Food and Agriculture Organization of the United Nations

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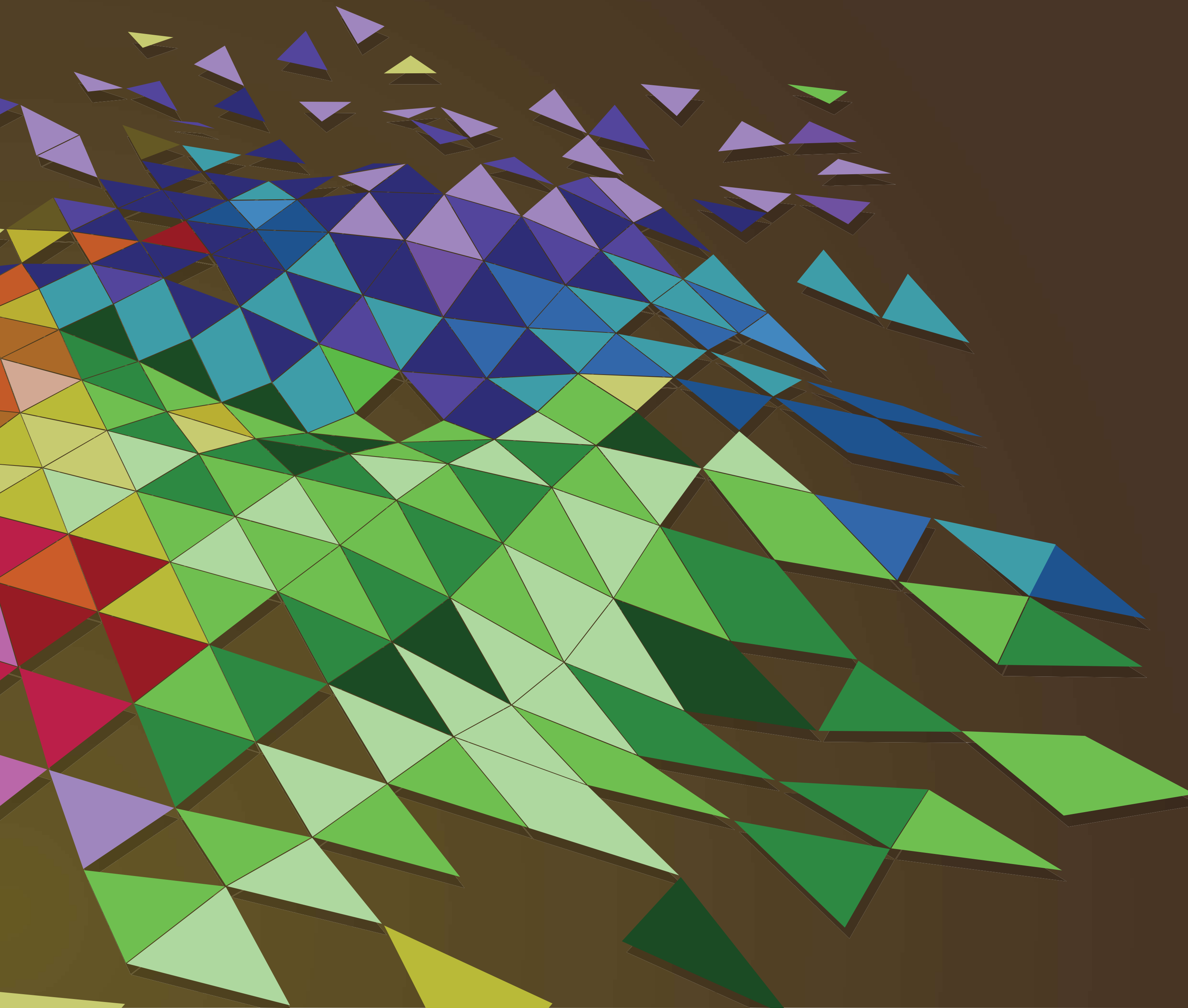
Harmonized World **Soil** Database

version 2.0



HARMONIZED WORLD SOIL DATABASE version 2.0

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Published by
the Food and Agriculture Organization of the United Nations
and
International Institute for Applied Systems Analysis
Rome and Laxenburg, 2023

Required citation:
FAO & IIASA. 2023. *Harmonized World Soil Database version 2.0*. Rome and Laxenburg. https://doi.org/10.4060/cc3823en

ISBN 978-92-5-137499-3

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ACKNOWLEDGEMENTS

The work on the Harmonized World Soil Database could not have been undertaken without the technical contributions to the earlier version of the Joint Research Center of the European Union, in particular Luca Montanarella and Arwyn Jones; ISRIC - World Soil Information in particular Niels Batjes, Vincent van Engelen en Koos Dijkshoorn and the Chinese Academy of Sciences (ISSCAS), in particular Xuezheng Shi.

This revision has made extensive use of the work of Niels Batjes from ISRIC - World Soil Information, whose contribution is particularly and gratefully acknowledged here.

The revision would not have been possible without the unwavering support in FAO of Gianluca Franceschini and Joyce Ahimbisibwe. At IIASA, the support of Gunther Fischer and Sylvia Tramberend are gratefully acknowledged.

In the context of the Environmental Information Systems project (EISD)[1] the Accra office of the Ghana Soil Research Institute (SRI) compiled as early as 1999 a digital national geo-referenced soils database from existing 1:250 000 scale analogue soil maps covering entire Ghana. We thank Enoch Boateng, SRI Chief Research Scientist and David Savory GIS Consultant for taking the lead in this major effort. This database was in 2019 turned in an NAEZ/HWSD compatible Soil Database at IIASA. We thank Gunther Fischer and Sylvia Tramberend for their effort.

The Afghan Soil Research Institute is acknowledged for supporting the compilation of the national harmonized soil database of Afghanistan through provision of various digital soil resources data sets and soil profile databases. Mohammed Ishaq Safi, FAO coordinator of national agroecological zoning study for Afghanistan, is gratefully acknowledged for his advice, active partition, and coordination. The compilation work for the harmonized soil database of Afghanistan was done at IIASA.

The compilation of the harmonized soil database covering Türkiye was facilitated by Ministry of Food, Agriculture and Livestock General Directorates of Agrarian Reform in Ankara by making available all 81 sheets of the 1:25 000 scale National Soil Database of Türkiye in digital formats. Important support was received from Ece Aksoy by means of extensive preparatory work done on spatialization of soil parameters in the context of the National Soil Organic Carbon Information System Project (SOC), supported by FAO. The compilation work for the harmonized soil database of Türkiye was done at IIASA.

The support of the FAO offices in Afghanistan, Ghana and Türkiye has also been essential in completing this task.

[1] EISD is supported by the Government of Ghana, DANIDA and World Bank. The lead agency and coordinator for the EISD is the Ghana Environmental Protection Agency.

ABBREVIATIONS AND ACRONYMS

AFGHSD	Harmonized Soil Database of Afghanistan
DSMW	Digital Soil Map of the World
EBN	European Soil Bureau Network
ESDB	European soil database
FAO	Food and Agriculture Organization of the United Nations
FAO90	Revised Legend of the Soil Map of the World
GHHSD	Harmonized Soil Database of Ghana
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied System Analysis
ISRIC	International Soil Reference and Information Centre
ISSCAS	Institute of Soil Science, Chinese Academy of Sciences
JRC	Joint Research Centre
NAEZ	national agroecological zoning
SMU	Soil Mapping Unit
SMW	Soil Map of the World
SOTER	Soil and Terrain Database
SOTWIS	Harmonized Continental SOTER and WISE-derived database
TURHSD	Harmonized Soil Database of Türkiye
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WISE	World Inventory of Soil Emission Potentials
WRB	World Reference Base for Soil Resources

1 INTRODUCTION

1.1 The Harmonized World Soil Database (HWSD v1.2)

The Harmonized World Soil Database (HWSD v1.2) was built by a partnership between FAO, who had produced the Soil Map of the World (FAO and UNESCO, 1974, 1981) which was converted to the Digital Soil Map of the World (DSMW) in 1995, ISRIC - World Soil Information who had been, with FAO, responsible for the development of regional Soil and Terrain databases (Sombroek, 1984) and the European Soil Bureau Network (ESBN) who had undertaken a major update of soil information for Europe and northern Eurasia (ESB, 2004). The incorporation of the 1:1 million scale Soil Map of China (Shi *et al.*, 2004) was an essential addition obtained through the cooperation with the Institute of Soil Science, Chinese Academy of Sciences (ISSCAS). The International Institute for Applied Systems Analysis (IIASA) had assured the harmonization of data, the GIS aspects and the integration in a data viewer.

The update of the HWSD was supported by the Global Soil Partnership in the context of the enhancement of national soil information systems (GSP, 2014).

