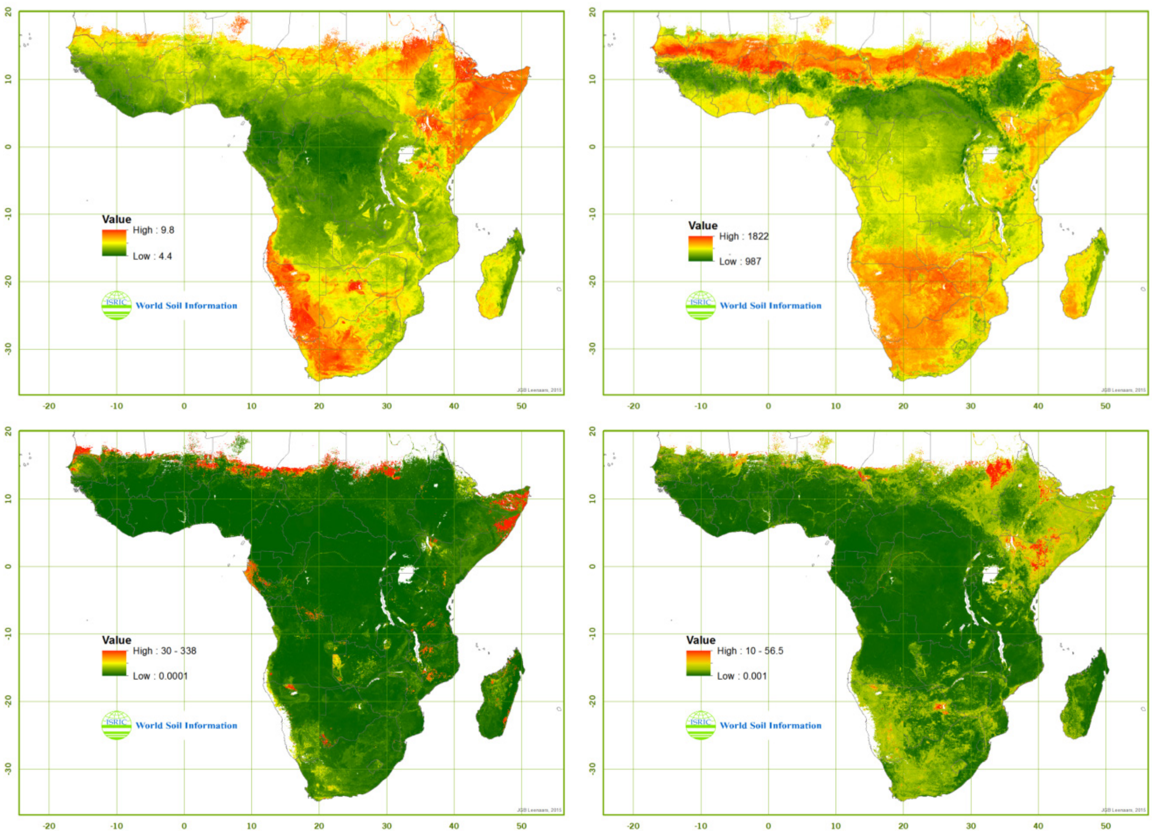

Figure 5
Predictions for standard depth interval 4 (30-60 cm) of (from upper left to lower right) pH (H_2O), bulk density (kg/m³), electrical conductivity (dS/m) and exchangeable sodium (cmolc/kg).

This pattern of prediction, where the variability of soil property values as reported in the soil profiles databases is smoothened in the prediction maps, thus loosing the upper and lower value ranges (and thus loosing more than only the extreme values) is, as said, inherent to geostatistical soil mapping and is comparable for other properties. (Note though that the upper and lower value ranges are most probably represented by the uncertainty ranges mapped with the predicted values). Exceptions to this smoothening effect are properties as electric conductivity and to a lesser extent exchangeable sodium, and also exchangeable acidity, which generally show low values but locally excessively high values within only small areas. These properties prove relatively difficult to predict accurately. The extreme high values are actually captured and represented but the spatial representation is not necessarily localised. The resulting mean value largely exceeds the median, by factor 10 for electric conductivity and factor 2 for exchangeable sodium and acidity (Annex 3a).

The pattern for exchangeable sodium shows high values in particularly areas with solonetz and solonchak soils and depressions in arid areas. Its presence seems overestimated for other arid lowland areas known for high alkalinity, e.g. the calcisol and gypsisol area of Ethiopia and Somalia (where rooting would be limited by induration), but such pattern is considered acceptable given that the preliminary maps predicted high sodium contents in *all* depression areas and given the argumentation in the paragraph above.

The SoilGrids, at 250 m and 1 km, can be validated if an independent dataset with additional accurately georeferenced soil observation and measurement data were available. Alternatively, conventional soil maps with attribute soil data can serve for validation, with the scale and extent of the maps determining the scope of validation. The scope concerns either coarse patterns for the whole extent, by using broad-scaled maps as the Soil atlas of Africa (Jones *et al.*, 2013) or the WISE30sec map which also provides soil property estimates with associated uncertainty (Batjes, 2015). Increasingly finer patterns for smaller extents can be validated within sample windows, using e.g. the SoTer databases at 1: 1- 2,000,000 scale, country territory map sheets at 1: 100- 250,000, or focus-area maps of (semi-) detailed scale.

These soil property maps serve as input to further analysis and the production of derived functional soil property maps in the coming sections.

3.4 Volumetric Soil Fine Earth Fraction

The volumetric coarse fragments content determines the volumetric soil fine earth fraction. AfSoilGrids250m, resampled to 1km, includes maps (grids) for the volumetric coarse fragments content per depth interval. The available grids are listed together with metadata in Annex 2. Summary statistics are given in Annex 3a, the histogram for the coarse fragments content over 150 cm depth in Annex 3b. As an example, the map for standard depth interval 4 (30-60 cm) is given in Figure 6 together with the associated histogram.

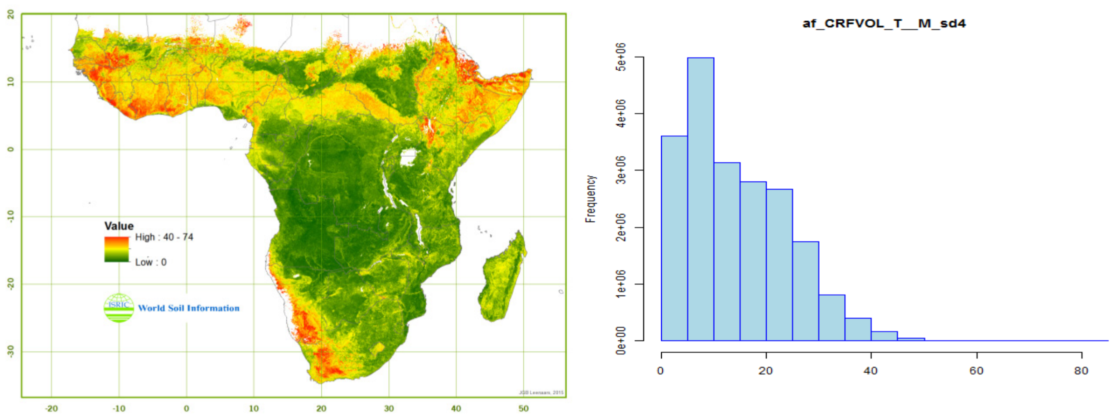

Figure 6
Prediction for standard depth interval 4 (30-60 cm) of the volumetric coarse fragments content (v%) and associated histogram with y-axis 0-6 M km².

The overall (0-150 cm) weighted mean value predicted for coarse fragments is 17.1 v%, with a standard deviation of 9.8 v% over a min-max range from 0 to 85 v% (Annex 3a) though mainly from 0 to 50 v% (Annex 3b). In the AfSP database, the corresponding observed values are on average 9 v% (± 20), 0 - 100 v%, which is nearly two times smaller. The prediction model hardly captures and represents any high values above 50 v%, which is a far too low maximum and requires improvement.

These soil property maps serve as input for further analysis and the production of derived functional soil property maps in the coming sections.

3.5 Plant-Available Water Holding Capacity

3.5.1 Moisture retention from soil profiles data

Moisture retention curves calculated for the layers of the AfSP database are visualised per broad texture class in Figure 7. The results are summarised in Table 5. The curves for the fine, medium and coarse texture classes are well separated, in terms of absolute moisture contents at given potentials, but the shapes are very comparable. The volumetric moisture contents at pF 0, 2, 2.5 and 4.2 are according to the average curve about 47, 33, 28, 19 v%, respectively. The corresponding averages of measured values are 42, 31, 21, 15 v% in the AfSP database. Apparently, the pedotransfer function slightly overestimates the values.

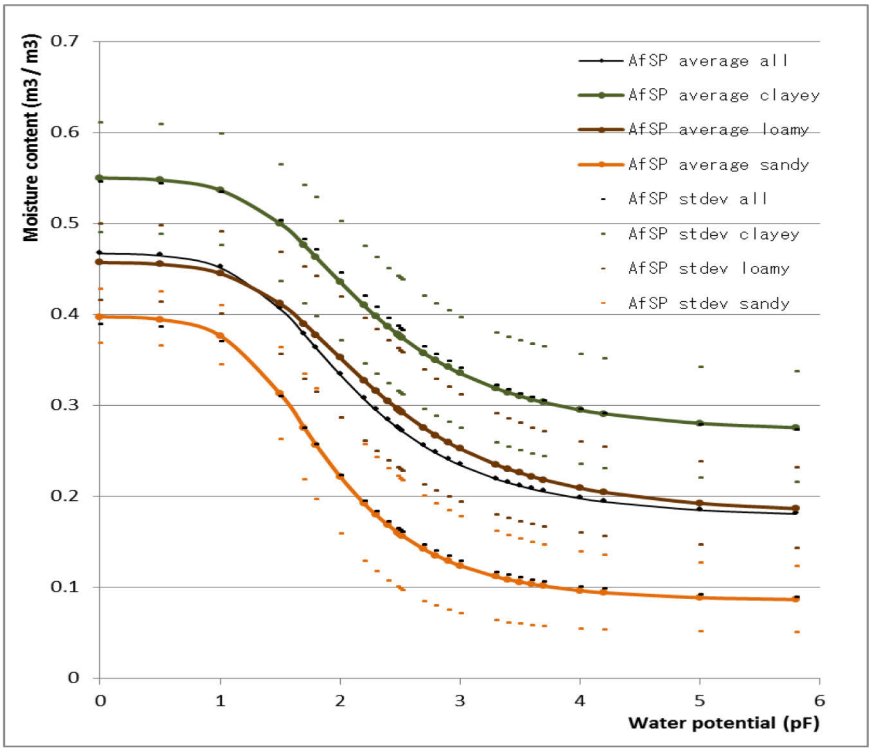

Figure **7**
Soil moisture retention curves calculated for coarse, medium and fine textured soil profile layers of the AfSP database.

Both Figure 7 and Table 5 show that the available water holding capacity, or the soil moisture content over the range between field capacity and permanent wilting point, is comparable for each of the three texture classes. The capacity is highest for the loamy or medium textured soil, followed by clayey or fine textured soil, and is lowest for the sandy or coarse textured soil, which is as expected. The available water holding capacity for medium textured soil exceeds that for coarse textured soil with only about 2.5 v%. The form of the curves is such that even the soil moisture content over the range between saturation and near oven-dry soil is similar (25-30 v%) for each of the texture classes. This range is with on average 27.4 v% near similar in the AfSP database.

More significant for the available water holding capacity is the impact of the definition of field capacity. The available water capacity is on average 7.9 v% with field capacity defined at pF 2.5 and 14.0 v% with field capacity defined at pF 2.0. The absolute difference is thus 6.1 v%. In the AfSP database these figures are on average 6.5 and 16.4 v%, thus with a difference of 10.0 v%.

It was considered to define field capacity for each texture class differently, as suggested by Gijsman *et al.* (2007), with field capacity defined as pF 2.5, 2.3 and 2.0 for fine, medium and coarse textured soils, respectively. The bold figures in Table 5 show the impact of such approach, implying that the plant-available water holding capacity would be 8.5, 11.1 and 12.8 v% for fine, medium and coarse textured soils, respectively. This does not correspond with the expected AWHC values (where a coarse textured soil has the lowest AWHC) and hence, it is concluded to apply a single definition for field capacity (i.e., pF 2.3 or 200 cm moisture potential). With that definition, the available water holding capacity is 10.7, 11.1 and 8.6 v% for fine, medium and coarse textured soils, respectively. The average is 10 v% which is similar to the average measured value in the AfSP database. Altogether though, the range of values for available water holding capacity calculated by the pedotransfer function appears to be rather narrow compared to the range of values measured.

Table 5

Available water holding capacity (v%) of the fine earth for coarse, medium and fine textured soil profile layers of the AfSP database, calculated by a pedotransfer function with field capacity defined at pF 2.5, 2.3 and 2.0 (300, 200 and 100 cm).

	pF 2.5-4.2	pF 2.3-4.2	pF 2.0-4.2
n	43672	43672	43672
Median AWHC	7.9	10.0	14.0
average AWHC	7.9	10.1	14.0
sdev AWHC	2.5	2.7	2.9
n clayey	14616	14616	14616
median AWHC clayey	8.4	10.6	14.4
average AWHC clayey	**8.5**	10.7	14.5
sdev AWHC clayey	1.7	2.0	2.4
n loamy	13498	13498	13498
median AWHC loamy	9.0	11.2	14.8
average AWHC loamy	9.0	**11.1**	14.8
sdev AWHC loamy	2.4	2.7	2.9
n sandy	15558	15558	15558
median AWHC sandy	6.0	8.1	12.5
average AWHC sandy	6.4	8.6	**12.8**
sdev AWHC sandy	2.4	2.8	3.1

The Africa Soil Profiles database provides an opportunity to further validate the outcomes of the pedotransfer function. The volumetric moisture retention calculated over the range of water potentials can be plotted against the measured volumetric moisture retention, for the entire dataset, as well as stratified by texture class. Preliminary analyses show a rather good fit over the entire moisture retention curve, as reported by Wösten *et al.* (2013), but the fit is particularly poor around field capacity. This can be partly explained by the change of laboratory method applied for assessing retention at low and high potentials as well as by the fact that the measured values reported by the AfSP database seem particularly odd for some of the water retention data. Note though that the PTF may also perform less optimal relative to the measured data due to the fact that incomplete data for bulk density in the AfSP database are substituted by PTF-derived data. This provides another opportunity for further validation by plotting the calculated bulk density against the measured bulk density. Challenges and other possibilities to predict water retention from heterogeneous soil databases are reported by Weynant *et al.* (2013). It is beyond the scope of this study to generate strata-specific moisture retention curves of different forms (e.g. for different texture groups).

3.5.2 Moisture retention maps

The pedotransfer function that was tested on the soil profiles data is next applied to the grids. The available data products (grids) are listed together with metadata in Annex 2. Summary statistics, per depth interval and for the profile up to 150 cm, are given in Annex 3a. The associated histograms are given in Annex 3b.

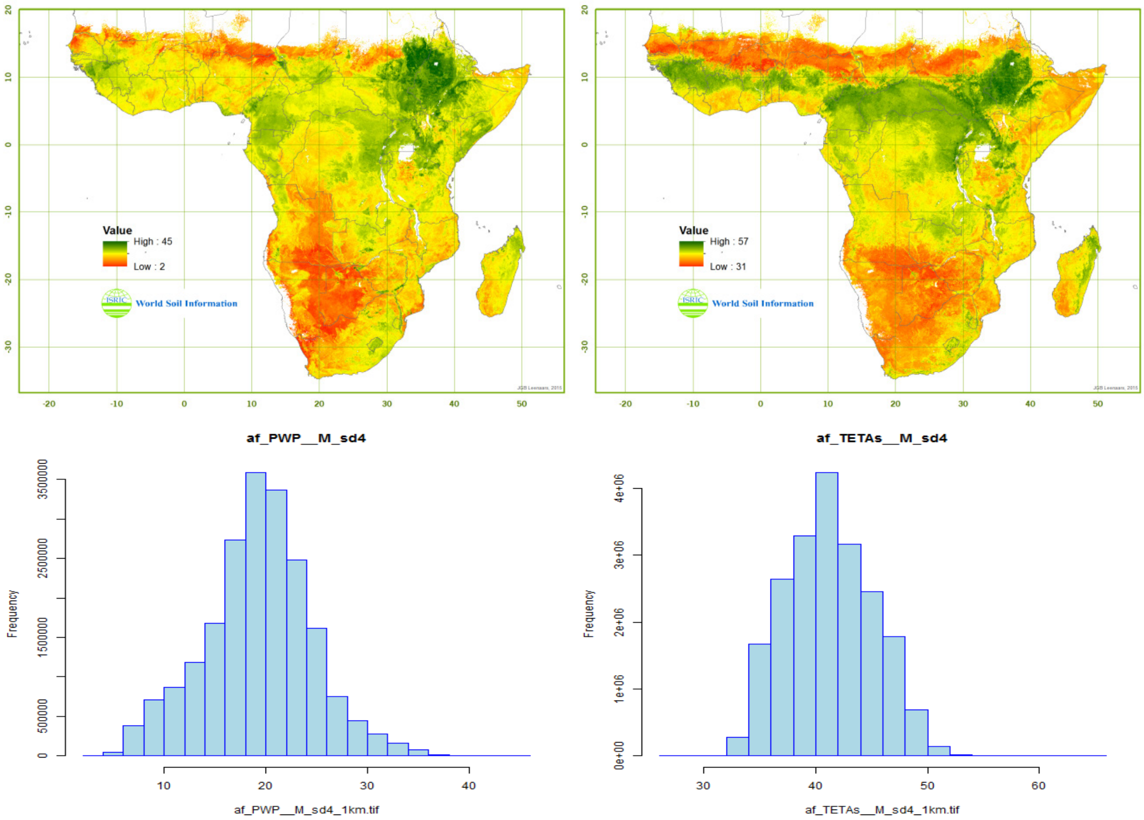

Figure 8
Predictions for standard depth interval 4 (30-60 cm) of the volumetric moisture content (v%) of the soil fine earth at permanent wilting point (left) and at saturation (right) above, and the associated histograms with y-axis 0-4 M km² below.

As an example, the volumetric moisture content at permanent wilting point (PWP) and at saturation, mapped for standard depth interval 4 (30-60 cm), is illustrated in Figure 8. The overall (0-150 cm) weighted mean value predicted at PWP is 19.6 v% (median = 19.8), with a standard deviation of 5.3 over a min-max range from 1 to 45 v% (Annex 3a), and mainly in the range 5 – 37 v% (Annex 3b). In the AfSP database, the corresponding measured values are 14.6 (±10.6), 0 - 83.3 v%, respectively. The PTF applied to the grids seems in general to overestimate moisture content at PWP with about 5 v%. The mean predicted value at saturation (TetaS), is 41.6 (sdev = 4.0) over a range from 25 to 65 v% (mainly 30 - 53 v%). The corresponding values in the AfSP database are 42 (±14.7), 5 - 85 v%. The average values coincide very well but, again, the maps do not depict any extreme values. The latter is likely, to a certain extent, a result of the fact that the underlying primary soil property maps do not depict any extreme values.

The available water holding capacity of the soil fine earth, mapped for standard depth interval 4 (30-60 cm), is illustrated in Figure 9. The overall (0-150 cm) weighted mean predicted value for AWHC is 9 v%, with a similar median, and the standard deviation is 1.6 over a min-max range from 0 to 20 v%. The histogram in Annex 3b shows that the prediction in nearly all cases is within a rather narrow range of 3 - 14 v%. The mean measured value recorded in the AfSP database is 11.4 v%, thus 25% larger.

The AWHC is remarkably low in the Blue Nile in-land delta (Gezira), an area reputed for its extensive vertisols. Surprisingly, relatively high AWHC is predicted over the entire Guinea/Soudan savannah zone stretching over west and central Africa. Overall, the spatial pattern of predicted AWHC shows very little variation.

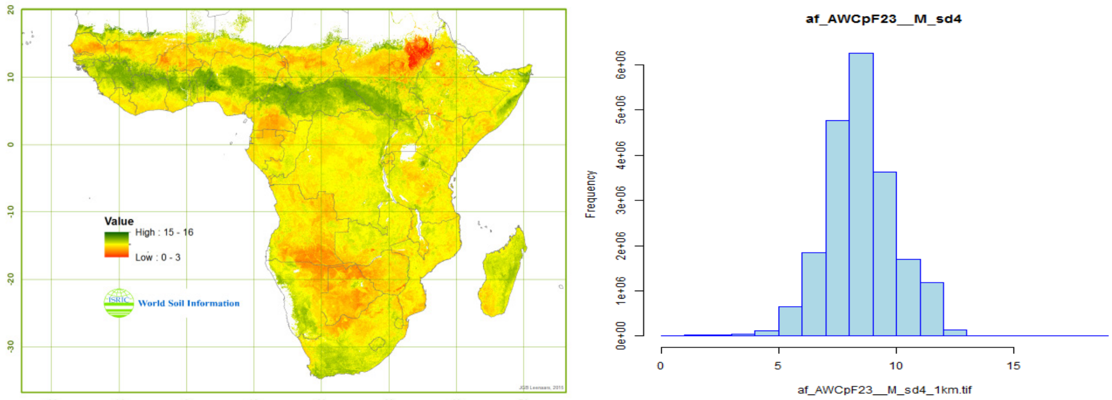

Figure 9
Prediction for standard depth interval 4 (30-60 cm) of the available water holding capacity (v%) of the soil fine earth and associated histogram with y-axis 0-6 M km².

These functional soil maps serve as input for producing further derived maps in the next sections.

3.6 Root Zone Depth

3.6.1 Rootability per soil layer

The soil property maps have been subjected to the rules given in Table 4 to assess the limiting rootability indices per soil layer and to assess the associated limiting factor. Properties associated with cementation (i.e., calcium carbonate and gypsum) are not mapped and the associated rules are not applied. For sodicity, only the rule with exchangeable sodium is applied while the one with exchangeable sodium percentage (ESP) was omitted.

The available data products (grids) with metadata are listed in Annex 2. Summary statistics are given in Annex 3a per depth interval and for the weighted average up to 150 cm depth. The corresponding histograms for the rootability index and the limiting factors, over 150 cm depth, are given in Annex 3b (18, 19, 20).

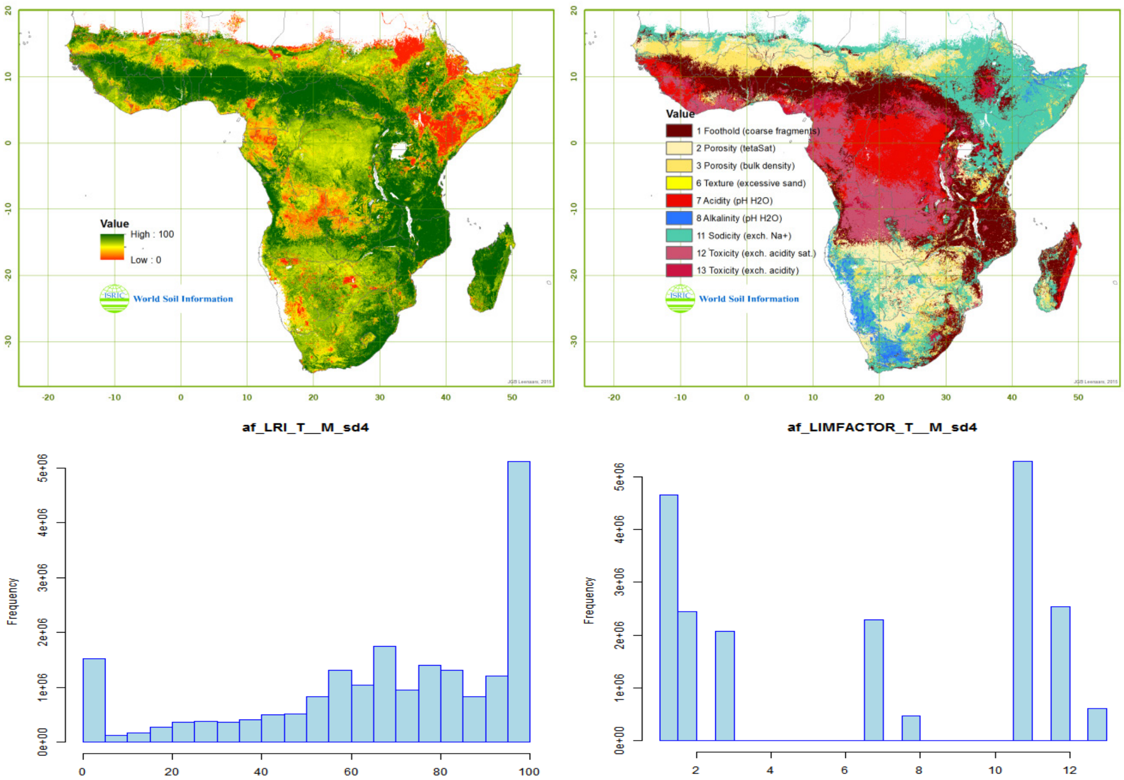

Figure 10
Predictions for standard depth interval 4 (30-60 cm) of the) limiting rootability index (%) (left) and the associated limiting factor (right) above, and associated histograms with y-axis 0-5 M km² below.

On 12.8% of the evaluated land area is the limiting rootability index (LRI) for at least one of the six depth intervals beyond the threshold index and thus limiting rootable depth. The area-weighted average of the LRI-derived rootable depth is 23 cm (± 22). Five of the eight soil factors evaluated for rootability per depth interval (or seven of the thirteen underlying soil properties) restrict rootability beyond the threshold index, in a small or large extent. To illustrate this, Figure 10 shows the limiting rootability index, mapped for standard depth interval 4 (30-60 cm), together with the frequency distribution. The LRI in this depth interval is beyond the threshold index on only 3.5% of the evaluated land area. Figure 10 also shows a map of the soil factors that are the most limiting (not necessarily beyond the threshold index) in this depth interval.

Table 6 indicates for each depth interval which soil factors, and underlying soil properties, are the most limiting factors (with lowest rootability index) and specifies the associated land areas (km²) in Table 6a and the associated average rootability index, with standard deviation, in Table 6b.

Note that foothold (soil volume), as restricted by coarse fragments content (the first soil variable), is in Figure 10 and Table 6a indicated as the most limiting soil factor, in any of the six depth intervals, on 25% of the land area, while Table 6b indicates that the corresponding LRI is 100% (±0). Apparently, in cases (in map voxels) where all factors have a rootability index of 100% (not limiting) this factor is 'incorrectly' identified as the most limiting one.

Table 6a

Soil area (km²) per depth interval specified per soil factor with the most limiting rootability index (lowest LRI), not necessarily beyond the threshold index.

Soil factor	Soil variable	Depth 0-5	Depth 5 -15	Depth 15-30	Depth 30-60	Depth 60-100	Depth 100-150	Depth 0-150 cm
		km²	km²	km²	km²	km²	km²	km²
Foothold (soil vol.)	CfPc	5832495	6071806	5306763	4650293	4408814	4311752	30581923
Porosity	TetaS	4171763	4392284	3531727	2446493	2120503	1977165	18639935
Porosity	f.BD	795844	1202715	1590434	2080600	2235389	2364783	10269765
Texture adequacy	Sand	1	1	0	0	828	141	971
Texture adequacy	f.Clay	0	0	46	0	0	0	46
Texture adequacy	f.Sand	0	0	0	6	0	3	9
Induration (cement.)	CaCO3	-	-	-	-	-	-	-
Induration (cement.)	CaSO4	-	-	-	-	-	-	-
Acidity	pH-H$_2$O	2827965	3032041	2443876	2299277	2183676	1987211	14774046
Alkalinity	pH-H$_2$O	487454	880995	818997	468599	570303	544266	3770614
Salinity	EC	0	0	0	0	0	0	0
Sodicity	f.ExNa	-	-	-	-	-	-	-
Sodicity	ExNa	4076181	2625853	3681961	5267346	5684692	5952227	27288260
Toxicity	f.ExAcid	958836	1160634	2292744	2539223	2587580	2612717	12151734
Toxicity	ExAcid	1220690	1004900	704681	619392	579444	620964	4750071
Total (km²)		20371229	20371229	20371229	20371229	20371229	20371229	6* 20371229

Table 6b

Limiting rooting index (LRI) per depth interval specified per soil factor (mean ± standard deviation), not necessarily beyond threshold index.

Soil factor	Soil variable	Depth 0-5	Depth 5 -15	Depth 15-30	Depth 30-60	Depth 60-100	Depth 100-150	Depth 0-150 cm
		LRI (%)	LRI (%)	LRI (%)	LRI (%)	LRI (%)	LRI (%)	LRI (%)
Foothold (soil vol.)	CfPc	100 (±0)	100 (±0)	100 (±0)	100 (±0)	100 (±0)	100 (±0)	100 (±0)
Porosity	TetaS	74 (±12)	75 (±12)	75 (±12)	74 (±11)	73 (±11)	70 (±13)	74 (±12)
Porosity	f.BD	67 (±18)	69 (±18)	68 (±18)	68 (±20)	64 (±24)	59 (±26)	65 (±22)
Texture adequacy	Sand	60 (±0)	0 (±0)	-	-	0 (±0)	0 (±0)	0 (±2)
Texture adequacy	f.Clay	-	-	64 (±21)	-	-	-	64 (±21)
Texture adequacy	f.Sand	-	-	-	90 (±6)	-	87 (±13)	89 (±8)
Induration (cement.)	CaCO3	-	-	-	-	-	-	-
Induration (cement.)	CaSO4	-	-	-	-	-	-	-
Acidity	pH-H$_2$O	73 (±14)	72 (±14)	73 (±14)	75 (±13)	76 (±12)	77 (±11)	74 (±13)
Alkalinity	pH-H$_2$O	63 (±15)	64 (±16)	62 (±16)	56 (±15)	56 (±17)	49 (±16)	59 (±17)
Salinity	EC	-	-	-	-	-	-	-
Sodicity	f.ExNa	-	-	-	-	-	-	-
Sodicity	ExNa	53 (±32)	60 (±33)	54 (±33)	45 (±34)	43 (±34)	37 (±33)	47 (±34)
Toxicity	f.ExAcid	68 (±16)	64 (±17)	52 (±24)	50 (±26)	51 (±26)	51 (±26)	54 (±25)
Toxicity	ExAcid	68 (±25)	67 (±26)	64 (±28)	65 (±27)	66 (±26)	67 (±26)	66 (±26)

3.6.2 Rootable soil depth

Figure 11 shows a map of the soil factors, with the underlying soil properties, which are limiting root zone depth and which are either the maximum rooting depth of maize (150 cm), the depth of soil (depth to bedrock), the depth of aerated soil (depth to oxygen shortage) or the depth to a layer with a root restricting soil factor. Where the root zone depth is restricted by soil conditions, this is in nearly all cases due to a limited soil depth or a limited depth of aerated soil. In only a relatively small area (12.8% of the total area) is the root zone depth limited due to a layer with a root restricting soil factor beyond the threshold. Only seven layer-related soil properties restrict root zone depth, out of the thirteen considered, and in practice only four as shown in Table 7 and by the histogram 20 given in Annex 3b.

The predicted root zone depth appears to be not limited by soil conditions in large parts (25%) of Africa, especially in the humid tropics. Root zone depth is limited by depth of soil in much of the highlands of eastern and southern Africa, the petro-plinthite areas in western Africa and the areas with calcium-cemented soils in the far south-west and far north-east of Africa. Aeration seriously limits root zone depth in much of the depressional areas and, to a lesser degree but over larger extents, in areas where pseudo-gley occurs and soils are only moderately well- or imperfectly drained. Root zone depth is strongly limited due to sodicity in depression areas in arid zones such as along the border of the Sahara, the inland deltas in Namibia and Botswana and especially in the arid lowlands bordering Ethiopia. Toxicity related to exchangeable acidity (aluminium) is limiting root zone depth in the south of the Democratic Republic of Congo and the wetter parts of Ivory Coast, Ghana, Cameroon and Ethiopia. Porosity is limiting root zone depth in parts of the Sahel from Senegal to Burkina.

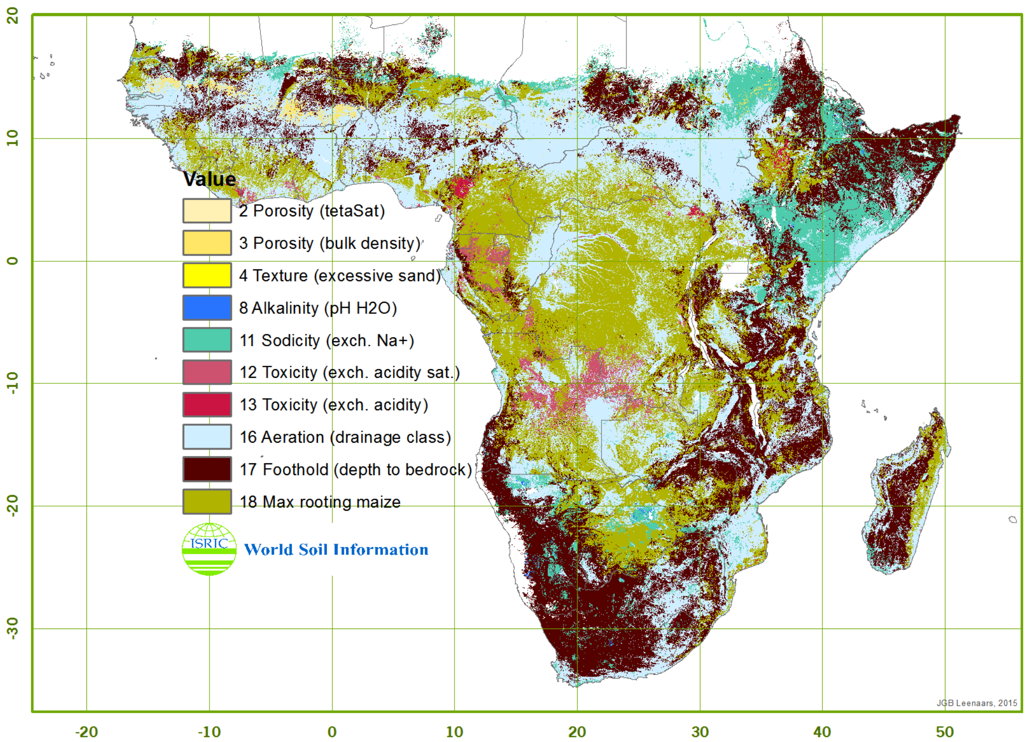

Figure 11
Soil factors limiting root zone depth.

Table 7

Soil area (km²) per RZD class specified per soil factor, and the mean depth (and standard deviation) at which the soil factor limits RZD.

Soil factor	Soil variable	RZD 0-5	RZD 5 -15	RZD 15-30	RZD 30-60	RZD 60-100	RZD 100-150	RZD 150	RZD 0-150 cm	RZD mean	RZD sd
		km²	km²	km²	km²	km²	km²	km²	km²	cm	cm
Foothold (soil volume)	CfPc	0	0	0	0	0	0	0	0	-	-
Porosity	TetaS	30	11	0	5	0	2	0	48	12	23
Porosity	f.BD	11650	4690	9701	44907	48846	3913	0	123707	51	27
Texture adequacy	Sand	0	1	0	0	14	127	0	142	131	25
Texture adequacy	f.Clay	0	0	0	0	0	0	0	0	-	-
Texture adequacy	f.Sand	0	0	0	0	0	0	0	0	-	-
Induration (cement.)	CaCO3	-	-	-	-	-	-	-	-	-	-
Induration (cement.)	CaSO4	-	-	-	-	-	-	-	-	-	-
Acidity	pH-H_2O	0	0	0	0	0	0	0	0	-	-
Alkalinity	pH-H_2O	6797	2213	4680	2938	686	219	0	17533	19	22
Salinity	EC	0	0	0	0	0	0	0	0	-	-
Sodicity	f.ExNa	-	-	-	-	-	-	-	-	-	-
Sodicity	ExNa	976975	27675	279762	575863	98611	27320	0	1986206	21	24
Toxicity	f.ExAcid	5538	35532	255486	79070	14851	1811	0	392288	27	14
Toxicity	ExAcid	86069	107	204	353	597	402	0	87732	2	10
Depth of aerated soil	f.Drain	0	759712	0	1290015	2313140	2989450	0	7352317	78	36
Depth of soil	RockDpth	0	2251	147896	627501	1136820	3327670	0	5242138	105	35
Maize max root depth		0	0	0	0	0	0	5169118	5169118	150	0
Total (km²)		1087059	832192	697729	2620652	3613565	6350914	5169118	20371229	96	49

The rules developed to assess the depth to a soil layer with a root restrictive soil factor, by evaluating the limiting rootability index, apparently have little impact, in terms of spatial extent, on the estimated root zone depth compared to the impact of the simpler rules to assess depth of soil and depth of aerated soil. This is probably not necessarily due to too strict rules defined but maybe to too strict threshold indices (at 20%). Another, more likely explanation is that the soil property maps lack extreme values due to the method for prediction modelling, which proves not able to adequately capture and represent extreme values. The examples in the previous paragraphs and the histograms in Annex 3b show that the maps for e.g. coarse fragments content and for pH lack values within the range of the evaluation rules developed, even though those values are provided by the actual input soil profile data. The solution would be to work with stochastic simulations but that is far beyond the scope of this study.

As a general statement, root zone depth is limited for a small extent, as mentioned here above, but to a large degree in cases that rootability is limited by a soil layer with a root restricting soil factor such as sodicity. Root zone depth is limited for a large extent but small degree in cases that rootability is limited by depth of soil or depth of aerated soil. The impact on the rootable soil volume (not considering coarse fragments content) is given in Table 8. The evaluated area has a size of 20.4 M km^2 which corresponds with a soil volume potentially rootable by maize of 30,600 km^3 in case that root zone depth wouldn't be restricted by soil conditions. This volume is reduced by 10,527 km^3 due to soil conditions restricting root zone depth, of which 4,785 km^3 are due to limited depth of aeration and 2,517 km^3 due to sodicity. Depth of soil reduces the rootable soil volume by 2478 km^3, aluminium toxicity by 606 km^3, porosity by 118 km^3, alkalinity by 23 km^3 and the other factors by practically 0 km^3.