The product had as its main aim to be of practical use to modelers and is to serve perspective studies in agroecological zoning, food security and climate change impacts. HWSD also serves an educational function, illustrating the geographical distribution of soils and their properties worldwide in an easy accessible, and user friendly fashion. HWSD is unique as a worldwide inventory of soils as holistic natural entities with morphological, chemical and physical properties. The HWSD approach, based on soil survey information, ascertains spatial integrity of occurrence of naturally stratified soil conditions.

A resolution of about 1 km (30 arc seconds by 30 arc seconds) was selected as appropriate for global, continental and regional modelling. The resulting raster database consisted of 21 600 rows and 43 200 columns, of which 221 million individual accessible grid cells cover the globe's land mass. Over 16 000 different soil association mapping units were recognized in the Harmonized World Soil Database (HWSD), which were linked to harmonized attribute data, derived from the ISRIC - WISE database that drew on information of 10 250 soil profiles. Use of a standardized structure allowed linkage of the attribute data with GIS to display or query the composition in terms of soil units and the characterization of selected soil parameters (organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry).

1.2 The Harmonized World Soil Database version 2.0 (HWSD v2.0)

The Harmonized World Soil Database version 2.0 (HWSD v2.0) is developed by FAO and IIASA and is geared especially for applications in biophysical models and agroecological assessments. HWSD v2.0 was built on the previous version, but with several improvements:

1. The replacement of soil data derived from the ISRIC - WISE database with soil data of the WISE30sec database (Batjes, 2015) more than doubled the number of soil profiles used from 10 250 to 21 000. This database uses a climatic co-variant based on the Köppen-Geiger climatic classification replacing the topsoil texture variant used in the original HWSD.
2. In the HWSD v1.2 soil attribute data were limited to two layers, topsoil (0–30 cm) and subsoil (30–100 cm). HWSD v2.0 uses seven depth layers as available from WISE30sec, namely 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–150 cm and 150–200 cm. The 2-layer approach has been considered a limitation for some modelling needs and is herewith corrected.
3. Soil attribute information could be expanded with additional attribute data available from WISE30sec namely: effective CEC, total nitrogen, nitrogen over carbon ratio (C/N) and aluminum saturation.
4. The incorporation of national soil databases from Afghanistan, Ghana and Türkiye improved detail through expanding the number of soil mapping units from 16 327 In HWSD v1.2 to 29 538 in HWSD v2.0. The inclusion of the three national harmonized data bases for Afghanistan, Ghana and Türkiye produced as spin-off development of standards for incorporation of national data in HWSD v2.0.
5. HWSD v2.0 uses the FAO 1990 Revised Legend for all soil units and a correlation of all soil units with the latest version of the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022), contributing to further harmonization of the database.
6. An up-to-date land cover layer was prepared to better identify built-up areas (Fischer, *et al.,* unpublished). This layer was used for identifying Urbic Anthrosols (FAO and ISRIC, 1990) and Technosols (IUSS Working Group WRB, 2022).
7. A number of soil parameters have been made more specific: (a) reference soil depth has been replaced by rootable soil depth and the available water capacity (AWC) has been recalculated accounting for rootable soil depth, mineralogy, granulometry and salinity (b) the USDA textural class and the Reference Bulk Density have been included for the seven depth layers.
8. Full use has been made of soil phase information globally available in the Digital Soil Map of the World. It was accounted for defining WRB Soil Reference Groups and Soil Units.
9. The HWSD viewer was enhanced for dealing with the expanded information in HWSD v2.0.
10. The 1 km (30 arc-second) resolution has been maintained, in line with the scale of the majority of the source material.
11. Error estimates and statistics (mean, standard deviation (SD) and standard error (SE); median and median of absolute deviation (MAD); upper and lower quartiles as well as 10 percent percentiles (where n > 10); and minimum and maximum recorded for the

given sample population.) of individual soil parameters are accessible through the WISE30sec database (Batjes, 2015, 2016).

1.3 Limitations of HWSD v2.0

HWSD v2.0 is a global product that combines soil inventories gathered at different times at different scales, with different survey and analytical procedures and precision. Consequently, the data should be treated with care and are appropriate to be used for regional and global modelling. For national studies it is advisable to create and use the national level harmonized soil databases.

Reliability of the information is variable: less reliable are the parts of the database that uses the Soil Map of the World (North America, Australia, parts of West Africa and South Asia). Reliability is better in areas covered by SOTER databases and national harmonized data bases.

In the WISE30sec soil attribute database (Batjes, 2015), estimates for each attribute are provided as means and standard deviations (SD), and has been subject to a robust data outlier detection scheme. For details reference is made to the WISE30sec report and database (Batjes, 2015, 2016).

For modelling applications characteristics of all the soil units in the soil association mapping unit must be accounted for. Relying on dominant soils within soil associations only, may lead to misleading results.

2 SOURCES, DATABASE CONTENTS AND FIELD DESCRIPTIONS OF HWSD v2.0

This section provides information on the contents of the HWSD v2.0, the sources of the individual datasets and a technical description.

2.1 Source databases

Seven source databases were used to compile version 2.0 of the HWSD: the European Soil Database (ESDB), the 1:1 million soil map of China, various regional and national SOTER databases (SOTWIS Database), the FAO/UNESCO Digital Soil Map of the World (FAO, 2003), the national soil map of Afghanistan (FAO and IIASA, 2022), the national soil map of Türkiye (Fischer and van Velthuizen, 2018b; TRGM, 2013) and the national soil map of Ghana (Boateng *et al.*, 1999b).

The complete list of maps/databases used is as follows:

The FAO/UNESCO Soil Map of the World:

- FAO, 1995, 2003. The Digitized Soil Map of the World Including Derived Soil Properties (version 3.5). FAO Land and Water Digital Media Series # 1. FAO, Rome.
- FAO, 1971–1981. The FAO - UNESCO Soil Map of the World. Legend and 9 volumes. UNESCO, Paris.

SOTER regional and national studies:

- FAO/IGADD/Italian Cooperation, 1998. Soil and terrain database for northeastern Africa and Crop production zones. Land and Water Digital Media Series # 2. FAO, Rome.
- FAO/IIASA/Dokuchaiev Institute/Academia Sinica, 1999. Soil and Terrain database for north and central Eurasia at 1:5 million scale. FAO Land and Water Digital Media series 7. FAO, Rome.
- FAO/UNEP/ISRIC/CIP, 1998. Soil and terrain digital database for Latin America and the Caribbean at 1:5 million scale. FAO Land and Water Digital Media series # 5. FAO, Rome.
- FAO/ISRIC, 2000. Soil and Terrain Database, Land Degradation Status and Soil Vulnerability Assessment for Central and Eastern Europe (1:2.5 million). Land and Water Digital Media Series # 10. FAO, Rome.
- FAO/ISRIC, 2003. Soil and Terrain Database for Southern Africa. Land and Water Digital Media Series # 26. FAO, Rome.
- Batjes, 2007. SOTER-based soil parameter estimates for Central Africa - DR of Congo, Burundi and Rwanda (SOTWIScaf, version 1.0) ISRIC - World Soil Information, Wageningen.
- Batjes, 2008. SOTER parameter estimates for Senegal and The Gambia derived from SOTER and WISE (SOTWIS-Senegal, version 1.0) ISRIC - World Soil Information, Wageningen.

- Batjes, 2010. Soil property estimates for Tunisia derived from SOTER and WISE (SOTWIS-Tunisia, ver. 1.0). Report 2010/01, ISRIC - World Soil Information, Wageningen.

The European Soil Database:

- European Commission - JRC - Institute for Environment and Sustainability, European Soil Bureau European Soil Database (vs. 2.0) (ESB, 2004).
- Agriculture and Agri-food Canada, USDA-NRCS, Dokuchaev Institute: Northern Circumpolar Soil Map and database with dominant soil characteristics, at a scale of 1:10 million (Tarnocai *et al.*, 2002).

The Soil Map of China 1:1 million scale:

- Chinese Academy of Sciences-The Soil Map of China is based on data of the office for the Second National Soil Survey of China (1995) and distributed by the Institute of Soil Science in Nanjing (Shi *et al.*, 2004).

Harmonized Soil Database of Afghanistan (AFGHSD):

- The Harmonized Soil Database of Afghanistan (AFGHSD) has been compiled at IIASA in 2019 from available gridded soil information from the USDA and USGS soil maps at scale 1:1 million, gridded land cover data and terrain slope data.

Harmonized Soil Database of Ghana (GHHSD):

- Ghana Soil Research Institute (SRI) compiled a national geo-referenced soils database from existing 1:250 000 scale analogue soil maps covering entire Ghana (Boateng *et al.*, 1999b). The Ghana soil classification system, based on the C. F Charter Interim System of Tropical Soil Classification provides a system of soil associations and Soil complexes made up of soil series, as documented in the SRI Soil Survey Memoirs.
- The Harmonized Soil Database of Ghana was compiled at IIASA in 2018.

Harmonized Soil Database of Türkiye (TURHSD):

- Ministry of Food, Agriculture and Livestock, General Directorates of Agrarian Reform, Ankara the 1:25 000 scale National Soil Database - Soil tables of great soil groups (BTG).
- The Harmonized Soil Database of Türkiye was compiled at IIASA in 2017.