Table 8
Reduced rootable soil volume (km^3) per RZD class and soil factor.

Soil factor	Soil variable	RZD 0-5	RZD 5 -15	RZD 15-30	RZD 30-60	RZD 60-100	RZD 100-150	RZD 0-150 cm
		km^3	km^3	km^3	km^3	km^3	km^3	km^3
Foothold (soil vol.)	CfPc	0	0	0	0	0	0	0
Porosity	TetaS	0	0	0	0	0	0	0
Porosity	f.BD	17.2	6.6	12.4	47.2	34.2	1.0	118.4
Texture adequacy	Sand	0	0	0	0	0	0	0
Texture adequacy	f.Clay	0	0	0	0	0	0	0
Texture adequacy	f.Sand	0	0	0	0	0	0	0
Induration (cement.)	CaCO3	-	-	-	-	-	-	-
Induration (cement.)	CaSO4	-	-	-	-	-	-	-
Acidity	pH-H_2O	0	0	0	0	0	0	0
Alkalinity	pH-H_2O	10.0	3.1	6.0	3.1	0.5	0.1	22.7
Salinity	EC	0	0	0	0	0	0	0
Sodicity	f.ExNa	-	-	-	-	-	-	-
Sodicity	ExNa	1441.0	38.7	356.7	604.7	69.0	6.8	2517.0
Toxicity	f.ExAcid	8.2	49.7	325.7	83.0	10.4	0.5	477.5
Toxicity	ExAcid	127.0	0.1	0.3	0.4	0.4	0.1	128.3
Depth of aerated soil	f.Drain	0	1063.6	0	1354.5	1619.2	747.4	4784.7
Depth of soil	RockDpth	0	3.2	188.6	658.9	795.8	831.9	2478.3
Maize max root depth		0	0	0	0	0	0	0
Total (km^3)		1603	1165	890	2752	2529	1588	10527

The map of the root zone depth is given in Figure 12. The mean predicted value for the root zone depth is 96 cm, with a standard deviation of 49 cm and a range between 1 and 150 cm. The median is 20 cm deeper with a value of 115 cm. In the AfSP database, the mean observed rooted depth (with the plant species unspecified) is 99 cm (sdev = 51), with a range between 0 and 400 cm.

The histogram associated with the root zone depth is given in annex 3b (21). The histogram is dominated by those situations where the depth of aerated soil, as interpreted from discrete drainage classes, is the limiting factor. This gives a somewhat awkward frequency distribution.

Table 7 summarises the extent (in km²) that each soil factor, and underlying soil properties, restricts root zone depth to specific soil depth classes and also the mean depth at which the restriction occurs is given. Table 8 summarises the associated reduction in soil volumes (km³) available for rooting.

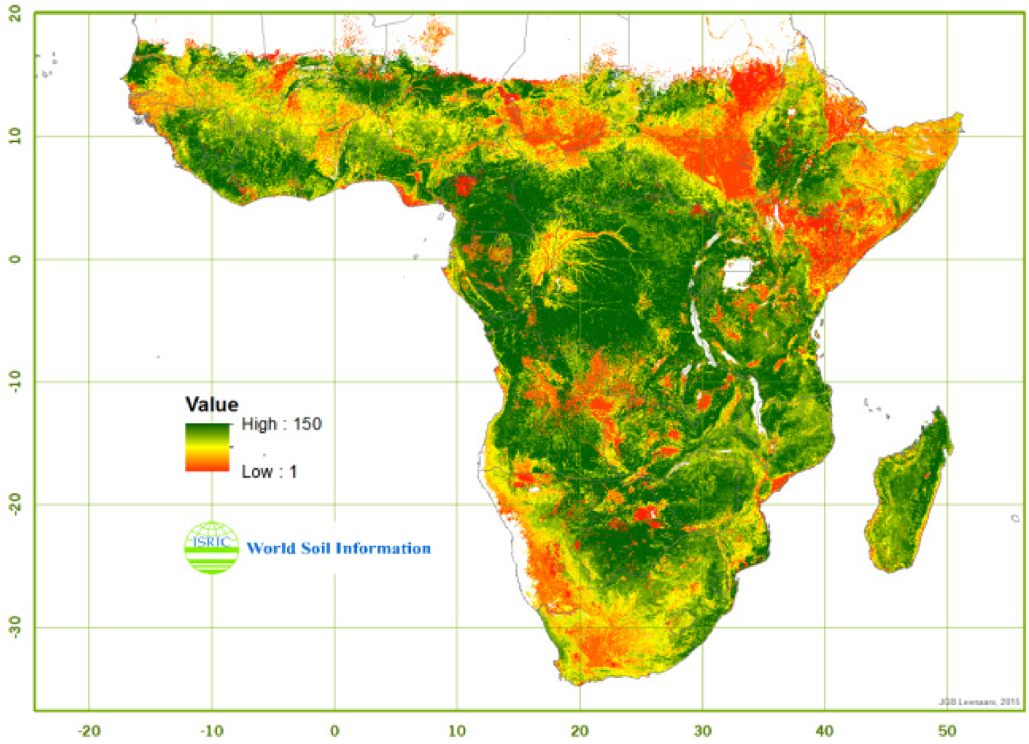

Figure 12
Root zone depth (cm).

(Note that the predicted minimum value for root zone depth is 1 cm while this figure is supposed to be 0 cm corresponding with the top of the shallowest depth interval. However, a scaled approach has been applied to interpolate the depth interval centre point specific LRI's to a continuous spline function of LRI over the full depth. Such spline produces a more detailed result, although it is not necessarily more precise).

The Africa Soil Profiles database allows further validation of the outcomes of mapping the root zone depth. The AfSP database gives georeferenced data for actually observed rooted depths, which can be plotted against the modelled root zone depths for maize at the same locations. Vågen *et al.* (in press.) mapped the probability of root restriction within the upper 50 cm of soil, and it would be worthwhile to compare both maps.

This functional soil map serves as input for producing the final maps in the next section.

3.7 Root zone plant-available water holding capacity

The functional soil maps produced in the previous sections are combined to express soil properties by a single value applicable for the whole soil over the root zone depth. The available data products (grids) together with metadata are listed in Annex 2. Summary statistics are given in Annex 3a and the associated histograms in Annex 3b (under the heading of final products). The next sections first give a few examples of soil properties and soil moisture retention expressed by a relative value (volumetric fraction) followed by the final product with soil moisture retention expressed by an absolute value (mm). The final product is summarised and explained by an overview (table) which gives the acreages (in km^2) for different classes for RZ-PAWHC (from 0-25 mm to 200-250 mm) combined with the acreages of the applicable root restricting soil factors.

Figure 13 shows the spatial distribution of the textural class of the root zone depth and of the volumetric moisture content at permanent wilting point of the fine earth of the root zone depth. The spatial patterns closely match and show that the sandier the soil is, the lower the value for the moisture content at PWP becomes.

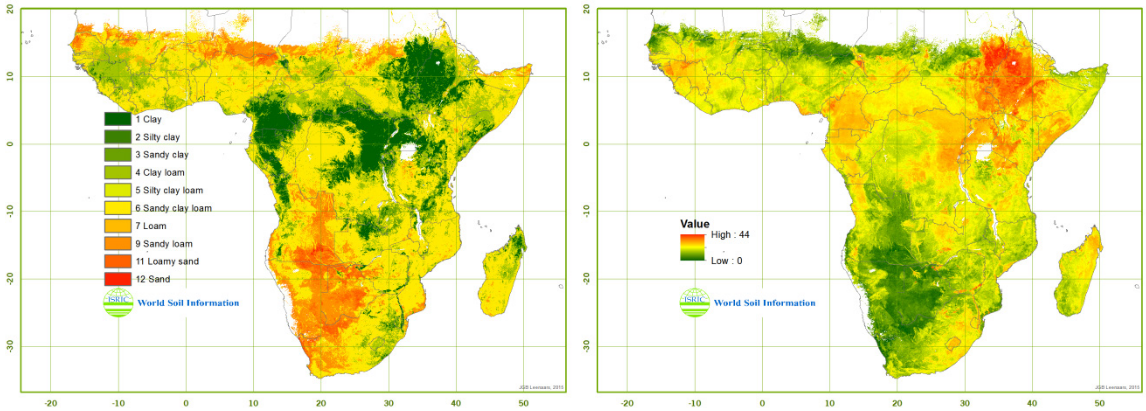

Figure 13
Textural class (left) and volumetric moisture content (v%) of the fine earth at permanent wilting point (right) of the root zone depth.

Figure 14 shows the map of the available water holding capacity of the root zone depth for the whole earth, including coarse fragments, plus the associated histogram. The mean AWHC of the root zone whole earth is 7.2 % (sdev = 1.4) with a range between 0 and 16 v%. Note from the histogram (also given in Annex 3b, Figure 33) that the range of predictions over the root zone depth is in fact limited to 3 - 11 v% only, for nearly all situations. The impact of coarse fragments on the AWHC of the whole earth is on average about 20% of the AWHC of the fine earth.

Note that the spatial pattern shown in Figure 14 does to a certain extent coincide with that for the water storage capacity suggested by Jones *et al.* (2013). Important differences occur as well. Figure 14 shows relatively high AWHC values for the Guinea/Sudan savannah zone stretching over west and central Africa, whereas Jones *et al.* (2013) give relatively low AWHC values (5 v%) in these areas. The gravel content predicted for this zone is relatively high, which smooths the spatial pattern for AWHC.

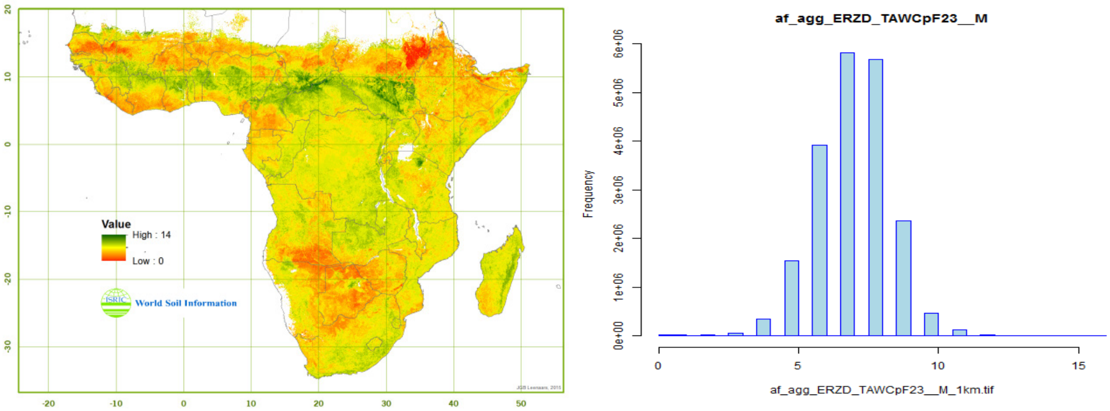

Figure 14
Available water holding capacity (v%) of the whole earth in the root zone depth and associated histograms (with y-axis 0-6 M km²).

The final result is given in Figure 15, which is the plant available water holding capacity of the effective soil volume in the root zone depth, expressed in mm. The mean predicted value for RZ-PAWHC is 73 mm (sdev = 39), with an almost similar median value and with a min-max range between 0 and 235 mm. The histogram in Annex 3b (24) shows that predictions above 150 mm rarely occur and that the predicted range is in fact rather narrow.

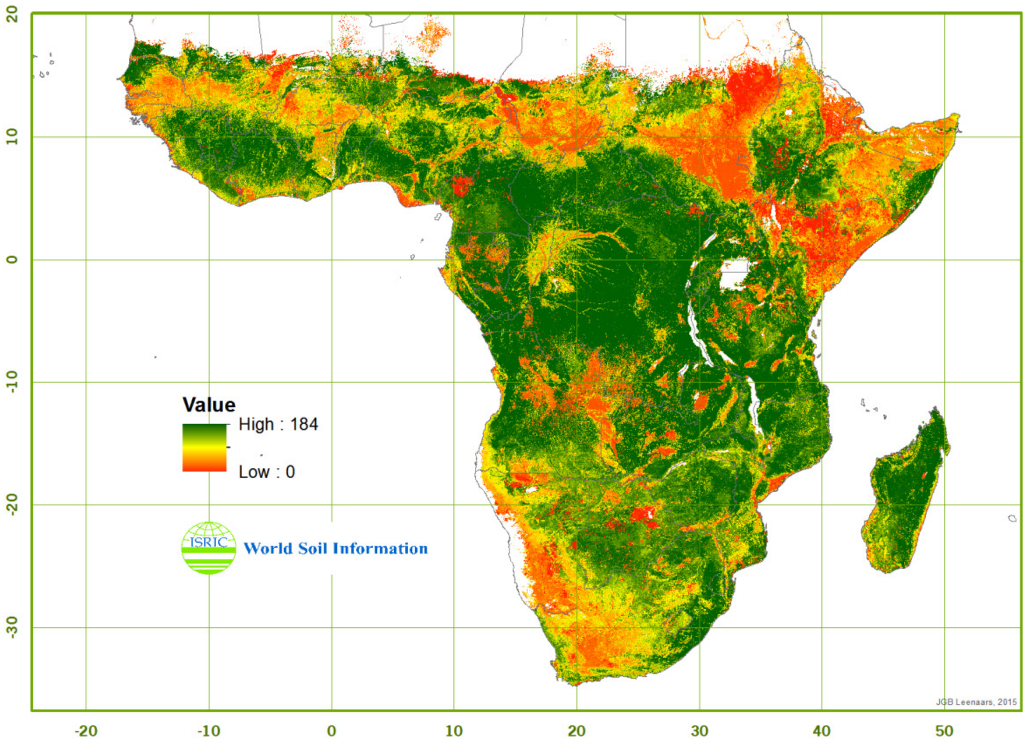

Figure 15
Root zone plant-available water holding capacity (mm).

The available grid map for RZ-PAWHC (mm) should be equal to the multiplication of the available grid maps for RZD (cm), PAWHC (v%) and volumetric fine earth fraction (v%)*1/1000. Because the available grid maps provide data by accident as truncated integers, rather than as rounded integers or with decimals, this is currently not the case.

Note that the variability of the absolute amount of soil water storage potentially available to the plant is predominantly determined by the depth of the soil in which the plant can root, followed by the content of coarse fragments (both defining the effective storage volume). The soil moisture retention characteristics of the fine earth have the least impact on the total amount of the plant available water storage capacity. However, the younger the plant is, the larger the relative impact of the latter characteristic becomes.

Table 9 summarises the extent (in km^2) and the degree (in mm) that RZ-PAWHC is limited by the various soil factors, and underlying soil properties, that limit root zone depth. As a general statement, RZ-PAWHC is limited to a small extent but large degree in cases that RZD is limited by a soil layer with a root restricting soil factor, as sodicity. RZ-PAWHC is limited to a large extent but small degree in cases that RZD is limited by depth of soil or depth of aerated soil.

Table 9

Soil area (km²) per RZ-PAWHC class specified per soil factor, and the mean RZ-PAWHC (and standard deviation) associated with each RZD-limiting soil factor

Soil factor	Soil variable	RZPAWHC 0-25	RZPAWHC 25-50	RZPAWHC 50-75	RZPAWHC 75-100	RZPAWHC 100-125	RZPAWHC 125-150	RZPAWHC 150-200	RZPAWHC 200-250	RZPAWHC 0-250 mm	RZPAWHC mean	RZPAWHC sd
		km²	km²	km²	km²	km²	km²	km²	km²	km²	mm	mm
Foothold (soil volume)	CfPc	0	0	0	0	0	0	0	0	0	-	-
Porosity	TetaS	46	0	2	0	0	0	0	0	48	6	12
Porosity	f.BD	50202	67793	5647	65	0	0	0	0	123707	26	14
Texture adequacy	Sand	1	7	7	0	36	84	7	0	142	121	28
Texture adequacy	f.Clay	0	0	0	0	0	0	0	0	0	-	-
Texture adequacy	f.Sand	0	0	0	0	0	0	0	0	0	-	-
Induration (cement.)	CaCO3	-	-	-	-	-	-	-	-	-	-	-
Induration (cement.)	CaSO4	-	-	-	-	-	-	-	-	-	-	-
Acidity	pH-H_2O	0	0	0	0	0	0	0	0	0	-	-
Alkalinity	pH-H_2O	14421	2211	517	367	16	1	0	0	17533	15	18
Salinity	EC	0	0	0	0	0	0	0	0	0	-	-
Sodicity	f.ExNa	-	-	-	-	-	-	-	-	-	4	-
Sodicity	ExNa	1460839	432776	67378	21724	3139	338	12	0	1986206	14	18
Toxicity	f.ExAcid	308725	74051	7910	753	686	163	0	0	392288	21	11
Toxicity	ExAcid	86398	435	658	195	45	1	0	0	87732	1	8
Depth of aerated soil	f.Drain	885805	1519707	2260051	1979793	703312	3649	0	0	7352317	62	30
Depth of soil	RockDpth	272300	847696	1123400	1748921	1060073	184827	4920	1	5242138	77	30
Maize max root depth	150 cm	2	19	101990	1124417	2343463	1553847	45378	2	5169118	113	18
Total (km²)		3078739	2944695	3567560	4876235	4110770	1742910	50317	3	20371229	73	39

4 Discussion and conclusions

This work resulted in a quantitative, spatially explicit, and consistent framework for assessing the plant-available water holding capacity of the root zone depth of Sub-Saharan African soil that can be relatively easily updated as more and higher quality geo-referenced soil data become available. This functional soil information is used to model and map yield potentials and yield gaps for major grain crops in Sub-Saharan Africa as part of the Global Yield Gap Atlas project (www.yieldgap.org).

Input soil data, soil property maps and derived functional soil information (gridded maps), as well as the parameterisation of the rules and thresholds to assess water retention and rootability, can easily be updated. Note that high demands are put on the computational capacity and efficiency but that the infrastructure is set in place so that updates indeed can be implemented and produced rapidly.

The framework allows to process soil data of fragmented and heterogeneous nature (originally generated by the use of various methods, standards and procedures), compiled from various sources and from various areas, into complete and consistent soil information (maps) which is applicable throughout Africa in a coherent manner.

Primary soil properties are mapped with an accuracy assessed from cross-validation. Results appear very promising. Based on the accuracy assessment combined with expert knowledge, it is concluded though that the accuracy of some soil properties need to be further improved. More input data, of possibly better quality or distribution, better identification of covariates and better prediction modelling techniques are needed. The extreme values measured, serving as input, appear to be not sufficiently well captured and represented by the predictions. The geostatistical way of soil mapping, and in some cases also conventional soil mapping, has a smoothening effect and this is an issue deserving attention for coming updates of the soil property maps. Relatively weak but key estimates are those related to soil volume (depth to bedrock, coarse fragments content and bulk density) due to limited data availability and data inaccuracies with coarse fragment contents derived from class values. Depth to bedrock and coarse fragments content are soil properties which are relatively easily observed in the field at low cost. For bulk density it is shown to be essential to consciously query the profiles database for excluding laboratory methods that measure the whole earth. It is worthwhile to consider mapping bulk density by applying PTF's to the grids, with PTF's validated on the profiles dataset. Also exchangeable sodium and electric conductivity proved difficult to predict, probably because of exceptionally high values in relatively small localised areas. More attention must be paid to search and find covariates that are likely relevant for predicting certain soil properties, based on soil scientific knowledge, including grids of relatively accurately mapped explanatory soil properties as clay content, pH or CEC. The introduction of a few additional covariates to support the updated predictions of sodicity, salinity and drainage proved relevant in this respect.

The predictions of water retention, by applying a pedotransfer function to the profiles database and to the grids, appear to be reasonably precise in terms of texture related absolute values. But the forms of the retention curves vary to a limited extent only and thus lead to values for available water holding capacity with little variation. This can be improved, for instance by adjusting the (Van Genuchten) parameters. The narrow range is probably also due to the narrow range, lacking extreme values, predicted by the underlying primary soil property grids.

Data availability does not permit to map and evaluate all soil factors and underlying soil properties, needed to assess the adequacy for root growth. For some soil factors and properties rules are hard to establish and parameterise robustly. Nevertheless, the framework includes a list of soil factors and associated soil properties, together with parameterised rules and threshold values. The parameterisation appears to be quite reliable for some properties, based on reasonably unambiguous data suggested by the literature, whereas it seems to be less reliable for other properties due to ambiguous data suggested by the literature and also due to possible misinterpretations. Many rules, applied to the layer data, are relevant only for rather extreme property values which did not occur on the maps. Consequently, such soil factors, as e.g. acidity (pH), are nowhere on the map identified as root restrictive. This in itself is valuable information too. The updateable framework permits to update the parameterisation of the rules and the threshold settings.

The current rules to estimate rootability are generic and are derived for maize. It is possible to derive parameters for other crops or crop groups. Further, the rules are scalable, with an index indicating the relative adequacy for rooting (0-100%) per soil layer. Instead of only assessing the maximal depth, i.e. the depth that limits the uptake capacity of the rooting system, as based on soil layer factors evaluated beyond a threshold index, it is also possible to assess the within root zone depth uptake capacity (comparable to root densities) based on the scaled indices.

We estimate the rooting depth as determined by four major depth parameters, i.e. (a) the genetic rooting depth potential of the crop, (b) the depth of soil, (c) the depth of aerated soil, and (d) the depth to the shallowest layer with a root restricting soil factor beyond the established threshold index. The main result from the applied procedure is that the first three depth parameters appear to dominate the outcomes, whereas most effort was put in developing the fourth parameter. This makes the procedure rather sensitive to possible errors in the maps with depth to bedrock and with drainage class, and to possible misinterpretations in the rule that relates drainage class to the depth to unaerated soil. Seven discrete depth classes, associated with the seven drainage classes mapped, are highly overrepresented in the frequency distribution and dominate the pattern of the root zone depth. Given this situation, it would be worthwhile to map an interpolated depth to unaerated soil from maps with interpolated ordinal drainage classes. Predicted root zone depth is on average 96 cm (standard deviation = 49).

Efforts to collect and compile additional soil profile data, either from existing data sources or new in the field, in support to updating the current estimate of root zone depth should include observations and measurements of the depth of soil (up to bedrock) and the depth of aeration in the soil (including drainage class and depth to groundwater) and, for each of the soil profile horizons, of the volumetric coarse fragments content, porosity, bulk density of the fine earth, texture (including sand, silt, clay contents) and abrupt textural changes, occurrence of cementation (CaCO3 and CaSO4 contents), acidity and alkalinity (pH-H_2O), salinity (EC), sodicity (exchangeable sodium content) and toxicity (contents of aluminium and others). Also relevant and sufficiently robust to map and parameterise, but not used in this study, are morphologic observations (expressed as boolean) on the presence of slickensides and of highly compacted and/or cemented layers such as a plow pan, duripan, iron pan, etc. Value would be added by collecting these data together with data on the actual root presence (or abundance) per soil layer or the actual rooted depth.

The predicted plant-available water holding capacity of the root zone whole earth, expressed as a volumetric fraction, is centred narrowly around 7.2 v% (with nearly all predictions in the range of 3 - 11 v%). The coarse fragments reduce the available water holding capacity with on average one-fifth. Expressed in absolute terms, the predicted plant-available water holding capacity of the root zone depth is on average 73 mm (standard deviation = 39 mm), with a nearly similar median value. There are practically no predictions in the range of 150 - 235 mm. The frequency distribution is somewhat irregular due to the irregular distribution of the underlying values for the root zone depth.

Concerning soil input data, an accurate evidence-based final product at high resolution (Africa soil property maps) is most cost-efficiently and rapidly produced on the basis of using a combination of legacy soil data and new soil data. Where the legacy soil data prove cost-efficient input for accurate mapping at especially reduced resolution, the accurately georeferenced and clustered new soil data are expensive but necessary as additional input to achieve an accurate high resolution. This conclusion is confirmed and illustrated by the updating of the SoilGrids product from 1km to 250m resolution for Sub-Saharan Africa, wherein legacy soil data and new soil data add value to each other. The current study builds on these achievements, and the legacy soil data and derived SoilGrids up to 200 cm depth prove particularly relevant for estimating and mapping root zone depth and, crucial for crop production and crop response to inputs, root zone plant-available water holding capacity.

Grain crop yields are strongly related to the RZ-PAWHC values in conditions where water supply from rain is uncertain and discontinuous, limiting crop production, and particularly when rainfall stops during the early grain filling period. Nutrient uptake efficiency as well as the plant's nutrient use efficiency, and thus the overall crop response to nutrient applications, are also related to the RZ-PAWHC in - common - conditions that water supply is suboptimal. Hence, experiments often show that measured grain yields are strongly related to the maximal plant available water capacity of the actually rooted depth under both fertilised and unfertilised conditions. A consistent framework for assessing soil fertility management practices thus considers both soil water and soil nutrient related properties. The framework and results here produced and reported contribute to that purpose.

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Acronyms

AfSIS	Africa Soil Information Service
AfSP	Africa Soil Profiles database
AfSS	Africa Sentinel Sites database
AGRA	Alliance for a Green Revolution in Africa
AWC	See PAWHC
AWHC	See PAWHC
BD	Bulk Density
BMGF	Bill and Melinda Gates Foundation
CfPc	Coarse fragments content
CEC	Cation Exchange Capacity
EC	Electric conductivity
ECEC	Effective Cation Exchange Capacity
ERZD	See RZD
ESP	Exchangeable Sodium Percentage
FC	Field Capacity
FTP	File Transfer Protocol
GSIF	Global Soil Information Facilities
GYGA	Global Yield Gap and water productivity Atlas
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ICRAF	World Agroforestry Centre
ICSU	International Counsil for Science
ISRIC	International Soil Reference and Information Centre
LDSF	Land Degradation Surveillance Framework
LRI	Limiting Rootability Index
PAWHC	Plant-Available Water Holding Capacity
PTF	Pedotransfer Function
PWP	Permanent Wilting Point
RZ-PAWHC	Roo Zone Plant-Available Water Holding Capacity
RZD	Root Zone Depth
SDEV	Standard Deviation
SOTER	Soil and Terrain database
SSA	Sub-Saharan Africa
TetaS	Soil porosity (or volumetric moisture content at saturation)
URL	Uniform Resource Locator
USDA	United States Department of Agriculture
VMC	Volumetric Moisture Content
WCS	Web Coverage Service
WISE	World Inventory of Soil Emission potentials / World Inventory of Soil property Estimates
WMS	Web Map Service

Annex 1a Metadata and script to assess AWHC using GSIF R package

METADATA
Global Soil Information Facilities (http://gsif.r-forge.r-project.org/).
http://gsif.r-forge.r-project.org/AWCPTF.html

AWCPTF {GSIF} R Documentation

Available soil water capacity

Description

Derive available soil water capacity (in cubic-meter per cubic-meter) based on a Pedo-Transfer Function developed using the Africa Soil Profile Database (Hodnett and Tomasella, 2002; Wösten *et al.* 2013).

Usage

AWCPTF(SNDPPT, SLTPPT, CLYPPT, ORCDRC,
BLD=1682, CEC, PHIHOX, h1=-10, h2=-20, h3=-31.6,
pwp=-1585, PTF.coef, fix.values=TRUE, print.coef=TRUE)

Arguments

SNDPPT	numeric; sand content in percent
SLTPPT	numeric; silt content in percent
CLYPPT	numeric; clay content in percent
ORCDRC	numeric; soil organic carbon concentration in permille or g / kg
BLD	numeric; bulk density in kg / cubic-meter for the horizon/solum
CEC	numeric; Cation Exchange Capacity in cmol per kilogram
PHIHOX	numeric; soil pH in water suspension
h1	numeric; moisture potential in kPa e.g. -10 (pF 2.0)
h2	numeric; moisture potential in kPa e.g. -20 (pF 2.3)
h3	numeric; moisture potential in kPa e.g. -31.6 (pF 2.5)
pwp	numeric; moisture potential at wilting point in kPa e.g. -1585 (pF 4.2)
PTF.coef	data.frame; optional conversion coefficients (Pedo-Transfer Function) with rows "ai1", "sand", "silt", "clay", "oc", "bd", "cec", "ph", "silt^2", "clay^2", "sand*silt", "sand*clay" and colums "lnAlfa", "lnN", "tetaS" and "tetaR" (see Wösten *et al.* 2013 for more details)
fix.values	logical; specifies whether to correct values of textures and bulk density to avoid creating nonsensical values
print.coef	logical; specifies whether to attach the PTF coefficients to the output object

Value

Returns a data frame with the following columns:
AWCh1: available soil water capacity (volumetric fraction) for h1;
AWCh2: available soil water capacity (volumetric fraction) for h2;
AWCh3: available soil water capacity (volumetric fraction) for h3;

WWP: available soil water capacity (volumetric fraction) at wilting point;
tetaS: saturated water content;

Note

Pedotransfer coefficients (PTF.coef) developed by Hodnett and Tomasella (2002). fix.values will correct sand, silt and clay fractions so they sum up to 100, and will replace bulk density values using global minimum maximum values.

Author(s)

Johan Leenaars, Maria Ruiperez Gonzalez and Tomislav Hengl

References

Hodnett, M. G., & Tomasella, J. (2002). Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: a new water-retention pedo-transfer functions developed for tropical soils. Geoderma, 108(3), 155-180.

Wösten, J. H. M., Verzandvoort, S. J. E., Leenaars, J. G. B., Hoogland, T., & Wesseling, J. G. (2013). Soil hydraulic information for river basin studies in semi-arid regions. Geoderma, 195, 79-86.

Examples

```
SNDPPT = 30
SLTPPT = 25
CLYPPT = 48
ORCDRC = 23
BLD = 1200
CEC = 12
PHIHOX = 6.4
x <- AWCPTF(SNDPPT, SLTPPT, CLYPPT, ORCDRC, BLD, CEC, PHIHOX)
str(x)
attr(x, "coef")

## predict AWC for AfSP DB profile:
data(afsp)
names(afsp$horizons)
## profile of interest:
sel <- afsp$horizons$SOURCEID=="NG 28440_Z5"
hor <- afsp$horizons[sel,]
## replace missing values:
BLDf <- ifelse(is.na(hor$BLD),
   mean(hor$BLD, na.rm=TRUE), hor$BLD)
hor <- cbind(hor, AWCPTF(hor$SNDPPT, hor$SLTPPT,
  hor$CLYPPT, hor$ORCDRC, BLD=BLDf*1000, hor$CEC,
  hor$PHIHOX))
str(hor)
```

R SCRIPT
https://github.com/cran/GSIF/blob/master/R/AWCPTF.R

```
# Purpose        : Available soil water capacity based on the Pedo-Transfer Function;
# Maintainer     : Tomislav Hengl (tom.hengl@wur.nl)
# Contributions : Johan Leenaars and Maria Ruiperez Gonzalez
# Dev Status     : Stable
# Note           : Formula available from [http://www.sciencedirect.com/science/article/pii/S001670611200417X]

AWCPTF <- function(SNDPPT, SLTPPT, CLYPPT, ORCDRC, BLD=1400, CEC, PHIHOX, h1=-10, h2=-20, h3=-31.6, pwp=-1585, PTF.coef, fix.values=TRUE, print.coef=TRUE){
 ## pedotransfer coefficients developed by Hodnett and Tomasella (2002)
 if(missing(PTF.coef)){
   PTF.coef <- data.frame(
     lnAlfa = c(-2.294, 0, -3.526, 0, 2.44, 0, -0.076, -11.331, 0.019, 0, 0, 0),
     lnN = c(62.986, 0, 0, -0.833, -0.529, 0, 0, 0.593, 0, 0.007, -0.014, 0),
     tetaS = c(81.799, 0, 0, 0.099, 0, -31.42, 0.018, 0.451, 0, 0, 0, -5e-04),
     tetaR = c(22.733, -0.164, 0, 0, 0, 0, 0.235, -0.831, 0, 0.0018, 0, 0.0026)
   )
 }
 ## standardize sand silt clay:
 if(fix.values){
   sum.tex <- CLYPPT+SLTPPT+SNDPPT
   CLYPPT <- CLYPPT/(sum.tex)*100
   SLTPPT <- SLTPPT/(sum.tex)*100
   SNDPPT <- SNDPPT/(sum.tex)*100
   BLD[BLD<100] <- 100
   BLD[BLD>2650] <- 2650  ## weight of quartz
 }
 ## rows:
 clm <- data.frame(SNDPPT, SLTPPT, CLYPPT, ORCDRC/10, BLD*0.001, CEC, PHIHOX, SLTPPT^2, CLYPPT^2, SNDPPT*SLTPPT, SNDPPT*CLYPPT)
 alfa <- apply(clm, 1, function(x){ exp((PTF.coef$lnAlfa[1] + sum(PTF.coef$lnAlfa[-1] * x))/100) })
 N <- apply(clm, 1, function(x){ exp((PTF.coef$lnN[1] + sum(PTF.coef$lnN[-1] * x))/100) })
 tetaS <- apply(clm, 1, function(x){ (PTF.coef$tetaS[1] + sum(PTF.coef$tetaS[-1] * x))/100 })
 tetaR <- apply(clm, 1, function(x){ (PTF.coef$tetaR[1] + sum(PTF.coef$tetaR[-1] * x))/100 })
 ## change negative of tetaR to 0
 tetaR[tetaR < 0] <- 0
 tetaS[tetaS > 100] <- 100
 m <- 1-1/N
 tetah1 <- tetaR + (tetaS-tetaR)/((1+(alfa*-1*h1)^N))^m
 tetah2 <- tetaR + (tetaS-tetaR)/((1+(alfa*-1*h2)^N))^m
 tetah3 <- tetaR + (tetaS-tetaR)/((1+(alfa*-1*h3)^N))^m
 WWP <- tetaR + (tetaS-tetaR)/((1+(alfa*-1*pwp)^N))^m
 if(fix.values){
   ## if any of the tetah values is smaller than WWP, then replace:
   sel <- which(WWP > tetah1 | WWP > tetah2 | WWP > tetah3)
   if(length(sel)>0){
```

```
      WWP[sel] <- apply(data.frame(tetah1[sel], tetah2[sel], tetah3[sel]), 1, function(x){min(x, na.rm=TRUE)})
      warning(paste("Wilting point capacity for", length(sel), "points higher than h1, h2 and/or h3"))
    }
  }
  AWCh1 <- tetah1 - WWP
  AWCh2 <- tetah2 - WWP
  AWCh3 <- tetah3 - WWP
  out <- data.frame(AWCh1=signif(AWCh1,3), AWCh2=signif(AWCh2,3), AWCh3=signif(AWCh3,3), WWP=signif(WWP,3), tetaS=signif(tetaS,3))
  if(print.coef==TRUE){
    attr(out, "coef") <- as.list(PTF.coef)
    attr(out, "PTF.names") <- list(variable=c("ai1", "sand", "silt", "clay", "oc", "bd", "cec", "ph", "silt^2", "clay^2", "sand*silt", "sand*clay"))
  }
  return(out)
}
```

Annex 1b Metadata and script to assess RZD using GSIF R package

METADATA
Global Soil Information Facilities (http://gsif.r-forge.r-project.org/).
http://gsif.r-forge.r-project.org/ERDICM.html

ERDICM {GSIF} R Documentation

Effective Rooting Zone depth

Description
Derive Effective Rooting Zone depth i.e. an effective depth suitable for plant growth. Usually minimum depth of soil out of three standard rooting depths: limiting soil properties, depth to water-stagnating layer and depth to bedrock.

Usage

```
ERDICM(UHDICM, LHDICM, minimum.LRI, DRAINFAO, BDRICM,
  threshold.LRI=20, srd=150, drain.depths, smooth.LRI=TRUE)
```

Arguments

`UHDICM`	numeric; upper horizon depth in cm
`LHDICM`	numeric; lower horizon depth in cm
`minimum.LRI`	numeric; minimum Limiting Rootability index
`DRAINFAO`	factor; FAO drainage class e.g. "V", "P", "I", "M", "W", "S", "E"
`BDRICM`	numeric; depth to bedrock in cm
`threshold.LRI`	numeric; treshold index for LRI
`srd`	numeric; maximum depth of interest
`drain.depths`	data.frame; estimate effective rooting depth per drainage class (`DRAINFAO`)
`smooth.LRI`	logical; specify whether to smooth LRI values using splines

Value
Returns a vector of effective rooting depth in cm.

Author(s)
Johan Leenaars, Maria Ruiperez Gonzalez and Tomislav Hengl

See Also
LRI

Annex 1c Script, with metadata, to assess LRI using GSIF R package

METADATA
Global Soil Information Facilities (http://gsif.r-forge.r-project.org/).
http://gsif.r-forge.r-project.org/LRI.html

LRI {GSIF} R Documentation

Limiting Rootability

Description
Derive Limiting Rootability <index> using observed soil properties at at least three depths.

Usage
```
LRI(UHDICM, LHDICM, SNDPPT, SLTPPT, CLYPPT, CRFVOL, BLD,
  ORCDRC, ECN, CEC, ENA, EACKCL, EXB, PHIHOX, CRB, GYP, tetaS,
  fix.values=TRUE, thresholds, print.thresholds=FALSE)
```

Arguments

UHDICM	numeric; upper horizon depth in cm
LHDICM	numeric; lower horizon depth in cm
SNDPPT	numeric; sand content in percent
SLTPPT	numeric; silt content in percent
CLYPPT	numeric; clay content in percent
CRFVOL	numeric; volume percentage of coarse fragments (> 2 mm)
BLD	numeric; bulk density in kg per cubic-meter for the horizon/solum
ORCDRC	numeric; soil organic carbon concentration in permille or g per kg
ECN	numeric; electrical conductivity in dS per m, of the unsaturated paste
CEC	numeric; Cation Exchange Capacity in cmolc per kilogram
ENA	numeric; exchangable Na in cmolc per kilogram
EACKCL	numeric; exchangable acidity in cmolc per kilogram
EXB	numeric; exchangable bases in cmolc per kilogram
PHIHOX	numeric; soil pH in water suspension
CRB	numeric; CaCO3 (carbonates) in g per kg (not used)
GYP	numeric; CaSO4 (gypsum) in g per kg (not used)
tetaS	numeric; volumetric percentage (optional; if not provided it will be derived using the AWCPTF Pedo-Transfer Function)
fix.values	logical; specifies whether to correct values of textures and bulk density to avoid creating nonsensical values
thresholds	data.frame; optional table containing threshold values for "CRFVOL", "tetaS" (volumetric

percentage), "BLD.f" (clay-adjusted BLD), "SNDPPT", "CLY.d" (difference in clay between horizons), "SND.d" (difference in sand between horizons), "PHIHOX.L" (lower limits for pH), "PHIHOX.H" (upper limits for pH), "ECN", "ENA.f" (exchangable saturated Na), "ENA", "EACKCL.f" (exchangable saturated acidity), "CRB" (carbonates), and "GYP" (gypsum)

print.thresholds logical; specifies whether to attach the threshold values to the output object

Value

Returns a vector with TRUE / FALSE values where FALSE indicates rooting not possible. Threshold values used to derive Limiting Rootability scores are set based on common soil agricultural productivity tresholds (e.g. in this case for maize), and can be adjusted via the thresholds argument. This functions also accounts for textural changes (sudden changes in sand and clay content) and porosity (derived from water content at saturation).