Soil parameter estimates based on the World Inventory of Soil Emission Potential (WISE30sec) database

The harmonized global dataset of derived soil properties (WISE30sec) is comprised of a soil-geographical and a soil attribute component. The GIS dataset was created using the soil map unit delineations of the Harmonized World Soil Database version 1.2, with minor corrections, overlaid by a climate zones map (Köppen-Geiger) as co-variate. The soil property estimates were derived from WISE30sec soil profile database for respective mapped "soil/climate" combinations (Batjes, 2016).

The dataset considers more than 20 soil properties commonly required for agroecological zoning, land evaluation, crop growth simulation, modelling of soil gaseous emissions, and analyses of global environmental change. It presents estimates for: organic carbon content, total nitrogen, C/N ratio, pH (H_2O), CECsoil, CECclay, effective CEC, total exchangeable bases (TEB), base saturation, aluminum saturation, calcium carbonate content, gypsum content, exchangeable sodium percentage (ESP), electrical conductivity, particle size distribution (content of sand, silt and clay), proportion of coarse fragments (more than 2 mm) and bulk density.

Soil property estimates are presented for fixed depth intervals of 20 cm up to a depth of 100 cm, respectively of 50 cm between 100 cm to 200 cm (or less when appropriate). The respective soil property estimates were derived from statistical analyses of data for some 21 000 soil profiles contained in the WISE30sec database. The WISE30sec report (Batjes, 2015) describes the use of an elaborate scheme of taxonomy-based transfer rules, complemented with expert-rules that safeguard "*in-pedon*" consistency of the predictions. The type of rules applied are flagged in the WISE30sec database to provide indicators of confidence. The estimates for each attribute are given as means as calculated for the sample populations that remained upon application of a robust data outlier detection scheme. Results of the analyses are linked to the spatial data through the unique map unit (grid cell) identifier, which is a combination of the soil unit and climate class code.

2.2 Database contents

The HWSD v2.0 is composed of a GIS raster image file linked to an attribute database in Microsoft Access format. While these two components are separate data files, they are linked through a commercial GIS system. A viewer provided with the database creates this link automatically and provides direct access to the two data sources; details are given in Annex III. The HWSD v2.0 attribute database provides information on the soil unit composition for each of the 29 385 soil association mapping units.

The database shows the composition of each soil mapping unit, and standardized soil parameters for seven depth layers. A soil mapping unit can have up to 12 soil unit/soil phase combination records in the database. An example is given below.

There are three blocks of data:

- Soil mapping unit identifiers,
- General soil unit information, and
- Specific physical and chemical soil unit characteristics for each of seven depth layers (D1 to D7).

Table 2.1. Example of soil mapping unit information contained in HWSD v2.0

Soil mapping unit identifiers			
Coverage		DSMW	
Soil Mapping Unit (SMU)		5 031	
Dominant soil unit (WRB 2022)		Akroskeletic Vitric Andosol (ANvikk)	
Dominant soil unit (FAO90)		Vitric Andosol (ANz)	
General soil unit information	**Dominant soil**	**Associated soils and inclusions**	
Sequence in soil mapping unit (i)	1	2	3
Share in soil mapping unit (%)	60	20	20
Database ID	44 446	44 448	44 447
National soil classification	n.a.	n.a.	n.a.
Soil unit symbol (WRB 2022)	ANvikk	PZab	CMdy
Soil unit name (WRB correlat. FAO90)	Vitric Andosols	Albic Podzols	Dystric Cambisols
Soil unit symbol (FAO90)	ANz	PZh	CMd
Soil unit name (FAO90)	Vitric Andosols	Haplic Podzols	Dystric Cambisols
Rootable soil depth (Class)	Deep	Deep	Deep
PHASE 1	Stony	-	-
PHASE 2	-	-	-
Obstacle to roots (ESDB) (code)	-	-	-
Impermeable layer (ESDB) (code)	-	-	-
Soil water regime (ESDB) (code)	-	-	-
Drainage class (class)	Moderately well	Moderately well	Moderately well
AWC for rootable soil depth (mm)	131	131	151
Gelic properties	-	-	-
Vertic properties	-	-	-
Depth layer D1			
Depth of top layer (cm)	0	0	0
Depth of bottom layer (cm)	20	20	20
Coarse fragments (% volume)	12	14	14
Sand (% weight)	52	54	43
Silt (% weight)	42	40	46
Clay (% weight)	6	6	11
Texture class (USDA conventions)	Sandy loam	Sandy loam	Loam
Bulk density (g/cm^3)	0.93	1.08	1.18
Reference bulk density (g/cm^3)	1.31	1.31	1.51
Organic carbon content (% weight)	4.5	7.2	4.7
pH in water ($-log(H^+)$)	6.2	4.7	5.1

Total nitrogen content (g/kg)	1.9	4	3.07
Carbon nitrogen ratio (C/N)	20	18	16
CEC_{soil} ($cmol_c$/kg)	19	25	18
CEC_{clay}, ($cmol_c$/kg)	110	74	54
ECEC ($cmol_c$/kg)	11	10	9
TEB ($cmol_c$/kg)	10	7	6
BS (% of CEC_{soil})	50	27	34
Aluminum saturation (% of ECEC)	0	33	33
ESP (%)	2	1	1
Calcium carbonate (% weight)	0	0	0
Gypsum content (% weight)	0	0	2
Electric conductivity (dS/m)	1	0	1
Depth layer D2 to D7 (Layers 2 to 7)			

Source: Authors' own elaboration.

2.3 Database field description

This section explains the content of the fields in the database. It describes the procedures used to correlate the various source data for the harmonized database. The soil mapping unit information has been linked to parameters derived from the World Inventory of Soil Emissions (WISE30sec) soil profile database (Batjes, 2015). The linkage was established through the FAO90 soil unit classification by 5 Köppen-Geiger climate classes (Tropical, Arid, Temperate, Cold and Polar) (Peel *et al.,* 2007).

2.3.1 Soil mapping unit identifiers

Coverage: Data source: ESDB, SOTWIS, DSMW, China, Afghanistan, Ghana, Türkiye.

Soil Mapping Unit: (SMU) (Code).

Dominant Soil Unit: (WRB 2022) (see Annex I).

Dominant Soil Unit: (FAO90) (see Annex I).

2.3.2 General soil unit information

This contains general information for each of the soil units occurring in the soil mapping unit (dominant soil unit and up to 11 associated soils).

SEQ (Sequence within the mapping unit): the sequence in which soil units within the soil mapping unit are presented (in order of percentage share). The dominant soil has sequence 1. The sequence can range between 1 and 12.

SHARE (Share of the soil unit): share of the soil unit within the mapping unit in percentage. Shares of soil units within a mapping unit always sum up to 100 percent.

DATABASE ID: internal database identifier.

NATIONAL SOIL CLASSIFICATION: name/symbol of the national/local soil classification system.

SOIL UNIT SYMBOL (WRB 2022) (WRB+phases): the full symbol of the WRB soil name taking into account phases and referring to the Soil Reference Group plus all primary qualifiers (see SOIL CLASSIFICATION for details).

SOIL UNIT NAME (WRB 2022): the name of the Soil Reference Group plus the most important primary qualifier (see Annex I for details).

SOIL UNIT SYMBOL (FAO90): the symbol for the soil unit in the Revised Legend (see Annex I for details).

SOIL UNIT NAME (FAO90): the name of the soil unit in the FAO90 Revised Legend (see Annex I for details).

ROOTABLE SOIL DEPTH: the depth to which plants can exploit the soil for nutrients and moisture. The rootable soil depth is derived from the FAO90 soil unit and soil phase information as follows:

- **Deep > 100 cm:** all soils, except Leptosols, except soils with depth limiting soil phases, except obstacles to roots (Class 2–6) and except impermeable layers Class1.
- **Moderately deep 50–100 cm:** soils with petroferric, petrocalcic, petrogypsic or placic soil phases, soils with other obstacles to roots Class2 and soils with Impermeable layer Class3.
- **Shallow 10–50 cm:** Leptosols (LPe, LPd, Lpk, LPm, LPu, LPi) and soils with Lithic Phase, soils with other obstacles to roots Class 3–5, and soils with Impermeable layer Class 4.
- **Very shallow <10 cm:** Lithic Leptosols (LPq), and soils with obstacles to roots Class 6 Bare Rock.