Note

Horizons need to be sorted by depth e.g. 0-5, 5-15, 15-30... For each soil property at least three depths are needed otherwise the function reports an error. Missing values are automatically replaced using smoothing splines.

Author(s)

Johan Leenaars and Maria Ruiperez Gonzalez

See Also

AWCPTF, ERDICM

Examples

```
## sample profile from Nigeria (ISRIC:NG0017):
UHDICM = c(0, 18, 36, 65, 87, 127)
LHDICM = c(18, 36, 65, 87, 127, 181)
SNDPPT = c(66, 70, 54, 43, 35, 47)
SLTPPT = c(13, 11, 14, 14, 18, 23)
CLYPPT = c(21, 19, 32, 43, 47, 30)
CRFVOL = c(17, 72, 73, 54, 19, 17)
BLD = c(1.57, 1.60, 1.52, 1.50, 1.40, 1.42)*1000
PHIHOX = c(6.5, 6.9, 6.5, 6.2, 6.2, 6.0)
CEC = c(9.3, 4.5, 6.0, 8.0, 9.4, 10.9)
ENA = c(0.1, 0.1, 0.1, 0.1, 0.1, 0.2)
EACKCL = c(0.1, 0.1, 0.1, NA, NA, 0.5)
EXB = c(8.9, 4.0, 5.7, 7.4, 8.9, 10.4)
ORCDRC = c(18.4, 4.4, 3.6, 3.6, 3.2, 1.2)
x <- LRI(UHDICM=UHDICM, LHDICM=LHDICM, SNDPPT=SNDPPT,
  SLTPPT=SLTPPT, CLYPPT=CLYPPT, CRFVOL=CRFVOL,
  BLD=BLD, ORCDRC=ORCDRC, CEC=CEC, ENA=ENA, EACKCL=EACKCL,
  EXB=EXB, PHIHOX=PHIHOX, print.thresholds=TRUE)
x
## Most limiting: BLD.f and CRFVOL, but nothing < 20

## Effective Rootable Depth:
sel <- x==FALSE
if(!all(sel==FALSE)){
```

```
  UHDICM[which(sel==TRUE)[1]]
} else {
  max(LHDICM)
}

xl <- attr(x, "minimum.LRI")
## derive Effective rooting depth:
ERDICM(UHDICM=UHDICM, LHDICM=LHDICM, minimum.LRI=xl, DRAINFAO="M")
```

R SCRIPT
https://github.com/cran/GSIF/blob/master/R/LRI.R

```
# Purpose        : Limiting Rootability index / Effective Rootable Depth;
# Maintainer     : Tomislav Hengl (tom.hengl@wur.nl)
# Contributions : Johan Leenaars and Maria Ruiperez Gonzalez
# Dev Status     : Stable
# Note           : Empirical formula by J. Leenaars; threshold values need to be fine-tuned;


.EffR <- function(x, hdepth, a0, b0, trend, r1, r2){
  ## replace missing values using smoothing spline:
   na.x <- is.na(x)
   if(sum(na.x)>0){
     x.f <- smooth.spline(hdepth[!na.x], x[!na.x], spar=0.05)
     x[which(na.x)] <- predict(x.f, hdepth[na.x])$y
   }
   x.f <- a0*x + b0
   trend <- rep(trend, length(x))
   EffR <- ifelse(trend==-1, ifelse(x < r1, 100, ifelse(x > r2, 0, x.f)), ifelse(x > r1, 100, ifelse(x < r2, 0, x.f)))
   return(EffR)
}


LRI <- function(UHDICM, LHDICM, SNDPPT, SLTPPT, CLYPPT, CRFVOL, BLD, ORCDRC, ECN, CEC, ENA, EACKCL, EXB, PHIHOX, CRB, GYP, tetaS, fix.values=TRUE, thresholds, print.thresholds=FALSE){

   if(length(UHDICM)<3){ stop("At least three horizons required for comparison") }
   rn <- c("range", "CRFVOL", "tetaS", "BLD.f", "SNDPPT", "CLY.d", "SND.d", "PHIHOX.L", "PHIHOX.H", "ECN", "ENA.f", "ENA", "EACKCL.f", "EACKCL", "CRB", "GYP")
   if(missing(thresholds)){
     thresholds <- data.frame(
      ERscore1 = c(100, 80, 50, 0, 95, 40, 40, 5.5, 7.8, 1.5, 10, 1, 35, 2.5, 150, 150),
      ERscore2 = c(0, 90, 30, 0.35, 100, 60, 60, 3.625, 9.05, 6.75, 25, 5, 85, 6.5, 750, 750),
      Trend = c(0, -1, 1, -1, -1, -1, -1, 1, -1, -1, -1, -1, -1, -1, -1, -1),
      Score = 20
     )
     row.names(thresholds) <- rn
   } else {
     if(any(!row.names(thresholds) %in% rn)){
       stop("Inconsistent row names. See '?LRI' for more details.")
     }
   }
if(all(is.na(CLYPPT))|all(is.na(CRFVOL))|all(is.na(SNDPPT))|all(is.na(CEC))|all(is.na(ENA))|all(is.na(EACKCL))|all(is.na(PHIHOX))){
     out <- rep(NA, length(UHDICM))
   } else {
     ## missing values:
     if(missing(BLD)){ BLD <- rep(1400, length(UHDICM)) }
```

```
if(missing(ECN)){ ECN <- rep(0.1, length(UHDICM)) }
if(missing(CRB)){ CRB <- rep(0, length(UHDICM)) }
if(missing(GYP)){ GYP <- rep(0, length(UHDICM)) }

if(fix.values){
  ## must be equal size:
  lst.s <- sapply(list(UHDICM, LHDICM, SNDPPT, SLTPPT, CLYPPT, CRFVOL, BLD, ORCDRC, ECN, CEC, ENA, EACKCL, EXB, PHIHOX, CRB, GYP), length)
  if(sd(lst.s)>0){
    stop("Vectors of non-constant length provided")
  }
  if(any(diff(UHDICM)<0)){ stop("Sorted values for 'UHDICM' required") }
  if(any(UHDICM > LHDICM)){
    stop("All 'UHDICM' depths must contain lower values than 'LHDICM' depths")
  }
  sum.tex <- CLYPPT+SLTPPT+SNDPPT
  CLYPPT <- CLYPPT/(sum.tex)*100
  SLTPPT <- SLTPPT/(sum.tex)*100
  SNDPPT <- SNDPPT/(sum.tex)*100
  BLD[BLD<100] <- 100
  BLD[BLD>2650] <- 2650  ## weight of quartz
}

## difference per horizon:
hdepth <- (UHDICM+LHDICM)/2
CLY.d <- c(0, diff(CLYPPT))
SND.d <- c(0, diff(SNDPPT))
## Derive tetaS (volumetric percentage):
if(missing(tetaS)){
  tetaS <- 100*AWCPTF(SNDPPT, SLTPPT, CLYPPT, ORCDRC, BLD, CEC, PHIHOX)$tetaS
}

## FAO Guidelines for soil description p.51:
BLD.f <- BLD/1000 - (1.6-(0.0035*CLYPPT))
## Exchangable saturated acidity
EACKCL.f <- EACKCL*100/(EXB+EACKCL)
ENA.f <- ENA*100/CEC
PHIHOX.H <- PHIHOX.L <- PHIHOX
## coefficients:
a <- 100/(thresholds$ERscore1 - thresholds$ERscore2)
b <- 100 - (a*thresholds$ERscore1)
Y <- list(NULL)
for(i in 2:length(rn)){
  Y[[i-1]] <- .EffR(get(rn[i]), hdepth=hdepth, a0=a[i], b0=b[i], trend=thresholds[i,"Trend"], r1=thresholds[i,"ERscore1"], r2=thresholds[i,"ERscore2"])
}
names(Y) <- rn[-1]
Y <- as.data.frame(Y)
out <- NULL
for(i in 1:nrow(Y)){
```

```
      out[i] <- ifelse(any(Y[i,]<=thresholds$Score[i]), FALSE, TRUE)
    }
  }
  if(!all(is.na(out))){
    attr(out, "minimum.LRI") <- signif(apply(Y, 1, function(x){ min(x, na.rm=TRUE)}), 3)
    attr(out, "most.limiting.factor") <- apply(Y, 1, function(x){ names(Y)[which(x == min(x, na.rm=TRUE))[1]]})
  } else {
    attr(out, "minimum.LRI") <- rep(NA, length(UHDICM))
    attr(out, "most.limiting.factor") <- rep(NA, length(UHDICM))
  }
  if(print.thresholds==TRUE){
    attr(out, "thresholds") <- as.list(thresholds)
    attr(out, "thresholds.names") <- list(variable=rn)
  }
  return(out)
}


ERDICM <- function(UHDICM, LHDICM, minimum.LRI, DRAINFAO, BDRICM, threshold.LRI=20, srd=150, drain.depths, smooth.LRI=TRUE){

  if(length(UHDICM)<3){ stop("At least three horizons required for comparison") }
  if(missing(BDRICM)){ BDRICM <- srd }

  if(all(is.na(UHDICM))|all(is.na(LHDICM))|all(is.na(minimum.LRI))){
    out <- NA
  } else {

    if(smooth.LRI==TRUE){
      ## estimate rooting depth using spline:
      hdepth <- (UHDICM+LHDICM)/2
      if(all(minimum.LRI > threshold.LRI)){
        mdepth0 <- max(LHDICM)
      } else {
        x.f <- smooth.spline(hdepth, minimum.LRI, spar=0.05)
        mdepth0 <- min(which(predict(x.f, 1:200)$y < threshold.LRI), na.rm=TRUE)
        if(is.null(mdepth0)){
          mdepth0 <- NA
        }
      }
    } else {
      sel <- ifelse(any(minimum.LRI<=threshold.LRI), FALSE, TRUE)==FALSE
      if(!all(sel==FALSE)){
        mdepth0 <- UHDICM[which(sel==TRUE)[1]]
      } else {
        mdepth0 <- max(LHDICM)
      }
```

```
    }

    if(missing(drain.depths)){
      drain.depths <- data.frame(
      levs = c("V", "P", "I", "M", "W", "S", "E"),
      mdepth = c(5,30,60,100,150,200,250)
      )
    }
    ## get effective depths per drainage class:
    suppressMessages( mdepth1 <- plyr::join(data.frame(levs=DRAINFAO), drain.depths, type="left", match="first")$mdepth )

    out <- min(c(mdepth0, mdepth1, BDRICM, srd), na.rm=TRUE)

  }
  return(out)
}
```

Annex 2a RZ-PAWHC metadata (grid name descriptions)

FileName	SeriesName	Attribute description
af_BDRICM_T__M_1km.tif	GYGA_Inputs	Depth (cm) to bedrock (R horizon) or to over 90 % coarse fragments, up to maximum 175 cm
af_BLD_T__M_sd1_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 2.5 cm depth
af_BLD_T__M_sd2_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 10 cm depth
af_BLD_T__M_sd3_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 22.5 cm depth
af_BLD_T__M_sd4_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 45 cm depth
af_BLD_T__M_sd5_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 80 cm depth
af_BLD_T__M_sd6_1km.tif	GYGA_Inputs	Bulk density (kg / cubic-m) of the fine earth, at 150 cm depth
af_CEC_T__M_sd1_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 2.5 cm depth
af_CEC_T__M_sd2_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 10 cm depth
af_CEC_T__M_sd3_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 22.5 cm depth
af_CEC_T__M_sd4_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 45 cm depth
af_CEC_T__M_sd5_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 80 cm depth
af_CEC_T__M_sd6_1km.tif	GYGA_Inputs	Cation exchange capacity (cmolc / kg) of the fine earth, at 150 cm depth
af_CLYPPT_T__M_sd1_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 2.5 cm depth
af_CLYPPT_T__M_sd2_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 10 cm depth
af_CLYPPT_T__M_sd3_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 22.5 cm depth

FileName	SeriesName	Attribute description
af_CLYPPT_T__M_sd4_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 45 cm depth
af_CLYPPT_T__M_sd5_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 80 cm depth
af_CLYPPT_T__M_sd6_1km.tif	GYGA_Inputs	Clay content (w%) of the fine earth, at 150 cm depth
af_CRFVOL_T__M_sd1_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 2.5 cm depth
af_CRFVOL_T__M_sd2_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 10 cm depth
af_CRFVOL_T__M_sd3_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 22.5 cm depth
af_CRFVOL_T__M_sd4_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 45 cm depth
af_CRFVOL_T__M_sd5_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 80 cm depth
af_CRFVOL_T__M_sd6_1km.tif	GYGA_Inputs	Coarse fragments content (v%) of the whole earth, at 150 cm depth
af_DRAINFAO_T__M_1km.tif	GYGA_Inputs	Drainage class of the soil profile (FAO)
af_EACKCL_T__M_sd1_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 2.5 cm depth
af_EACKCL_T__M_sd2_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 10 cm depth
af_EACKCL_T__M_sd3_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 22.5 cm depth
af_EACKCL_T__M_sd4_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 45 cm depth
af_EACKCL_T__M_sd5_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 80 cm depth
af_EACKCL_T__M_sd6_1km.tif	GYGA_Inputs	Exchangeable acidity (cmolc / kg) of the fine earth, at 150 cm depth
af_ECN_T__M_sd1_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 2.5 cm depth
af_ECN_T__M_sd2_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 10 cm depth
af_ECN_T__M_sd3_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 22.5 cm depth
af_ECN_T__M_sd4_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 45 cm depth

FileName	SeriesName	Attribute description
af_ECN_T__M_sd5_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 80 cm depth
af_ECN_T__M_sd6_1km.tif	GYGA_Inputs	Electrical conductivity (dS / m) of unsaturated paste of the fine earth, at 150 cm depth
af_ENAX_T__M_sd1_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 2.5 cm depth
af_ENAX_T__M_sd2_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 10 cm depth
af_ENAX_T__M_sd3_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 22.5 cm depth
af_ENAX_T__M_sd4_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 45 cm depth
af_ENAX_T__M_sd5_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 80 cm depth
af_ENAX_T__M_sd6_1km.tif	GYGA_Inputs	Exchangeable sodium (cmolc / kg) of the fine earth, at 150 cm depth
af_EXBX_T__M_sd1_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 2.5 cm depth
af_EXBX_T__M_sd2_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 10 cm depth
af_EXBX_T__M_sd3_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 22.5 cm depth
af_EXBX_T__M_sd4_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 45 cm depth
af_EXBX_T__M_sd5_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 80 cm depth
af_EXBX_T__M_sd6_1km.tif	GYGA_Inputs	Exchangeable bases (cmolc / kg) of the fine earth, at 150 cm depth
af_ORCDRC_T__M_sd1_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 2.5 cm depth
af_ORCDRC_T__M_sd2_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 10 cm depth
af_ORCDRC_T__M_sd3_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 22.5 cm depth
af_ORCDRC_T__M_sd4_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 45 cm depth
af_ORCDRC_T__M_sd5_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 80 cm depth
af_ORCDRC_T__M_sd6_1km.tif	GYGA_Inputs	Organic carbon content (g / kg) of the fine earth, at 150 cm depth

FileName	SeriesName	Attribute description
af_PHIHOX_T__M_sd1_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 2.5 cm depth
af_PHIHOX_T__M_sd2_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 10 cm depth
af_PHIHOX_T__M_sd3_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 22.5 cm depth
af_PHIHOX_T__M_sd4_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 45 cm depth
af_PHIHOX_T__M_sd5_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 80 cm depth
af_PHIHOX_T__M_sd6_1km.tif	GYGA_Inputs	pH (x 10) of soil-water solution, at 150 cm depth
af_SLTPPT_T__M_sd1_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 2.5 cm depth
af_SLTPPT_T__M_sd2_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 10 cm depth
af_SLTPPT_T__M_sd3_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 22.5 cm depth
af_SLTPPT_T__M_sd4_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 45 cm depth
af_SLTPPT_T__M_sd5_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 80 cm depth
af_SLTPPT_T__M_sd6_1km.tif	GYGA_Inputs	Silt content (w%) of the fine earth, at 150 cm depth
af_SNDPPT_T__M_sd1_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 2.5 cm depth
af_SNDPPT_T__M_sd2_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 10 cm depth
af_SNDPPT_T__M_sd3_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 22.5 cm depth
af_SNDPPT_T__M_sd4_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 45 cm depth
af_SNDPPT_T__M_sd5_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 80 cm depth
af_SNDPPT_T__M_sd6_1km.tif	GYGA_Inputs	Sand content (w%) of the fine earth, at 150 cm depth
AfSP012Qry_GYGA	GYGA_Inputs	Africa Soil Profiles Database (AfSP), incl. data filtered for BD and EC for 2nd run
af_AWCpF23__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 2.5 cm depth, with field capacity defined at pF 2.3

FileName	SeriesName	Attribute description
af_AWCpF23__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 10 cm depth, with field capacity defined at pF 2.3
af_AWCpF23__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 22.5 cm depth, with field capacity defined at pF 2.3
af_AWCpF23__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 45 cm depth, with field capacity defined at pF 2.3
af_AWCpF23__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 80 cm depth, with field capacity defined at pF 2.3
af_AWCpF23__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	Available water capacity (v%) of the fine earth, at 150 cm depth, with field capacity defined at pF 2.3
af_PWP__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 2.5 cm depth, with PWP defined at pF 4.2
af_PWP__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 10 cm depth, with PWP defined at pF 4.2
af_PWP__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 22.5 cm depth, with PWP defined at pF 4.2
af_PWP__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 45 cm depth, with PWP defined at pF 4.2
af_PWP__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 80 cm depth, with PWP defined at pF 4.2
af_PWP__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at permanent wilting point, at 150 cm depth, with PWP defined at pF 4.2
af_TETAs__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 2.5 cm depth
af_TETAs__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 10 cm depth
af_TETAs__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 22.5 cm depth
af_TETAs__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 45 cm depth
af_TETAs__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 80 cm depth
af_TETAs__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	Moisture content (v%) of the fine earth at saturation, at 150 cm depth
AfSP012Qry_AWC_PTF_Layers_texture classesAnalysis.xlsx	GYGA_Intermediate_results_AWC	Africa Soil Profiles Database (AfSP) - PTF applied to assess BD, VMC(-psi) and AWC of Profile Layers and per textural class
af_ERZD_rules_Update.xlsx	GYGA_Intermediate_Results_ERZD	Rules applied to assess ERZD
af_LIMFACTOR_T__M_sd1_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 2.5 cm depth