SOIL PHASES:

- **Phase1–Phase2:** phases are subdivisions of soil units based on characteristics which are significant for the use or management of the land but are not diagnostic for the separation of the soil units themselves. Phases numbered 1 to 12 were used in the Soil Map of the World (FAO74), phases 13 to 21 were used in association with the Revised Legend of the Soil Map of the World (FAO90), while phases 22 to 25 are specific for the European Soil Database.
- **No phase**
- **Stony phase**: marks areas where the presence of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable. Hand tools can normally be used and also simple mechanical equipment if other conditions are particularly favorable. Fragments up to 7.5 cm are considered as gravel; larger fragments are called stones and boulders.
- **Lithic phase**: this phase is used when continuous coherent and hard rock occurs within 50cm of the soil surface. For Leptosols the lithic phase is not shown as it is implied in the soil unit name.
- **Petric phase:** the petric phase marks soils with a layer consisting of 40 percent or more, by volume, of oxidic concretions or of hardened plinthite, or ironstone or other coarse

fragments with a thickness of at least 25 cm, the upper part of which occurs within 100 cm of the surface. The petric phase differs from the petroferric phase in that the concretionary layer of the petric phase is not cemented.

- **Petrocalcic phase**: marks soils in which the upper part of a petrocalcic horizon (> 40 percent lime, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface.
- **Petrogypsic phase**: used for soils in which the upper part of a petrogypsic horizon (> 60 percent gypsum, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface.
- **Petroferric phase:** the petroferric phase marks soils in which the upper part of the petroferric horizon occurs within 100 cm from the soil surface. A petroferric horizon is a continuous layer of indurated material in which iron is an important cement and organic matter is absent.
- **Phreatic phase**: the phreatic phase marks soils which have a groundwater table between 3 and 5 metres from the surface.
- **Fragipan phase:** the fragipan phase marks soils which have the upper level of the fragipan occurring within 100 cm of the surface. The fragipan is a loamy subsurface horizon with a high bulk density relatively to the horizon above it. It is hard or very hard and seemingly cemented when dry. Dry fragments slake or fracture in water. A fragipan is low in organic matter and is only slowly permeable.
- **Duripan phase**: the duripan phase marks soils in which the upper level of a duripan occurs within 100 cm of the soil surface. A duripan is a subsurface horizon that is cemented by silica and contains often accessory cements mainly iron oxides or calcium carbonate.
- **Saline phase:** the saline phase marks soils in which in some horizons within 100 cm of the soil surface show electric conductivity values higher than 4 dS/m. The saline phase is not shown for Solonchaks because their definition implies a high salt content.
- **Sodic phase**: the sodic phase marks soils which have more than 6 percent saturation with exchangeable sodium in some horizons within 100 cm of the soil surface. The sodic phase is not shown for Solonetz because their definition implies a high ESP.
- **Cerrado phase:** cerrado is the Brazilian name for level open country of tropical savannas composed of tall grasses and low contorted trees. This type of vegetation is closely related to the occurrence of strongly depleted soils on old land surfaces.
- **Anthraquic phase**: the anthraquic phase marks soils showing stagnic properties within 50 cm of the surface due to surface water logging associated with long continued irrigation, particularly of rice.
- **Gelundic phase**: the gelundic phase marks soils showing formation of polygons on their surface due to frost heaving.
- **Gilgai phase**: gilgai is a microrelief typical of clayey soils, mainly Vertisols. The microrelief consists of either a succession of enclosed micro-basins and micro-knolls in nearly level areas, or of microvalleys and micro-ridges that run up and down the slope.

- **Inundic phase**: the inundic phase is used when standing or flowing water is present on the soil surface for more than 10 days during the growing period.
- **Placic phase**: the placic phase refers to the presence of a thin iron pan, a black to dark reddish layer cemented by iron with manganese or organic matter. Its thickness varies from 2 to 10 mm.
- **Rudic phase:** the rudic phase marks areas where the presence of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable.
- **Skeletic phase**: the skeletic phase refers to soil material which contains more than 40 percent coarse fragments or oxidic concretions.
- **Takyric phase**: the takyric phase applies to heavy textured soils with cracks into polygonal elements that form a platy or massive surface crust.
- **Yermic phase**: the yermic phase applies to soils which are low in organic carbon and have features associated with deserts or very arid conditions (desert varnish, presence of palygorskyte, cracks filled with sand, presence of blown sands on a stable surface.
- **Gravelly:** the gravelly phase is used in ESDB and indicates over 35 percent gravels with diametre <7.5 cm.
- **Concretionary:** the concretionary phase is used in ESDB and indicates over 35 percent concretions, diametre <7.5 cm near the surface.
- **Glaciers**: permanent snow-covered areas and glaciers.
- **Soils disturbed by man**: areas filled artificially with earth, trash, or both, occur most commonly in and around urban areas.

Two phases can be listed for each soil unit, in order or importance. More information on phases and their use for WRB classification purpose is given in Annex II.

ADDITIONAL PHASES ONLY USED IN ESDB:

- **Obstacle to roots**: provides the depth class of an obstacle to roots.

  Class1 No obstacle to roots between 0 and 80 cm

  Class 2 Obstacle to roots between 60 and 80 cm depth

  Class 3 Obstacle to roots between 40 and 60 cm depth

  Class 4 Obstacle to roots between 20 and 40 cm depth

  Class 5 Obstacle to roots between 0 and 80 cm

  Class 6 Obstacle to roots between 0 and 20 cm

- **Impermeable layer**: indicates the presence of an impermeable layer within the soil profile.

  Class 1 No impermeable layer within 150 cm

  Class 2 Impermeable layer between 80 and 150 cm

  Class 3 Impermeable layer between 40 and 80 cm

Class 4 Impermeable layer within 40 cm

- **Soil water regime:** indicates the dominant annual average soil water regime class.

  Class 1 Not wet within 80 cm over 3 months, not wet within 40cm for over 1 month.

  Class 2 Wet within 80 cm 3 to 6 months, but not wet within 40 cm for over 1 month.

  Class 3 Wet within 80 cm over 6 months, but not wet within 40 cm over 11 months.

  Class 4 Wet within 40 cm depth for over 11 months.

REFERENCE SOIL DRAINAGE CLASS: soil drainage refers to the natural capability of a soil to remove excess water. The drainage capacity of a soil depends on the soil type, its texture, the presence or absence of impermeable layers and the slope on which the soil occurs. The reference soil drainage class that is given in HWSD v2.0 refers to the estimated soil drainage on a flat (slope 0–0.5 percent) surface by soil type and topsoil texture. The following classes have been used (FAO and ISRIC, 1990):

- **Excessively drained**: water is removed from the soil very rapidly Soils are commonly very coarse textured or rocky, shallow or on steep slopes;
- **Somewhat excessively drained:** water is removed from the soil rapidly. Soils are commonly sandy and very pervious;
- **Well drained:** water is removed from the soil readily but not rapidly. Soils commonly retain optimum amounts of moisture, but wetness does not inhibit root growth for significant periods
- **Moderately well drained:** Water is removed from the soil somewhat slowly during some periods of the year. For a short period, soils are wet within the rooting depth, they commonly have an almost impervious layer;
- **Imperfectly drained**: Water is removed slowly so that soil is wet at a shallow depth for significant periods. Soils commonly have an impervious layer, a high-water table, or additions of water by seepage;
- **Poorly drained:** Water is removed so slowly that soils are commonly wet at a shallow depth for considerable periods. Soils commonly have a shallow water table which is usually the result of an almost impervious layer, or seepage, and
- **Very poorly drained**: Water is removed so slowly that the soils are wet at shallow depths for long periods. Soils have a very shallow water table and are commonly in level or depressed sites.

AWC FOR ROOTABLE DEPTH: the maximum amount of water that the soil can hold that is available for plant growth. It is the difference between the amount of water in the soil at field capacity and the amount of water in the soil at wilting point. It is also referred to as Available Water Capacity (AWC). AWC depends on physical and chemical characteristics, but above all on effective depth or volume of the soil (FAO, 1995). The presence of a root-restricting layer reduces the water holding capacity, therefore the AWC is calculated until the rootable depth of a soil[2].

The following procedure was followed to determine AWC (Dixon and Weed, 1990; FEWS.net, 2010).

A relationship has been established between the textural class and the Available soil Water Capacity (USDA, 1967) presented in Table 2.2.

Table 2.2. AWC as function of USDA texture class

Texture based AWC	
USDA texture classes	**USDA AWC (mm/m)**
Heavy Clay	175
Silty Clay	175
Clay	175
Silty Clay Loam	158
Clay Loam	158
Silt	158
Silt Loam	158
Sandy Clay	175
Loam	158
Sandy Clay Loam	158
Sandy Loam	125
Loamy Sand	75
Sand	75
Peat and Mucks (Histosols)	208

Source: USDA. 1967*. Part 652 Irrigation Guide. National Engineering Handbook.* Washington DC, United States Department of Agriculture, Natural Resources Conservation Service.

Clay mineralogy: the type of clay also influences the AWC and soils with a clay fraction dominated by kaolinite are considered to have 20 percent less capacity to store water than soils with other clay minerals. In the program, a kaolinitic clay mineralogy is considered when the CEC of the clay is less than 24 $cmol_c/kg$.

Coarse fragments: the presence of coarse fragments (gravel, cobbles, stones, and boulders larger than 2 mm) reduces the AWC because they do not hold water. The reduction is estimated at 1 percent for each percentage of coarse fragments.

Salinity: salts reduce the soil's water holding capacity. A soil that is salty can be wet and yet not have any water available for plant growth. This is because the salts have such a strong attraction for water that the roots cannot overcome it. The reduction effect is given in Table 2.3.

[2] Soil phase information affecting effective soil volume and soil chemistry have not been considered for AWC estimations for reasons of spatial uncertainties of soil phase occurrences. For national and regional studies, it is recommended to review and update the presented AWC values based on accurate soil phase data.

Available Water Capacity (AWC) for a soil unit is determined for every layer and summed for rootable soil depth.

ADD_PROP (Additional property): certain soil properties, inherent to the soil unit definition that are relevant for agricultural use of the soil are vertic and gelic. The additional field provides details on gelic properties (gelic soil groups in FAO90) and vertic properties (Vertisols, vertic soil groups in FAO90).

Table 2.3. Reduction of AWC as a function of salinity levels (dS/m)

Salinity reduction of AWC (interpolate)	
EC (dS/m)	**AWC reduction %**
4	10
6	20
12	30
16	40
18	50
20	60
22	70
25	80
30	90

Source: USDA. 1967. *Part 652 Irrigation Guide. National Engineering Handbook.* Washington DC, United States Department of Agriculture, Natural Resources Conservation Service.

2.3.3 Soil Attributes per depth layer

These are the derived chemical and physical soil properties that are provided for each of the seven depth layers (D1 to D7) separately.

DEPTH OF TOP LAYER. The upper limit of the soil layer concerned: for D1 = 0 cm, for D2 = 20 cm, for D3 = 40 cm, for D4 = 60 cm, for D5 = 80 cm, for D6 =100 cm for D7 = 150 cm.

DEPTH OF BOTTOM LAYER. The lower limit of the soil layer concerned: for D1 = 20 cm, for D2 = 40 cm, for D3 = 60 cm, for D4 = 80 cm, for D5 = 100 cm, for D6 = 150 cm for D7 = 200 cm.

COARSE FRAGMENTS (>2 mm vol percent). A coarse fragment is any primary soil particle with a nominal diametre greater than 2 mm. The data are directly available from the WISE30sec database.

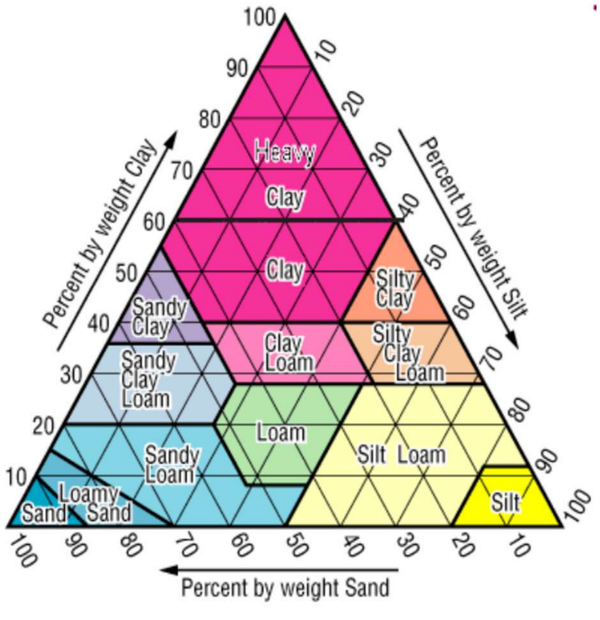
SAND (weight, percentage). Sand comprises particles, or granules, ranging in diametre from 0.050 to 2 mm. An individual particle in this range size is termed a sand grain. Sand feels gritty when rubbed between the fingers (silt, by comparison, feels like flour). Sand is commonly divided into five sub-categories based on size: very fine sand (1/16–1/8 mm diametre), fine sand (1/8–1/4 mm), medium sand (1/4–1/2 mm), coarse sand (1/2–1 mm), and very coarse sand (1–2 mm). The data are directly available from the WISE30sec database.

SILT (weigh, percentage). Silt is produced by the mechanical weathering of rock, as opposed to the chemical weathering that results in clays. This mechanical weathering can be due to grinding by glaciers, eolian abrasion (sandblasting by the wind) as well as water erosion of rocks on the beds of rivers and streams. Silt is sometimes known as "rock flour" or "stone dust", especially when produced by glacial action. Mineralogically, silt is composed mainly of quartz and feldspar. Silt size is between 0.002 and 0.050 mm (USDA classification). The data are directly available from the WISE30sec database.

CLAY (weigh, percentage). Clay is naturally occurring firm earthy material, composed primarily of fine-grained (diametre less than 0.002 mm) that is plastic when wet and hardens when heated and that consists primarily of hydrated silicates or aluminum. Clay is mostly composed of clay minerals which are phyllo-silicate minerals and minerals which impart plasticity and harden when fired or dried. The definition of "fine grained" used above is particles smaller than 2 µm, colloid chemists (and Eastern European soil scientists) may use 1 µm. In the database no difference is made between the two, but reported figures are used, whatever the source; these values are also used to determine the "USDA texture class" as given below. The data are directly available from the WISE30sec database.

TEXTURE CLASS (USDA convention). USDA texture class name and code. Soil texture is a soil property used to describe the relative proportion of different grain sizes of mineral particles in a soil. Particles are grouped according to their size into what are called soil separates (clay, silt, and sand). The soil texture class (e.g. sand, clay, loam, etc.) corresponds to a particular range of separate fractions, and is diagrammatically represented by the soil texture triangle.

Figure 2.1. USDA texture classes



Code	Texture
1	clay (heavy)
2	silty clay
3	clay
4	silty clay loam
5	clay loam
6	silt
7	silt loam
8	sandy clay
9	loam
10	sandy clay loam
11	sandy loam
12	loamy sand
13	sand

Source: Adapted from USDA. 1951. *Soil Survey Manual. Handbook No. 18, Soil Survey Staff.* Washington DC.

Coarse textured soils contain a large proportion of sand, medium textures are dominated by silt, and fine textures by clay http://www.pedosphere.com/resources/bulkdensity/triangle_us.cfm). The classes are calculated.

BULK DENSITY (g/cm³). Bulk density is defined as "*the mass of the many particles of the material divided by the total volume they occupy*". Data are directly available in the WISE30sec database.

REFERENCE BULK DENSITY (g/cm³). Reference bulk density is a property of particulate materials. It is the mass of many particles of the material divided by the volume they occupy. The volume includes the space between particles as well as the space inside the pores of individual particles. The calculation procedures are in: http://www.pedosphere.com/resources/bulkdensity/index.html.

ORGANIC CARBON CONTENT (g/kg) Organic Carbon is together with pH, the best simple indicator of the health status of the soil. Moderate to high amounts of organic carbon are associated with fertile soils with a good structure. Data are directly derived from WISE30sec.

pH in water (-log (H^+)). This field gives the soil reaction. The pH, measured in a soil-water solution, is a measure for the acidity and alkalinity of the soil. Data are directly derived from WISE30sec.

TOTAL NITROGEN CONTENT (g/kg) Soil total nitrogen is a major determinant and indicator of soil fertility and quality in an agricultural ecosystem. Data are directly derived from WISE30sec

C/N RATIO. A carbon-to-nitrogen ratio is a ratio of the mass of carbon to the mass of nitrogen in soil material. The C:N ratio is a key indicator as it describes a balance between energetic foods (represented by carbon) and material to build protein with (represented by nitrogen). An optimal C:N ratio of around 24:1 provides for higher microbial activity (USDA, 2011). Data are directly derived from WISE30sec. Note that C/N ratios have been calculated as is from the measured data (CNrt), not as the ratio of the derived values for C and N, ditto for CECclay, as this would introduce additional errors.

CATION EXCHANGE CAPACITY (CEC) of the fine earth fraction ($cmol_c$/kg). The total nutrient fixing capacity of a soil is well expressed by its Cation Exchange Capacity. Soils with low CEC have little resilience and cannot build up stores of nutrients. Many sandy soils have CEC less than 4 $cmol_c$/kg. The clay content, the clay type and the organic matter content all determine the total nutrient storage capacity. Values more than 10 $cmol_c$/kg are considered satisfactory for most crops. Data are derived directly from the WISE30sec database.

CEC_{clay}, corrected for contribution of organic matter ($cmol_c$/kg). This field gives the cation exchange capacity of the clay fraction corrected for the organic matter content in the layer concerned. The type of clay mineral dominantly present in the soil often characterizes a specific set of pedogenetic factors in which the soil has developed. Tropical, leaching climates produce the clay mineral kaolinite, while confined conditions rich in Ca and Mg in climates with a pronounced dry season encourage the formation of the clay mineral smectite (montmorillonite). CEC_{clay} is calculated from CEC_{soil} by assuming a mean contribution of 350 $cmol_c$/kg OC, the common range being from 150 to over 750 $cmol_c$/kg (Klamt and Sombroek, 1988). Data are directly derived from the WISE30sec database.