FileName	SeriesName	Attribute description
af_LIMFACTOR_T__M_sd2_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 10 cm depth
af_LIMFACTOR_T__M_sd3_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 22.5 cm depth
af_LIMFACTOR_T__M_sd4_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 45 cm depth
af_LIMFACTOR_T__M_sd5_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 80 cm depth
af_LIMFACTOR_T__M_sd6_1km.tif	GYGA_Intermediate_Results_ERZD	Factor (soil quality) Limiting Rootability, at 150 cm depth
af_LRI_T__M_sd1_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 2.5 cm depth
af_LRI_T__M_sd2_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 10 cm depth
af_LRI_T__M_sd3_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 22.5 cm depth
af_LRI_T__M_sd4_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 45 cm depth
af_LRI_T__M_sd5_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 80 cm depth
af_LRI_T__M_sd6_1km.tif	GYGA_Intermediate_Results_ERZD	Limited Rootability Index (0-100), at 150 cm depth
af_agg_30cm_AWCpF23__M_1km.tif	GYGA_results	Available water capacity (v%) of the fine earth, aggregated over the top 30 cm, with field capacity defined at pF 2.3
af_agg_30cm_CRFVOL__M_1km.tif	GYGA_results	Coarse fragments content (v%) of the whole earth, aggregated over the top 30 cm
af_agg_30cm_PWP__M_1km.tif	GYGA_results	Moisture content (v%) of the fine earth at permanent wilting point, aggregated over the top 30 cm, with PWP defined at pF 4.2
af_agg_30cm_TAWCpF23__M_1km.tif	GYGA_results	Total available water capacity (v%) of the whole earth (incl. both fine earth and coarse fragments), aggregated over the top 30 cm, with field capacity defined at pF 2.3
af_agg_30cm_TAWCpF23mm__M_1km.tif	GYGA_results	Absolute total available water capacity (mm), aggregated over the top 30 cm
af_agg_30cm_TETAs__M_1km.tif	GYGA_results	Moisture content (v%) of the fine earth at saturation, aggregated over the top 30 cm
af_agg_30cm_TEXCLSS__M_1km.tif	GYGA_results	Textural class (USDA) of the fine earth, aggregated over the top 30 cm
af_agg_ERZD_AWCpF23__M_1km.tif	GYGA_results	Available water capacity (v%) of the fine earth, aggregated over the Effective Root Zone Depth for Maize, with field capacity defined at pF 2.3
af_agg_ERZD_CRFVOL__M_1km.tif	GYGA_results	Coarse fragments content (v%) of the whole earth, aggregated over the Effective Root Zone Depth for Maize

FileName	SeriesName	Attribute description
af_agg_ERZD_PWP__M_1km.tif	GYGA_results	Moisture content (v%) of the fine earth at permanent wilting point, aggregated over the Effective Root Zone Depth for Maize, with PWP defined at pF 4.2
af_agg_ERZD_TAWCpF23__M_1km.tif	GYGA_results	Total available water capacity (v%) of the whole earth (incl. both fine earth and coarse fragments), aggregated over the Effective Root Zone Depth for Maize, with field capacity defined at pF 2.3
af_agg_ERZD_TAWCpF23mm__M_1km.tif	GYGA_results	Absolute total available water capacity (mm) of the whole earth, aggregated over the Effective Root Zone Depth for Maize, with field capacity defined at pF 2.3
af_agg_ERZD_TETAs__M_1km.tif	GYGA_results	Moisture content (v%) of the fine earth at saturation, aggregated over the Effective Root Zone Depth for Maize
af_agg_ERZD_TEXCLSS__M_1km.tif	GYGA_results	Textural class (USDA) of the fine earth, aggregated over the Effective Root Zone Depth for Maize
af_ERZD__M_1km.tif	GYGA_results	Effective Root Zone Depth (cm) for Maize
af_ERZD_LIMFACTOR__M_1km.tif	GYGA_results	Factor (soil quality) limiting Effective Root Zone Depth for Maize
af_ERZD_LIMFACTOR_legend_complete.csv	GYGA_results	Legend Factor Limiting ERZD
TEXCLSS_legend.csv	GYGA_results	Legend Textural class (USDA)

Annex 2b RZ-PAWHC metadata (grid details)

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_BDRICM_T__M_1km.tif	GYGA_Inputs	None	None	None	cm	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_BLD_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	kg / m³	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CEC_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CLYPPT_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CLYPPT_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CLYPPT_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_CLYPPT_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CLYPPT_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CLYPPT_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_CRFVOL_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	v%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_DRAINFAO_T__M_1km.tif	GYGA_Inputs	None	None	None	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EACKCL_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ECN_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ECN_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ECN_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ECN_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_ECN_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ECN_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	dS / m	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_ENAX_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	cmolc / kg	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_EXBX_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	cmolc / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_ORCDRC_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	g / kg	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_PHIHOX_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_PHIHOX_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_PHIHOX_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_PHIHOX_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_PHIHOX_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_PHIHOX_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	index*10	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SLTPPT_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd1_1km.tif	GYGA_Inputs	sd1	0.00 m	0.05 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd2_1km.tif	GYGA_Inputs	sd2	0.05 m	0.15 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd3_1km.tif	GYGA_Inputs	sd3	0.15 m	0.30 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd4_1km.tif	GYGA_Inputs	sd4	0.30 m	0.60 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd5_1km.tif	GYGA_Inputs	sd5	0.60 m	1.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
af_SNDPPT_T__M_sd6_1km.tif	GYGA_Inputs	sd6	1.00 m	2.00 m	w%	LAEA -m WGS84	1000 m	resampled from 250 m	ftp://gyga:gygagyga@ftp.isric.org
AfSP012Qry_GYGA	GYGA_Inputs	–	–	–	–	–	–	–	ftp://gyga:gygagyga@ftp.isric.org
DRAINAGE_legend.csv	GYGA_Inputs	–	–	–	–	–	–	–	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_AWCpF23__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	sd1	0.00 m	0.05 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_AWCpF23__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	sd2	0.05 m	0.15 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_AWCpF23__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	sd3	0.15 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_AWCpF23__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	sd4	0.30 m	0.60 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_AWCpF23__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	sd5	0.60 m	1.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_AWCpF23__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	sd6	1.00 m	2.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	sd1	0.00 m	0.05 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	sd2	0.05 m	0.15 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	sd3	0.15 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	sd4	0.30 m	0.60 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	sd5	0.60 m	1.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_PWP__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	sd6	1.00 m	2.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd1_1km.tif	GYGA_Intermediate_results_AWC	sd1	0.00 m	0.05 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd2_1km.tif	GYGA_Intermediate_results_AWC	sd2	0.05 m	0.15 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd3_1km.tif	GYGA_Intermediate_results_AWC	sd3	0.15 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd4_1km.tif	GYGA_Intermediate_results_AWC	sd4	0.30 m	0.60 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd5_1km.tif	GYGA_Intermediate_results_AWC	sd5	0.60 m	1.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_TETAs__M_sd6_1km.tif	GYGA_Intermediate_results_AWC	sd6	1.00 m	2.00 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
AfSP012Qry_AWC_PTF_Layers_textureclassesAnalysis.xlsx	GYGA_Intermediate_results_AWC	–	–	–	–	–	–	–	ftp://gyga:gygagyga@ftp.isric.org
af_ERZD_rules_Update.xlsx	GYGA_Intermediate_results_ERZD	–	–	–	–	–	–	–	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_LIMFACTOR_T__M_sd1_1km.tif	GYGA_Intermediate_results_ERZD	sd1	0.00 m	0.05 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LIMFACTOR_T__M_sd2_1km.tif	GYGA_Intermediate_results_ERZD	sd2	0.05 m	0.15 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LIMFACTOR_T__M_sd3_1km.tif	GYGA_Intermediate_results_ERZD	sd3	0.15 m	0.30 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LIMFACTOR_T__M_sd4_1km.tif	GYGA_Intermediate_results_ERZD	sd4	0.30 m	0.60 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LIMFACTOR_T__M_sd5_1km.tif	GYGA_Intermediate_results_ERZD	sd5	0.60 m	1.00 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LIMFACTOR_T__M_sd6_1km.tif	GYGA_Intermediate_results_ERZD	sd6	1.00 m	2.00 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd1_1km.tif	GYGA_Intermediate_results_ERZD	sd1	0.00 m	0.05 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd2_1km.tif	GYGA_Intermediate_results_ERZD	sd2	0.05 m	0.15 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd3_1km.tif	GYGA_Intermediate_results_ERZD	sd3	0.15 m	0.30 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd4_1km.tif	GYGA_Intermediate_results_ERZD	sd4	0.30 m	0.60 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd5_1km.tif	GYGA_Intermediate_results_ERZD	sd5	0.60 m	1.00 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_LRI_T__M_sd6_1km.tif	GYGA_Intermediate_results_ERZD	sd6	1.00 m	2.00 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_AWCpF23__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_CRFVOL__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_PWP__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_TAWCpF23__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_TAWCpF23mm__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	mm	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_TETAs__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_30cm_TEXCLSS__M_1km.tif	GYGA_results	Aggregated	0.00 m	0.30 m	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org
af_agg_ERZD_AWCpF23__M_1km.tif	GYGA_results	Aggregated	0.00 m	ERZD	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyga@ftp.isric.org

FileName	SeriesName	Depth interval	Lyr Up depth	Lyr Low depth	Units of measure	Geo-Ref	Spatial resolute	Pre-process	Download FTP URL
af_agg_ERZD_CRFVOL__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_agg_ERZD_PWP__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_agg_ERZD_TAWCpF23__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_agg_ERZD_TAWCpF23mm__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	mm	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_agg_ERZD_TETAs__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	v%	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_agg_ERZD_TEXCLSS__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_ERZD__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	cm	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_ERZD_LIMFACTOR__M_1km.tif	GYGA_results	Aggre gated	0.00 m	ERZD	–	LAEA -m WGS84	1000 m	rerun in 1km, 04-2015	ftp://gyga:gygagyg a@ftp.isric.org
af_ERZD_LIMFACTOR_legend_complete. csv	GYGA_results	–	–	–	–	–	–	–	ftp://gyga:gygagyg a@ftp.isric.org
TEXCLSS_legend.csv	GYGA_results	–	–	–	–	–	–	–	ftp://gyga:gygagyg a@ftp.isric.org

LAEA -m WGS84. Datum is WGS84, projection is Lambert Azimuth Equal Area, coordinates in meters.

Annex 2c RZ-PAWHC ftp conversion table

Download FTP URL	SeriesName	FileName	Download FTP URL	SeriesName	FileName
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Inputs/AfSP012Qry_ GYGA/	AfSP012Qry_Profiles.dbf	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/inputs/	AfSP012Qry_Profiles.dbf
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Inputs/AfSP012Qry_ GYGA/	AfSP012Qry_Layers.dbf	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/inputs/	AfSP012Qry_Layers.dbf
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Inputs/	*tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	*tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Inputs/	DRAINAGE_legend.csv	N/A	N/A	N/A
N/A	N/A	N/A	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/recent/	*_250m.tif (including not-recent versions)
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ AWC/	af_AWCpF23__M_sd1-6_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_AWCh2__M_sd1-6_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ AWC/	af_PWP__M_sd1-6_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_WWP__M_sd1-6_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ AWC/	af_TETAs__M_sd1-6_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_tetaS__M_sd1-6_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ AWC/	AfSP012Qry_AWC_PTF_Layers_texture classesAnalysis.xlsx	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/inputs/	AfSP012Qry_AWC_PTF_Layers_texture classesAnalysis.xlsx
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ ERZD/	af_ERZD_rules_Update.xlsx	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_ERZD_rules_Update.xlsx
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ ERZD/	af_ERZD_LIMFACTOR_legend_complete .csv	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_ERZD_LIMFACTOR_legend_complete .csv
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ ERZD/	af_LIMFACTOR_T__M_sd1-6_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_LIMFACTOR_T__M_sd1-6_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_Intermediate_results_ ERZD/	af_LRI_T__M_sd1-6_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/aggregated/1km /	af_LRI_T__M_sd1-6_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_AWCpF23__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_AWCh2__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_CRFVOL__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_CRFVOL__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_PWP__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_WWP__M_1km.tif

Download FTP URL	SeriesName	FileName	Download FTP URL	SeriesName	FileName
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_TAWCpF23__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_TAWCh2__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_TAWCpF23mm__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_TAWCh2mm__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_TETAs__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_tetaS__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	af_agg_30cm_TEXCLSS__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_30cm_TEXCLSS__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated over30cm/	TEXCLSS_legend.csv	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	TEXCLSS_legend.csv
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_AWCpF23__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_AWCh2__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_CRFVOL__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_CRFVOL__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_PWP__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_WWP__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_TAWCpF23__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_TAWCh2__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_TAWCpF23mm__M_1km .tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_TAWCh2mm__M_1km .tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_TETAs__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_tetaS__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_agg_ERZD_TEXCLSS__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_agg_ERDICM_TEXCLSS__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_ERZD__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_ERDICM__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_ERZD_LIMFACTOR__M_1km.tif	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_ERDICM_LIMFACTOR__M_1km.tif
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	af_ERZD_LIMFACTOR_legend_ complete.csv	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	af_ERDICM_LIMFACTOR_legend_ complete.csv
ftp://gyga:gygagyga @ftp.isric.org	GYGA_results/Aggregated overERZD/	TEXCLSS_legend.csv	ftp://soilgrids:soilgrids @ftp.isric.org	data/AF/GYGA/	TEXCLSS_legend.csv

Annex 3a RZ-PAWHC summary statistics

FileName	SeriesName	min	max	mean	std dev	median	dev *
af_BDRICM_T__M_1km.tif	GYGA_inputs	6	175	142	36	153	7.3
af_BLD_T__M_sd1_1km.tif	GYGA_inputs	0.74	1.91	1.44	0.11	1.43	0.3
af_BLD_T__M_sd2_1km.tif	GYGA_inputs	0.74	1.91	1.44	0.11	1.44	0.2
af_BLD_T__M_sd3_1km.tif	GYGA_inputs	0.74	1.91	1.45	0.11	1.44	0.1
af_BLD_T__M_sd4_1km.tif	GYGA_inputs	0.74	1.91	1.45	0.11	1.45	0.2
af_BLD_T__M_sd5_1km.tif	GYGA_inputs	0.74	1.96	1.45	0.11	1.45	0.3
af_BLD_T__M_sd6_1km.tif	GYGA_inputs	0.74	1.99	1.46	0.12	1.45	0.6
af_CEC_T__M_sd1_1km.tif	GYGA_inputs	1.0	75	15.1	9.2	12.0	26.1
af_CEC_T__M_sd2_1km.tif	GYGA_inputs	0.0	76	13.5	8.9	10.0	35.5
af_CEC_T__M_sd3_1km.tif	GYGA_inputs	1.0	76	13.0	9.0	10.0	30.0
af_CEC_T__M_sd4_1km.tif	GYGA_inputs	1.0	76	13.3	9.3	10.0	32.9
af_CEC_T__M_sd5_1km.tif	GYGA_inputs	1.0	76	13.4	9.3	10.0	33.9
af_CEC_T__M_sd6_1km.tif	GYGA_inputs	1.0	76	13.5	9.2	10.0	34.8
af_CLYPPT_T__M_sd1_1km.tif	GYGA_inputs	0.0	71	24.9	9.3	24.0	3.8
af_CLYPPT_T__M_sd2_1km.tif	GYGA_inputs	1.0	73	26.0	9.6	26.0	0.2
af_CLYPPT_T__M_sd3_1km.tif	GYGA_inputs	1.0	75	28.5	9.4	28.0	1.7
af_CLYPPT_T__M_sd4_1km.tif	GYGA_inputs	1.0	77	31.8	9.6	32.0	0.6
af_CLYPPT_T__M_sd5_1km.tif	GYGA_inputs	1.0	77	32.6	9.7	33.0	1.3
af_CLYPPT_T__M_sd6_1km.tif	GYGA_inputs	1.0	73	31.9	9.6	32.0	0.3
af_CRFVOL_T__M_sd1_1km.tif	GYGA_inputs	0.0	82	9.6	7.9	7.3	32.1
af_CRFVOL_T__M_sd2_1km.tif	GYGA_inputs	0.0	85	9.4	8.0	7.0	35.3
af_CRFVOL_T__M_sd3_1km.tif	GYGA_inputs	0.0	85	12.0	9.0	9.6	24.4
af_CRFVOL_T__M_sd4_1km.tif	GYGA_inputs	0.0	82	14.5	9.7	12.5	16.0

FileName	SeriesName	min	max	mean	std dev	median	dev *
af_CRFVOL_T__M_sd5_1km.tif	GYGA_inputs	0.0	82	16.7	9.7	15.4	8.5
af_CRFVOL_T__M_sd6_1km.tif	GYGA_inputs	0.0	82	19.9	10.2	19.8	0.6
af_DRAINFAO_T__M_1km.tif	GYGA_inputs	1.0	7	4.5	1.5	5.0	10.3
af_EACKCL_T__M_sd1_1km.tif	GYGA_inputs	0.0	23	1.0	1.2	0.4	157.3
af_EACKCL_T__M_sd2_1km.tif	GYGA_inputs	0.0	23	0.9	1.2	0.3	164.4
af_EACKCL_T__M_sd3_1km.tif	GYGA_inputs	0.0	23	0.9	1.1	0.3	165.6
af_EACKCL_T__M_sd4_1km.tif	GYGA_inputs	0.0	23	0.9	1.1	0.3	162.4
af_EACKCL_T__M_sd5_1km.tif	GYGA_inputs	0.0	23	0.9	1.1	0.3	162.9
af_EACKCL_T__M_sd6_1km.tif	GYGA_inputs	0.0	23	0.9	1.1	0.3	167.0
af_ECN_T__M_sd1_1km.tif	GYGA_inputs	0.0	361	4.3	16.1	0.6	664.4
af_ECN_T__M_sd2_1km.tif	GYGA_inputs	0.0	359	4.1	16.1	0.4	844.5
af_ECN_T__M_sd3_1km.tif	GYGA_inputs	0.0	350	4.2	16.3	0.4	864.2
af_ECN_T__M_sd4_1km.tif	GYGA_inputs	0.0	508	5.3	23.1	0.5	1077.4
af_ECN_T__M_sd5_1km.tif	GYGA_inputs	0.0	560	6.1	27.3	0.5	1164.7
af_ECN_T__M_sd6_1km.tif	GYGA_inputs	0.0	573	6.5	29.0	0.5	1084.4
af_ENAX_T__M_sd1_1km.tif	GYGA_inputs	0.0	175	1.0	1.7	0.4	180.1
af_ENAX_T__M_sd2_1km.tif	GYGA_inputs	0.0	178	0.7	1.4	0.2	193.9
af_ENAX_T__M_sd3_1km.tif	GYGA_inputs	0.0	180	1.0	1.8	0.3	216.1
af_ENAX_T__M_sd4_1km.tif	GYGA_inputs	0.0	180	1.4	2.4	0.4	264.3
af_ENAX_T__M_sd5_1km.tif	GYGA_inputs	0.0	177	1.5	2.5	0.4	235.0
af_ENAX_T__M_sd6_1km.tif	GYGA_inputs	0.0	177	1.7	2.8	0.5	231.8
af_EXBX_T__M_sd1_1km.tif	GYGA_inputs	0.0	190	13.6	10.4	10.0	35.9
af_EXBX_T__M_sd2_1km.tif	GYGA_inputs	0.0	190	13.2	10.8	9.0	47.1
af_EXBX_T__M_sd3_1km.tif	GYGA_inputs	0.0	213	13.0	11.4	9.0	44.2
af_EXBX_T__M_sd4_1km.tif	GYGA_inputs	0.0	212	13.2	11.7	9.0	47.0
af_EXBX_T__M_sd5_1km.tif	GYGA_inputs	0.0	211	13.6	11.9	10.0	35.5
af_EXBX_T__M_sd6_1km.tif	GYGA_inputs	0.0	212	14.2	12.3	10.0	41.9
af_ORCDRC_T__M_sd1_1km.tif	GYGA_inputs	0.0	162	16.3	10.9	14.0	16.4
af_ORCDRC_T__M_sd2_1km.tif	GYGA_inputs	0.0	157	13.2	9.0	11.0	19.8