EFFECTIVE CEC ($cmol_c$/kg) (ECEC). ECEC is defined as the sum of exchangeable (Ca++, Mg++, K+, Na+) plus the sum of exchangeable (H+, Al+++) (Van Reeuwijk, 2002). Data are derived directly from the WISE30sec database.

TOTAL EXCHANGEABLE BASES (TEB). Total exchangeable bases stand for the sum of exchangeable cations in a soil: sodium (Na^+), calcium (Ca^{++}), magnesium (Mg^{++}) and Potassium (K^+). Data are directly derived from the WISE30sec database.

BASE SATURATION AS PERCENTAGE OF CEC_{soil} (BS). The base saturation measures the sum of exchangeable cations (nutrients) Na+, Ca++, Mg++ and K+ as a percentage of the overall exchange capacity of the soil (including the same cations plus H+ and Al+++). The value often shows a near linear correlation with pH. Data are derived directly from the WISE30sec database.

ALUMINUM SATURATION AS PERCENTAGE OF ECEC. The exchangeable aluminum percentage (ALSA) has been set at zero when pH_{water} is higher than 5.5. Data are derived directly from the WISE30sec database.

EXCHANGEABLE SODIUM PERCENTAGE (ESP) The exchangeable sodium percentage has been used to indicate levels of sodium in soils. It is calculated as the ratio of Na in the CEC (or sum of cations) ESP= Na*100/CEC_{soil}. Data are derived directly from the WISE30sec database.

CALCIUM CARBONATE CONTENT (weight, percentage) Calcium carbonate is a chemical compound (a salt), with the chemical formula $CaCO_3$. It is a common substance found as rock in all parts of the world. Calcium carbonate is quite common in soils particularly in drier areas and it may occur in different forms as mycelium-like threads, as soft powdery lime, as harder concretions or cemented in petrocalcic horizons. Low levels of calcium carbonate enhance soil structure and are generally beneficial for crop production but at higher concentrations they may induce iron deficiency and when cemented limit the water storage capacity of soils. Data are derived directly from the WISE30sec database.

GYPSUM CONTENT (weight, percentage) Gypsum is a chemical compound (a salt) which occurs occasionally in soils particularly in the driest areas of the globe where it can occur in a flower-like form typically opaque with embedded sand grains called desert rose. In soils it may occur in fibers, crystals or soft. Data are derived directly from the WISE30sec database.

ELECTRIC CONDUCTIVITY (dS/m) Coastal and desert soils can be enriched with water-soluble salts or salts more soluble than gypsum. The salt content of a soil can be roughly estimated from the Electrical Conductivity of the soil measured in a saturated soil paste or a more diluted suspension of soil in water. Data are directly derived from the WISE30sec database.

3 HARMONIZATION OF THE DATABASES

This section describes the harmonization process which has been applied to bring the HWSD v2.0 soil database components (HWSD v1.2, Afghanistan, Türkiye, and Ghana) into the uniform HWSD v2.0 format. Attribute database and spatial data merging procedures are described separately.

Due to soil correlation process in the individual countries multiple occurrences of identical SMU's occur; there are however locational differences. Experience has learned that for spatial applications of HWSD, it is best to keep these SMU's separate. For example, when HWSD is combined with other information like terrain slope, land cover/land use, farming system zones etc. (in AEZ unique soil/slope units are created which make up, may be different in identical HWSD SMU's).

3.1 Attribute database

The recoding, conversion, and handling of missing data of the base information (DSMW, ESBD, China and SOTERWIS) was already done and described in HWSD v1.2 (Nachtergaele *et al.*, 2009).

3.1.1 Recoding of the Afghanistan, Ghana and Türkiye databases

Since the release of HWSD v1.2, harmonized national soil databases had been developed for Afghanistan, Ghana, and Türkiye for national agroecological zoning assessments in those countries. Because of these assessments, soil data had already been prepared in a format consistent with HWSD v1.2. According to HWSD v1.2 standards, a geographic raster map of soil mapping units was available, along with a linked database of the dominant soil, associated soils, and soil parameters for topsoil (0–30cm) and subsoil (30–100cm).

However, because of the needs of the individual national assessments and the available sources of soil data, the country raster maps and databases were in various resolutions and qualities. The national soil databases needed to be harmonized to 30 arc-second resolution and updated to HWSD v2.0 standards in terms of soil parameter information, number of soil layers, and depth. The soil raster maps also needed to be adjusted to match the boundaries of the global HWSD v2.0 raster, with land area now based on a digital elevation model from the Japan Aerospace Exploration Agency (JAXA) using some 3 million data images acquired by the Advanced Land Observing Satellite "DAICHI" (ALOS).

First, the raster soil maps of Afghanistan and Türkiye were aggregated to 30 arc-second resolution from their respective original resolution of 7.5 and 3 arc-seconds. The most frequently occurring soil map unit within a new 30 arc-second grid-cell was selected to represent that grid-cell.

For the inland national borders, all 30 arc-second cells that were equal to or greater than 50 percent covered by national data were kept. At the land/sea coast in Türkiye, any cell with any national data at all, which was at least 5 percent land was kept. Coastlines were further adjusted to match a land/sea mask created from the ALOS DEM data. Any coastal pixels that were missing national soil information were filled in with the soil information of the nearest neighbor. The aggregation of the rasters reduced the number of mapping units by about 14 percent in

Afghanistan (from 2 287 to 1 966), and by about 15 percent in Türkiye (from 12 831 to 10 911). The soil map resolution in Ghana was already 30 arc-seconds, so it did not need to be aggregated, and only the coastline was adjusted in Ghana.

The two-layer (topsoil and subsoil) soil unit attribute data combined from various sources has been replaced and harmonized by seven-layer attributes from the WISE30sec attribute database which is organized by FAO90 soil units and Köppen-Geiger climate classes.

For this purpose, the Köppen-Geiger climate raster map from Peel et al, 2007 at 0.1 degrees was resampled using nearest-neighbor resampling to 30 arc-seconds and adjusted to HWSD v2.0 borders. The Köppen-Geiger climate mask was then overlain with the soil maps and the appropriate climate class was assigned to each SMU, according to which climate class the majority of the SMU fell within.

Finally, WRB soil classes were assigned to each soil type using the FAO90 legend and soil phase information.

3.1.2 Harmonization of the National Soil Databases

Harmonized Soil Database of Ghana (GHHSD)

Ghana Soil Research Institute (SRI) compiled a national geo-referenced soils database from existing 1:250 000 scale analogue soil maps covering entire Ghana. The Ghana soil classification system, based on the USDA Soil Taxonomy system is providing a system of soil associations made up of a total of 360 different soil series (Effland *et al.*, 2009), as documented in the SRI Soil Survey Memoirs (Adu *et al.*, 2003). The Accra office of the Ghana Soil Research Institute (SRI) compiled in 1999 a digital national geo-referenced soils database (Boateng *et al.*, 1999a, 1999b). The database contains soil association mapping units with a dominant and up to 11 associated soils series. The 360 unique soil series were correlated to FAO90 (FAO and ISRIC, 1990) soil units and soil phases.

In 2019 the digital national soil database was turned in an NAEZ/HWSD compatible Soil Database at IIASA (Fischer and van Velthuizen, 2018a) using WISE II soil profile attributes (Batjes, 2002) for respectively topsoil and subsoil layers . This data base was used for assessment of climate change impact on crop production in Ghana (Fischer *et al.*, 2022).

The NAEZ format, resolution (30 arc-seconds) with FAO90 soil classification allowed a rather straightforward conversion to HWSD v2.0. Rootable soil depth, AWC of rootable soil depth, Reference soil drainage and Reference bulk density of individual soil series and its FAO90 equivalents were re-estimated based on available general soil unit information and linked 7-layers attributes of WISE30sec database (Batjes, 2015). The 360 soil series/FAO90 units and soil phases were correlated with the WRB 2022 classification and has been included as well. Soil series acronyms/symbols are given under National Soil Information (MU_SOURCE2) link to descriptions provided in the SRI Soil Memoirs. In this way format and contents of the Ghana database are harmonized and fully compatible within HWSD v2.0.

Table 3.1 presents an extract of the GHHSD with Ghana specific data entries.

Table 3.1. Extract soil database for Ghana

ID	MU_GLOBAL	MU_SOURCE1	MU_SOURCE2	ISSOIL	SHARE	SEQ	SU_SYM90
1	2	AEA	EJA	1	40	1	ACf
2	2	AEA	KEE	1	20	2	ACf
3	2	AEA	KRO	1	10	3	ACf
4	2	AEA	ANM	1	10	4	ACf
5	2	AEA	ABO	1	5	5	LXh
6	2	AEA	ANO	1	5	6	LXf
7	2	AEA	AWU	1	5	7	LXg
8	2	AEA	NKA	1	5	8	GLe

__ID:__ Record identifier; __MU_GLOBAL:__ Global Mapping Unit Code (1–32000?); __MU_SOURCE1:__ Soil Association Symbol, AEA = Abonku-Eja/Awuaya-Nkansaku; __MU_SOURCE2:__ Soil Series Symbols, EJA = Eja, KEE = Kese, KRO = Kromantsin, ANM = Anomabu, ABO = Abonku, ANO = Anochi, AWU = Awuaya, NKA = Nkansaku; __ISSOIL:__ Soil indicator, indicates whether soil (code 1) or non-soil (code 0); __SHARE:__ Percentage occurrence of soil series within soil association; __SEQ:__ Sequence number of soil series within soil association; __SU_SYM90:__ FAO90 equivalent.

Source: Authors' own elaboration.

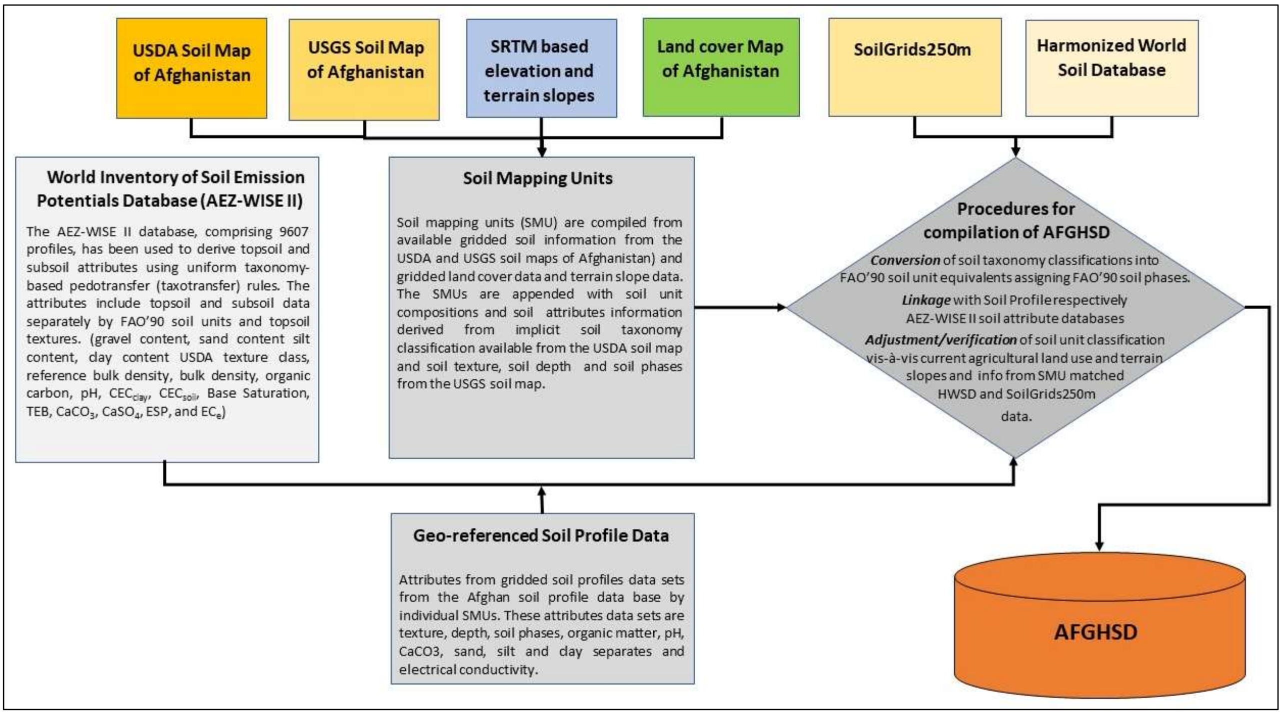
Harmonized Soil Database of Afghanistan (AFGHSD)

For a national agroecological zoning (NAEZ) study for Afghanistan a soil database was compiled to serve as source of soil resources data for spatially detailed evaluation of soil qualities and edaphic soil suitability.

The national harmonized soil database (AFGHSD) contains general soil information such as soil depth, soil drainage and occurrence of soil phases relevant for agricultural land use plus 17 HWSD soil profile attributes, each for 0–30 cm and 30–100 cm soil depth from WISE II (Batjes, 2002). For the compilation of AFGHSD, various soil resources maps and data sets (FAO and IIASA, 2019) varying in detail and quality, are used. This includes four different soil resources maps or spatial databases: (i) the USDA Soil Map of Afghanistan (USDA, 2005) (ii) the USGS Soil Map of Afghanistan (USGS) (iii) the SoilGrid250m database (Hengl *et al.*, 2017) and (iv) the Harmonized World Soil Database (HWSD). Median altitude and terrain slope data were derived from SRTM digital elevation data (Jarvis *et al*., 2008), land use/land cover data were obtained from the Land Cover Atlas of the Islamic Republic of Afghanistan (FAO, 2016). These different sources were integrated to define national soil association mapping units of the national harmonized soil database Figure 3.1.

Soil attributes in AFGHSD were compiled mainly from the World Inventory of Soil Emissions Database (WISE II). AFGHSD covers the entire territory of Afghanistan with 1 966 soil association map units with soils classified according to the revised soil legend of the FAO/UNESCO Soil Map of the World (FAO90).

Figure 3.1. Data integration for the National Afghanistan Harmonized Soil Database (AFGHSD)



Source: FAO & IIASA. 2022. *Afghanistan's agr-ecological zoning atlas. Part 2: Agroecological assessments. First revision.* Rome.

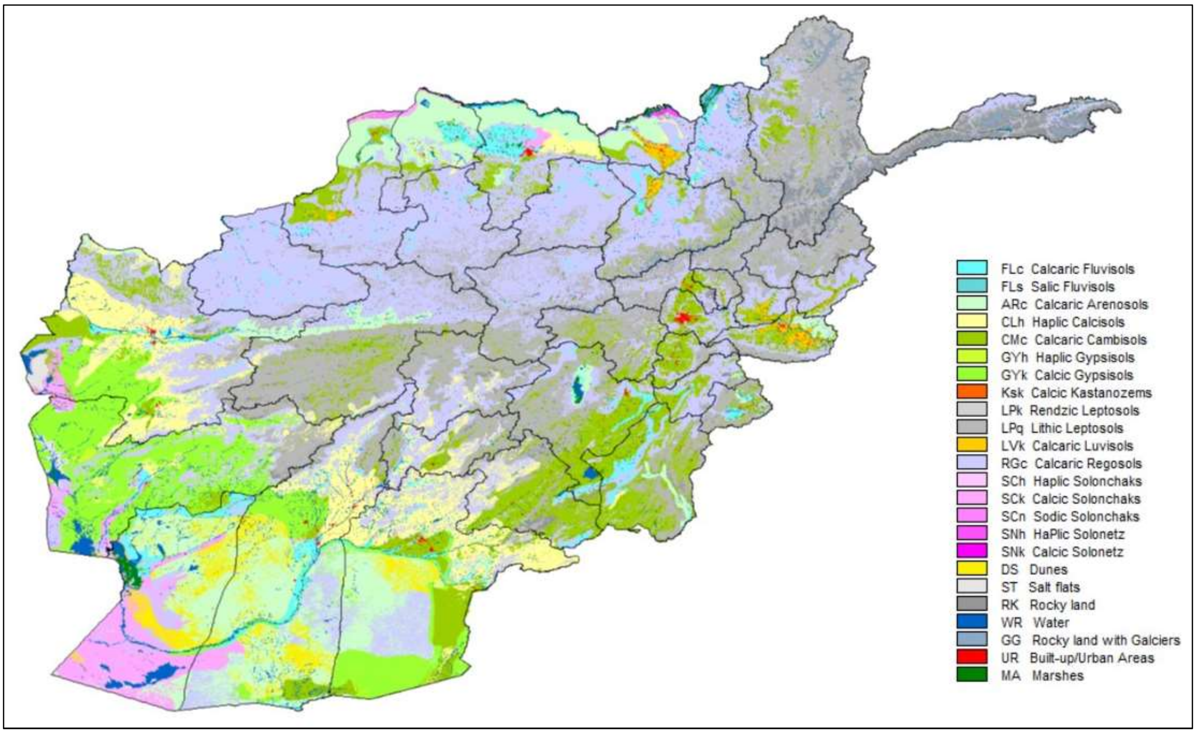
Details of make-up of AGHSD and full descriptions of the individual data layers used are fully documented in the agroecological atlas of Afghanistan Part 2 agroecological assessments, Section 1.4: Soil and Terrain Data and Annex 3: Compilation of Afghanistan Harmonized Soil Database (FAO and IIASA, 2019, 2022).

The resolution of AFGHSD is 7.5 arc-seconds, this has been aggregated to the 30 arc-second resolution to match the HWSD resolution. The AFGHSD format and soil classification allowed a rather straightforward conversion to HWSD v2.0. Rootable soil depth, AWC of rootable soil depth, Reference soil drainage and Reference bulk density were re-estimated based on available general soil unit information and linked 7-layers attributes of WISE30sec database (Batjes, 2015). The soil units were correlated with the WRB 2022 classification which is included. In this way format and contents of the AFGHSD are harmonized and fully compatible within HWSD v2.0.