FileName	SeriesName	min	max	mean	std dev	median	dev *
af_ORCDRC_T__M_sd3_1km.tif	GYGA_inputs	0.0	160	8.9	6.3	7.0	27.4
af_ORCDRC_T__M_sd4_1km.tif	GYGA_inputs	0.0	149	6.1	5.0	5.0	22.1
af_ORCDRC_T__M_sd5_1km.tif	GYGA_inputs	0.0	121	4.3	3.8	3.0	42.5
af_ORCDRC_T__M_sd6_1km.tif	GYGA_inputs	0.0	111	3.2	3.2	2.0	61.2
af_PHIHOX_T__M_sd1_1km.tif	GYGA_inputs	4.2	10.5	6.3	0.9	6.1	2.7
af_PHIHOX_T__M_sd2_1km.tif	GYGA_inputs	4.2	10.6	6.3	1.0	6.1	2.6
af_PHIHOX_T__M_sd3_1km.tif	GYGA_inputs	4.2	10.6	6.3	1.0	6.1	2.9
af_PHIHOX_T__M_sd4_1km.tif	GYGA_inputs	4.2	10.6	6.3	1.0	6.1	3.7
af_PHIHOX_T__M_sd5_1km.tif	GYGA_inputs	4.2	10.5	6.4	1.1	6.2	3.4
af_PHIHOX_T__M_sd6_1km.tif	GYGA_inputs	4.4	10.5	6.5	1.1	6.3	3.6
af_SLTPPT_T__M_sd1_1km.tif	GYGA_inputs	2.0	50	18.7	6.4	19.0	1.8
af_SLTPPT_T__M_sd2_1km.tif	GYGA_inputs	1.0	49	18.2	6.5	18.0	0.9
af_SLTPPT_T__M_sd3_1km.tif	GYGA_inputs	1.0	47	17.5	6.3	17.0	2.7
af_SLTPPT_T__M_sd4_1km.tif	GYGA_inputs	1.0	45	16.8	6.0	17.0	1.3
af_SLTPPT_T__M_sd5_1km.tif	GYGA_inputs	1.0	44	16.6	5.9	17.0	2.6
af_SLTPPT_T__M_sd6_1km.tif	GYGA_inputs	0.0	46	16.6	5.8	17.0	2.1
af_SNDPPT_T__M_sd1_1km.tif	GYGA_inputs	9.0	97	56.4	13.7	56.0	0.8
af_SNDPPT_T__M_sd2_1km.tif	GYGA_inputs	8.0	96	55.8	14.1	55.0	1.5
af_SNDPPT_T__M_sd3_1km.tif	GYGA_inputs	7.0	95	54.1	13.8	54.0	0.1
af_SNDPPT_T__M_sd4_1km.tif	GYGA_inputs	7.0	95	51.4	13.7	50.0	2.8
af_SNDPPT_T__M_sd5_1km.tif	GYGA_inputs	6.0	95	50.9	13.6	50.0	1.7
af_SNDPPT_T__M_sd6_1km.tif	GYGA_inputs	8.0	97	51.4	13.4	50.0	2.9
af_AWCpF23__M_sd1_1km.tif	GYGA_intermediate_AWC	0.0	20	9.6	1.6	10.0	4.2
af_AWCpF23__M_sd2_1km.tif	GYGA_intermediate_AWC	0.0	20	9.5	1.6	9.0	5.6
af_AWCpF23__M_sd3_1km.tif	GYGA_intermediate_AWC	0.0	19	9.3	1.6	9.0	3.4
af_AWCpF23__M_sd4_1km.tif	GYGA_intermediate_AWC	0.0	19	9.0	1.5	9.0	0.1
af_AWCpF23__M_sd5_1km.tif	GYGA_intermediate_AWC	0.0	19	9.0	1.5	9.0	0.5
af_AWCpF23__M_sd6_1km.tif	GYGA_intermediate_AWC	0.0	18	9.0	1.6	9.0	0.0
af_PWP__M_sd1_1km.tif	GYGA_intermediate_AWC	2.0	44	18.3	5.6	18.0	1.9

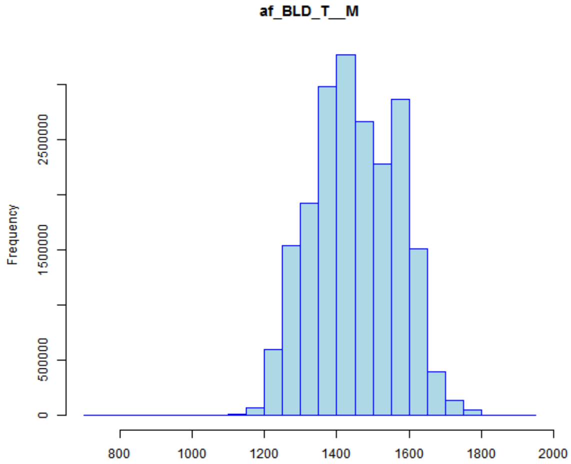
FileName	SeriesName	min	max	mean	std dev	median	dev *
af_PWP__M_sd2_1km.tif	GYGA_intermediate_AWC	1.0	45	18.3	5.6	18.0	1.4
af_PWP__M_sd3_1km.tif	GYGA_intermediate_AWC	2.0	45	18.8	5.4	19.0	1.1
af_PWP__M_sd4_1km.tif	GYGA_intermediate_AWC	2.0	45	19.8	5.3	20.0	1.0
af_PWP__M_sd5_1km.tif	GYGA_intermediate_AWC	2.0	45	20.0	5.2	20.0	0.2
af_PWP__M_sd6_1km.tif	GYGA_intermediate_AWC	2.0	44	19.7	5.2	20.0	1.6
af_TETAs__M_sd1_1km.tif	GYGA_intermediate_AWC	27.0	64	41.5	3.8	41.0	1.3
af_TETAs__M_sd2_1km.tif	GYGA_intermediate_AWC	27.0	64	41.5	3.9	41.0	1.1
af_TETAs__M_sd3_1km.tif	GYGA_intermediate_AWC	27.0	65	41.6	3.8	41.0	1.4
af_TETAs__M_sd4_1km.tif	GYGA_intermediate_AWC	27.0	65	41.8	3.9	42.0	0.5
af_TETAs__M_sd5_1km.tif	GYGA_intermediate_AWC	26.0	65	41.8	4.0	42.0	0.4
af_TETAs__M_sd6_1km.tif	GYGA_intermediate_AWC	25.0	65	41.5	4.2	42.0	1.1
af_LIMFACTOR_T__M_sd1_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LIMFACTOR_T__M_sd2_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LIMFACTOR_T__M_sd3_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LIMFACTOR_T__M_sd4_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LIMFACTOR_T__M_sd5_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LIMFACTOR_T__M_sd6_1km.tif	GYGA_intermediate_ERZD	1	13	-	-	-	
af_LRI_T__M_sd1_1km.tif	GYGA_intermediate_ERZD	0.0	100	76.0	24.9	81.0	6.2
af_LRI_T__M_sd2_1km.tif	GYGA_intermediate_ERZD	0.0	100	78.1	22.6	84.0	7.1
af_LRI_T__M_sd3_1km.tif	GYGA_intermediate_ERZD	0.0	100	73.5	26.3	78.0	5.8
af_LRI_T__M_sd4_1km.tif	GYGA_intermediate_ERZD	0.0	100	68.2	30.0	73.0	6.6
af_LRI_T__M_sd5_1km.tif	GYGA_intermediate_ERZD	0.0	100	66.1	31.2	72.0	8.2
af_LRI_T__M_sd6_1km.tif	GYGA_intermediate_ERZD	0.0	100	62.9	32.7	68.0	7.4
af_agg_30cm_AWCpF23__M_1km.tif	GYGA_results_over 30cm	0.0	19	9.3	1.6	9.0	3.0
af_agg_30cm_CRFVOL__M_1km.tif	GYGA_results_over 30cm	0.0	84	10.2	8.4	8.0	27.9
af_agg_30cm_PWP__M_1km.tif	GYGA_results_over 30cm	1.0	44	18.2	5.6	18.0	1.1
af_agg_30cm_TAWCpF23__M_1km.tif	GYGA_results_over 30cm	0.0	16	7.7	1.4	8.0	3.3
af_agg_30cm_TAWCpF23mm__M_1km.tif	GYGA_results_over 30cm	0.0	48	24.4	4.2	25.0	2.6
af_agg_30cm_TETAs__M_1km.tif	GYGA_results_over 30cm	27.0	64	41.4	3.8	41.0	1.0

FileName	SeriesName	min	max	mean	std dev	median	dev *
af_agg_30cm_TEXCLSS__M_1km.tif	GYGA_results_over 30cm	1	12	6	2	6	1.5
af_agg_ERZD_AWCpF23__M_1km.tif	GYGA_results_over ERZD	0.0	19	8.9	1.6	9.0	0.6
af_agg_ERZD_CRFVOL__M_1km.tif	GYGA_results_over ERZD	0.0	83	13.6	8.8	12.0	13.6
af_agg_ERZD_PWP__M_1km.tif	GYGA_results_over ERZD	0.0	44	18.9	5.4	19.0	0.7
af_agg_ERZD_TAWCpF23__M_1km.tif	GYGA_results_over ERZD	0.0	16	7.2	1.4	7.0	2.6
af_agg_ERZD_TAWCpF23mm__M_1km.tif	GYGA_results_over ERZD	0.0	235	72.7	39.4	79.0	8.0
af_agg_ERZD_TETAs__M_1km.tif	GYGA_results_over ERZD	0.0	64	41.3	4.1	41.0	0.8
af_agg_ERZD_TEXCLSS__M_1km.tif	GYGA_results_over ERZD	1	12	5	2	6	10.2
af_ERZD__M_1km.tif	GYGA_results_over ERZD	1.0	150	96.1	49.2	115.0	16.5
af_ERZD_LIMFACTOR__M_1km.tif	GYGA_results_over ERZD	2	18	-	-	-	
Name (weighted average over 150 cm)	**SeriesName**	**min**	**max**	**mean**	**std dev**	**median**	**dev ***
af_BLD_T__M_1km.tif	GYGA_inputs	0.7	2.0	1.5	0.1	1.4	0.4
af_CEC_T__M_1km.tif	GYGA_inputs	0.0	76.0	13.4	9.2	10.1	33.8
af_CLYPPT_T__M_1km.tif	GYGA_inputs	0.0	77.0	31.3	9.6	31.4	0.7
af_CRFVOL_T__M_1km.tif	GYGA_inputs	0.0	85.4	17.1	9.8	16.1	8.8
af_EACKCL_T__M_1km.tif	GYGA_inputs	0.0	23.4	0.9	1.1	0.3	165.0
af_ECN_T__M_1km.tif	GYGA_inputs	0.0	573.0	5.9	25.8	0.5	1060.4
af_ENAX_T__M_1km.tif	GYGA_inputs	0.0	180.0	1.5	2.5	0.4	232.9
af_EXBX_T__M_1km.tif	GYGA_inputs	0.0	213.0	13.8	11.9	9.7	41.7
af_ORCDRC_T__M_1km.tif	GYGA_inputs	0.0	162.0	5.1	4.3	3.8	45.9
af_PHIHOX_T__M_1km.tif	GYGA_inputs	4.2	10.6	6.4	1.1	6.2	3.5
af_SLTPPT_T__M_1km.tif	GYGA_inputs	0.0	50.0	16.8	5.9	17.1	2.0
af_SNDPPT_T__M_1km.tif	GYGA_inputs	6.0	97.0	51.9	13.6	50.7	2.3
af_AWCpF23__M_1km.tif	GYGA_intermediate_AWC	0.0	20.0	9.1	1.6	9.0	0.8
af_PWP__M_1km.tif	GYGA_intermediate_AWC	1.0	45.0	19.6	5.3	19.8	1.2
af_TETAs__M_1km.tif	GYGA_intermediate_AWC	25.0	65.0	41.6	4.0	41.9	0.9
af_LRI_T__M_1km.tif	GYGA_intermediate_ERZD	0.0	100.0	66.2	30.8	71.4	7.3

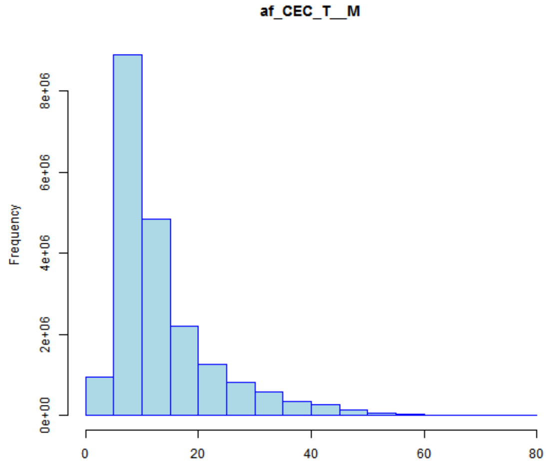
* dev = deviation of mean from median, relative to median (in %)

Annex 3b RZ-PAWHC histograms

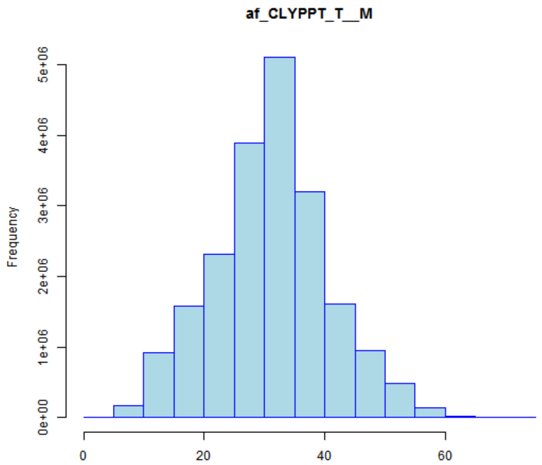
GYGA inputs (weighted averages over 150 cm depth)



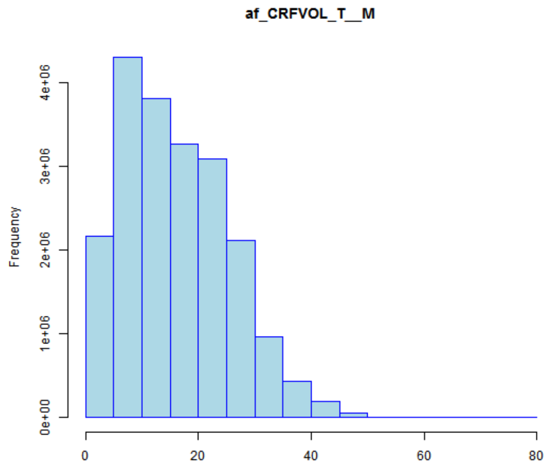
1. Bulk density (kg/m³); y-axis 0-3 M km²



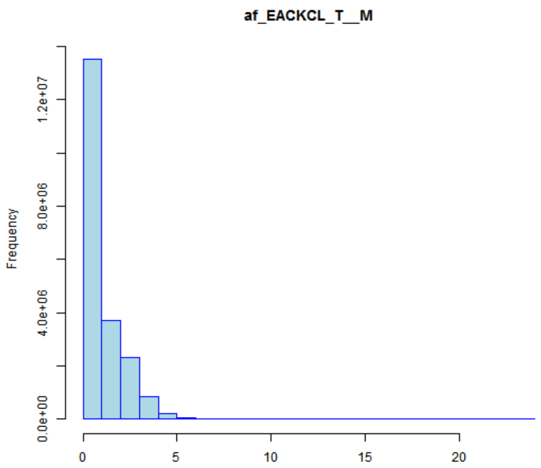
2. Cation Exchange Capacity (cmolc/kg); y-axis 0-8 M km²



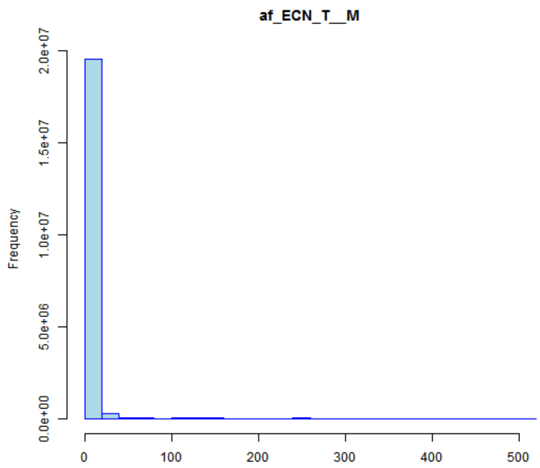
3. Clay content (w%); y-axis 0-5 M km²



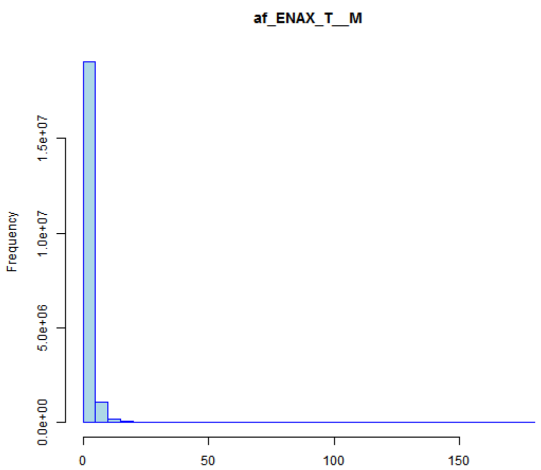
4. Coarse fragments content (v%); y-axis 0-4 M km²



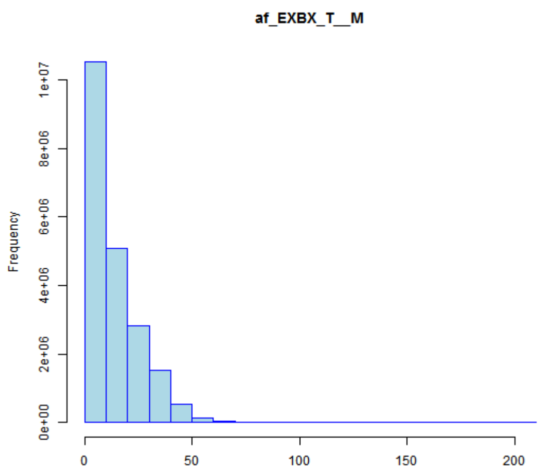
5. Exchangeable acidity (cmolc/kg); y-axis 0-12 M km²



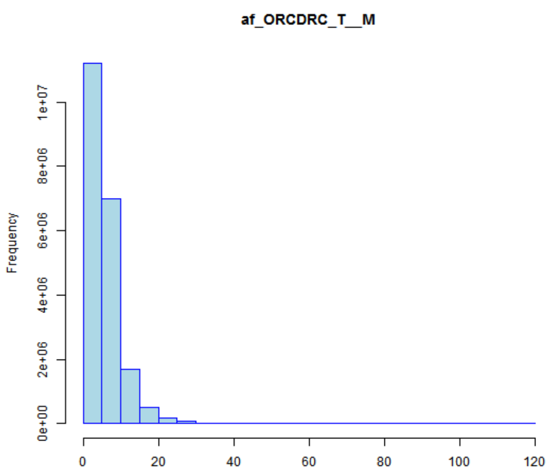
6. Electric conductivity (dS/m); y-axis 0-20 M km²



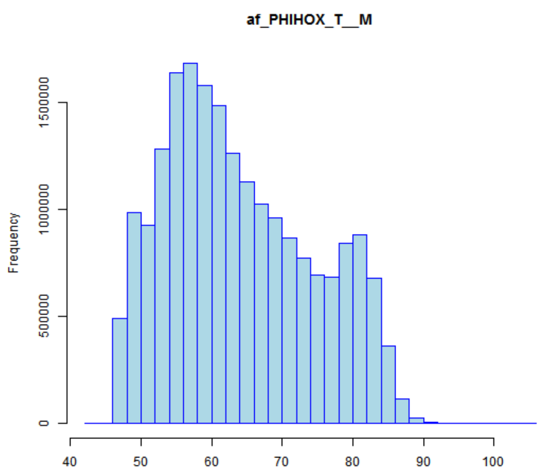
7. Exchangeable sodium (cmolc/kg); y-axis 0-15 M km²



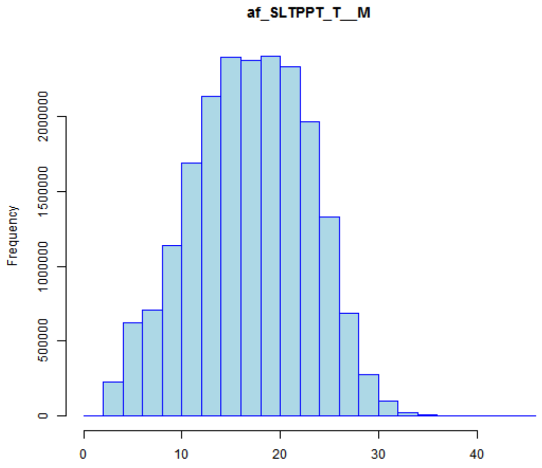
8. Exchangeable bases (cmolc/kg); y-axis 0-10 M km²



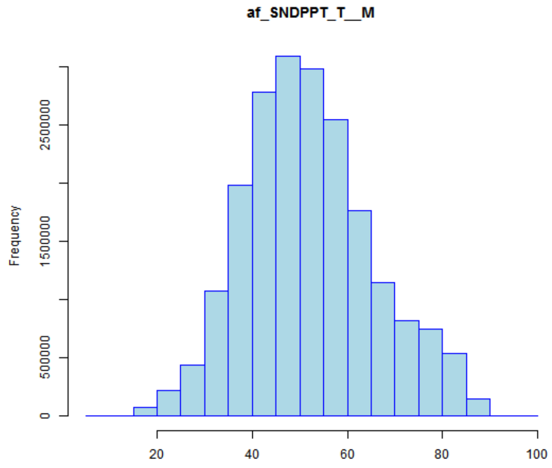
9. Organic carbon content (g/kg); y-axis 0-10 M km²



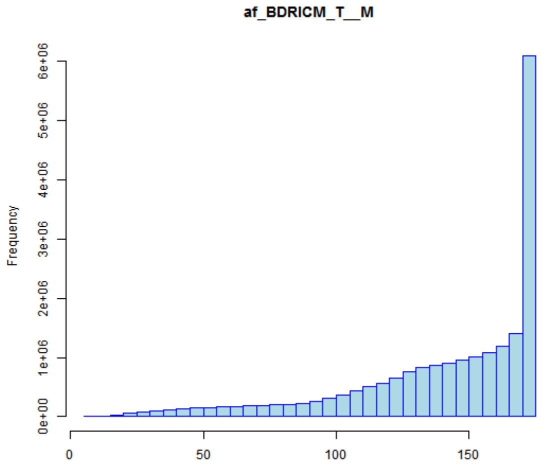
10. pH-H_2O (index*10); y-axis 0-1.5 M km²



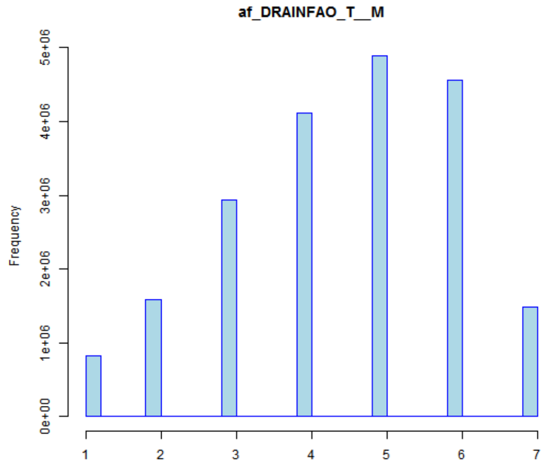
11. Silt content (w%); y-axis 0-2 M km²



12. Sand content (w%); y-axis 0-3 M km²

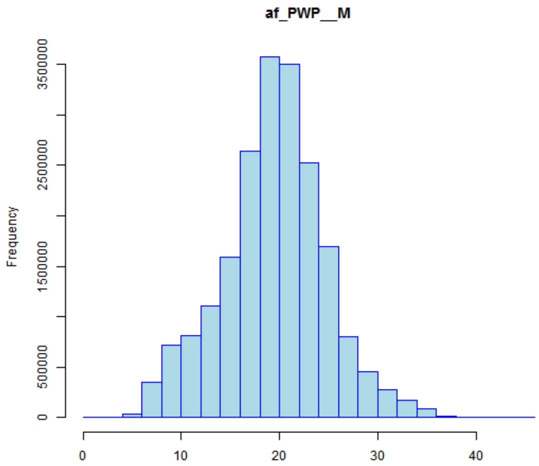


13. Depth to bedrock (cm); y-axis 0-6 M km²

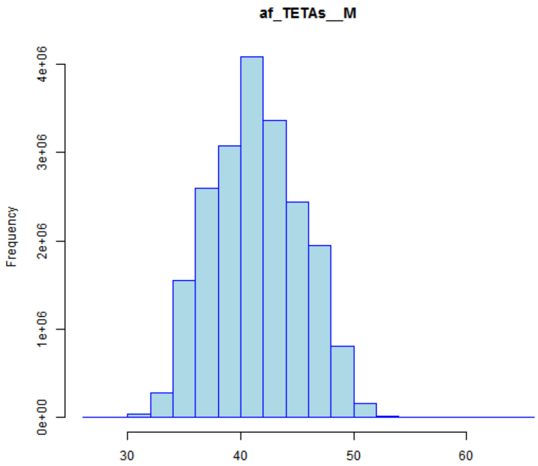


14. Drainage class (1-7 for classes 0-6); y-axis 0-5 M km²

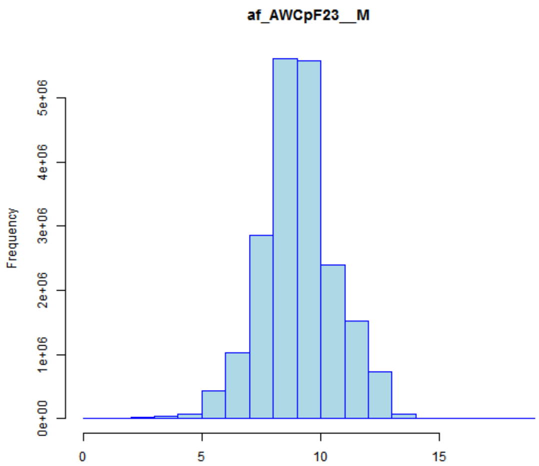
GYGA intermediate results AWC (weighted averages over 150 cm depth)



15. Moisture content at PWP (v%); y-axis 0-3.5 M km²

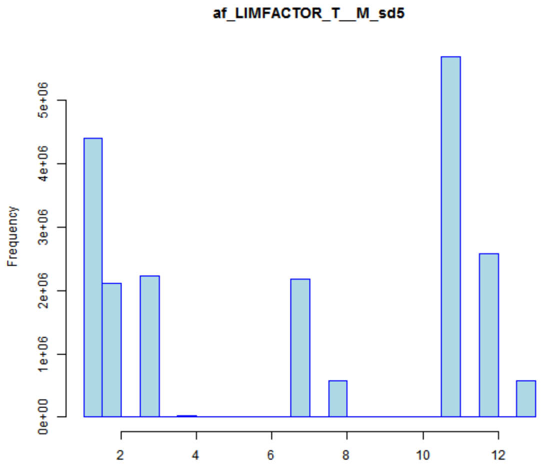


16. Moisture content at saturation (v%); y-axis 0-4 M km²

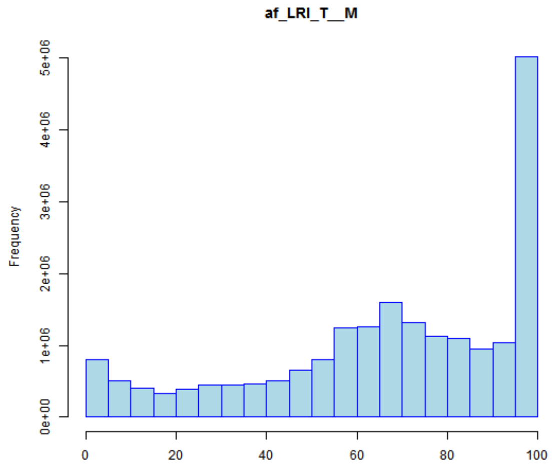


17. Available water holding capacity (v%); y-axis 0-5 M km²

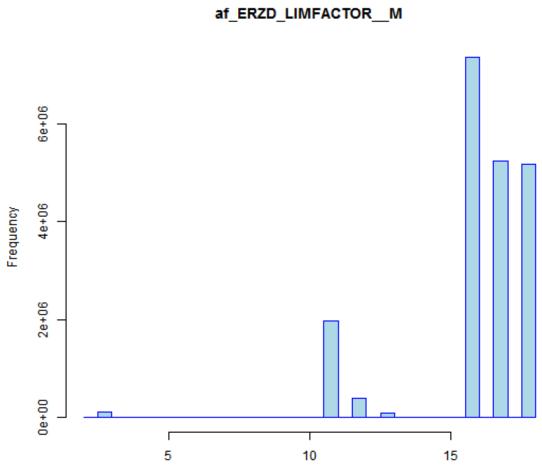
GYGA intermediate results ERZD (weighted averages over 150 cm depth)



18. Soil factors limiting layer rootability; y-axis 0-5 M km²

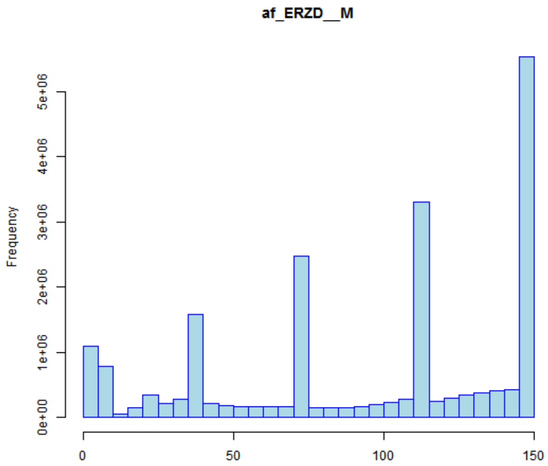


19. Limiting rootability index (%); y-axis 0-5 M km²

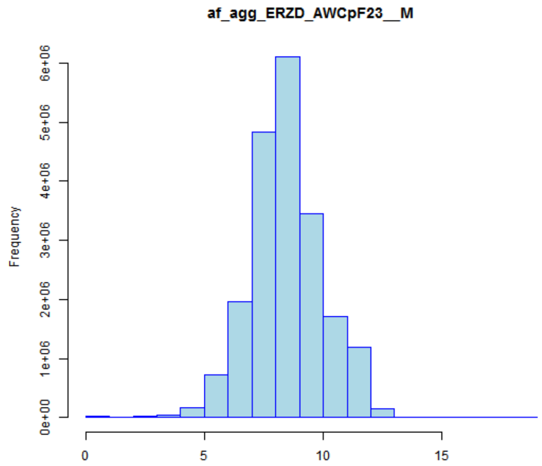


20. Soil factors limiting root zone depth; y-axis 0-6 M km²

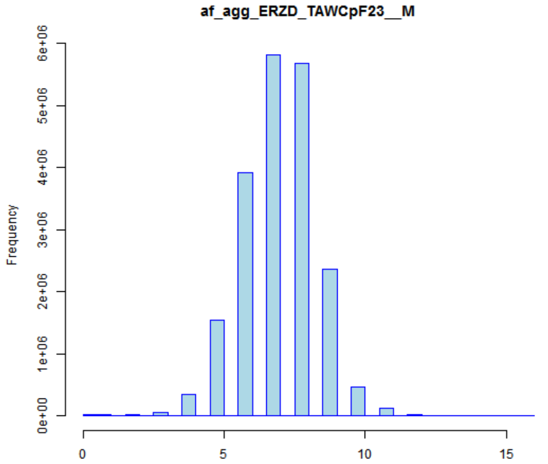
GYGA final results (aggregates over RZD)



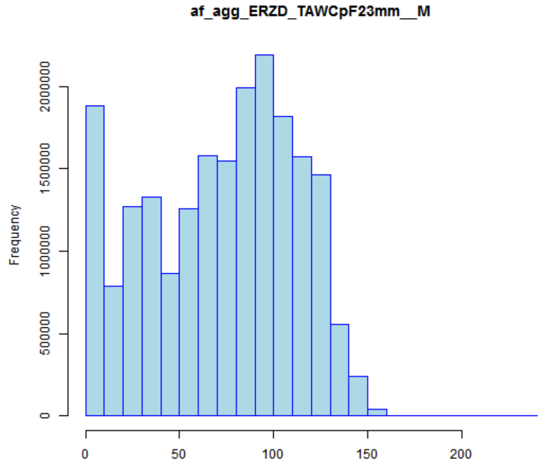
21. Root zone depth (cm); y-axis 0-5 M km²



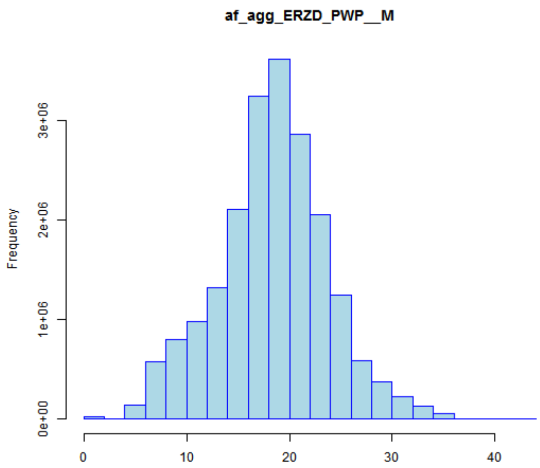
22. Available water holding capacity (v%) of the root zone fine earth; y-axis 0-6 M km²



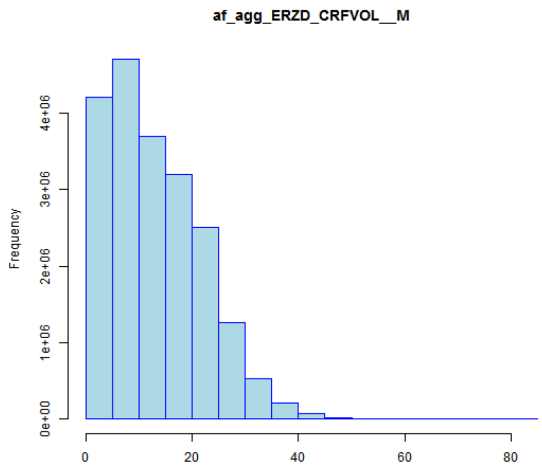
23. Available water holding capacity (v%) of the root zone whole earth; y-axis 0-6 M km²



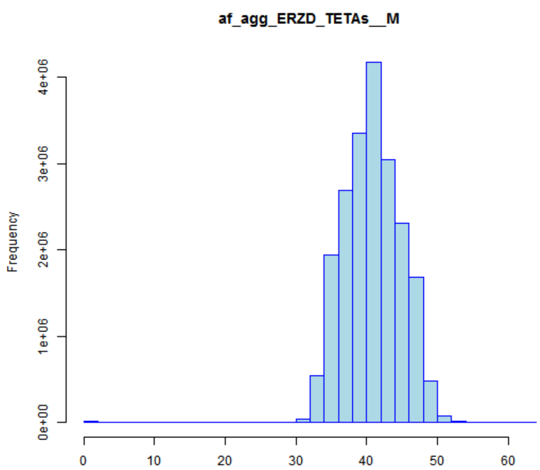
24. Root zone plant-available water holding capacity (mm); y-axis 0-2 M km²



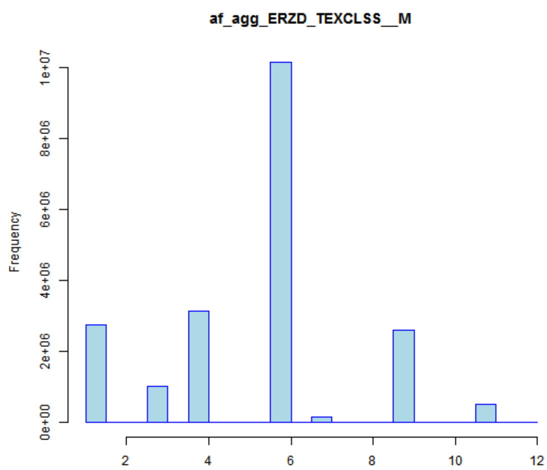
25. Moisture content (v%) of the root zone fine earth at PWP; y-axis 0-3 M km²



26. Coarse fragments content (v%) of the root zone; y-axis 0-4 M km²



27. Moisture content (v%) of the root zone fine earth at saturation; y-axis 0-4 M km²



28. Textural class of the root zone; y-axis 0-10 M km²

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