Basic information layers defining soil associations and soil units are comprising Provinces (34); USDA classes (S1–S156); USGS classes (G1–G11), and Land cover/land use classes (L1–L8). These classes are provided under National Soil Information (MU_SOURCE1) in the HWSD v2.0. Full details of the individual layer classifications are provided in Annex 3 of the agroecological atlas of Afghanistan, Part 2 agroecological assessments (FAO and IIASA, 2022).

Figure 3.2 presents the national soil map (dominant soils) of Afghanistan compiled for the national agroecological zones assessment of Afghanistan.

Figure 3.2. Dominant soils of Afghanistan



Source: FAO & IIASA. 2022. *Afghanistan's agroecological zoning atlas. Part 2: Agroecological zssessments. First revision.* Rome.

Table 3.2 presents an extract of the AFGHSD with Afghanistan specific data entries.

Table 3.2. Extract soil database for Afghanistan

ID	MU_GLOBAL	MU_SOURCE1	MU_SOURCE2	ISSOIL	SHARE	SEQ	SU_SYM90
6	5	01_S036_G11_L3	-	1	90	1	LPq
7	5	01_S036_G11_L3	-	1	10	2	RGc

ID: *Record identifier;* ***MU_GLOBAL:*** *Global Mapping Unit Code (1–32000?);* ***MU_SOURCE1:*** *Soil Association Symbol, 01_S036_G11_L3;* ***MU_SOURCE2:*** *not used;* ***ISSOIL:*** *Soil indicator, indicates whether soil (code 1) or non-soil (code 0);* ***SHARE:*** *Percentage occurrence of soil series within soil association;* ***SEQ:*** *Sequence number of soil series within soil association;* ***SU_SYM90:*** *FAO90 equivalent.*
Soil Association Symbol: 01_S036_G11_L3

- *01: Province Badakhshan;*
- *S036: USDA Soil Class, Rocky land with Lithic Cryorthents, Aridic, Cryic/Frigid;*
- *G11: USGS Soil Class, Partly shallow, fine, medium, and coarse textured soils with stony phase and partly rockland, and*
- *L3: Land use/land cover, Forest, shrub land and rangeland.*

Source: Authors' own elaboration.

Harmonized Soil Database of Türkiye (TURHSD)

In the context of the FAO project: Agricultural implications for ecosystems-based adaptation (EBA) to climate change in steppe ecosystem Project (GCP/TUR/063/EC) a national agroecological zones assessment (NAEZ) was carried out at IIASA. One of the activities comprised the compilation of a detailed National Harmonized Soil Database of Türkiye (TURHSD).

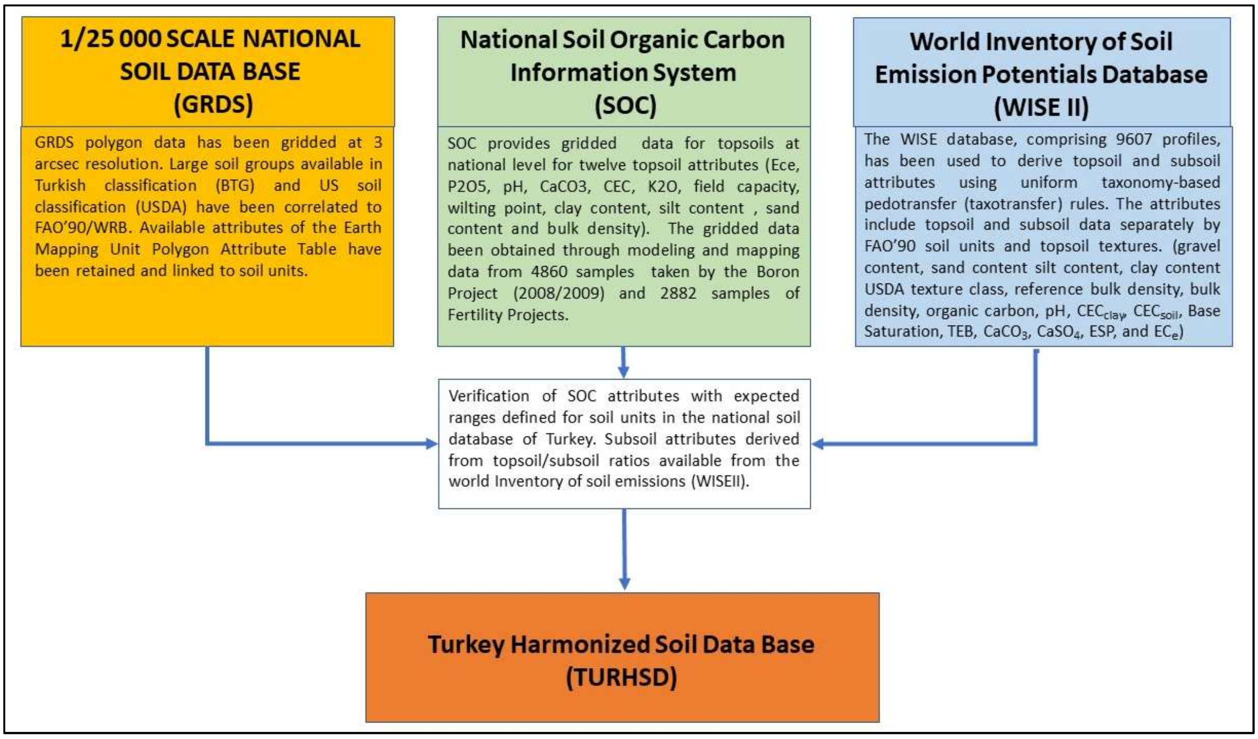
As detailed source of soil information, some 81 shape files were provided to IIASA from the 1:25 000 scale national soil database (Soil survey and soil data of Türkiye, 1966, 1971) of Türkiye established by the General Directorate of Rural Services (CDAR-TRGM, 2013). This database provides polygons of great geographical detail and gives soil information in terms of a system of Great Soil Groups (BTG, using 23 group symbols). Depending on soil group, different sets of soil attributes are attached and quantified in terms of a few attribute classes. Soil characteristics described in this way include soil depth, terrain slope, drainage, soil texture, soil salinity, erosion status, and actual land use

While these datasets are very valuable due to the great spatial detail, a disadvantage is that several soil attributes required for the NAEZ soil evaluation are not available from the 1:25 000 scale national soil database and attributes available are rather coarse for use in modelling.

For the estimation of soil properties in a harmonized way, two additional soil data bases were used, namely gridded soil attribute data from the National Soil Organic Carbon Information System (SOC) (Aksoy, 2015; Sonmez *et al.*, 2017) and from the World Inventory of Soil Emission Potentials Database (WISE II) (Batjes, 2015) which was used for the compilation of the Harmonized World Soil database (HWSD). Selected and scrutinized attribute data from these attribute datasets together with attribute data already contained in the national soil map were linked of with a gridded version of the national soil map of Türkiye. The combination of gridded soil map and attribute data is referred to as the Turkish Harmonized Soil Database (TURHSD), see Figure 3.3 below.

To allow linkage between the soil units of the national soil map of Türkiye with the WISE II attribute data, the Turkish soil classification (BTG) data has been correlated with the FAO90 soil classification. Based on data available from the publication on Integration of the Soil Database of Türkiye into European Soil Database 1:1 million scale (Aksoy *et al.*, 2010) and a recent publication of soils in Türkiye (Kapur *et al.*, 2018), in a few instances correlations were varied locally (by province). The correlations used are presented in Table 3.3 below.

Figure 3.3. Data integration for the National Harmonized Soil Database of Türkiye (TURHSD)



Source: Fischer, G. & van Velthuizen, H. 2018. *Climate change Impacts on suitability of main crops in Türkiye for agricultural implications for ecosystems-based adaptation (EBA) to climate change in steppe ecosystem Project (GCP/TUR/063/EC).* Laxenburg, Austria, IIASA and Rome, FAO.

Table 3.3. Correlations of BTG with USDA and FAO90 and miscellaneous units

Large soil group (BTG)		USDA	FAO '90	
P	Kırmızı Sarı Podzolik Topraklar	Red Yellow Podzolic Soils	ACh, LPe, LVh, LVk,	Haplic Acrisol, Eutric Leptosol, Haplic Luvisol, Calcic Luvisol
G	Gri Kahverengi Podzolik Topraklar	Gray Brown Podzolic Soils	LPe, LPq, LVh, LXh	Eutric Leptosol, Lithic Leptosol, Haplic Luvisol, Haplic Lixisol
M	Kahverengi Orman Toprakları	Brown Forest Soils	CMc, LPk, LPq	Calcaric Cambisols, Rendzic Leptosol, Lithic Leptosol
N	Kireçsiz Kahverengi Orman Topraklar	Non calcareous Brown Forest Soils	CMx, LPd, LPe, LPq	Chromic Cambisol, Dystric Leptosol, Eutric Leptosol, Lithic Leptosol
CE	Kestanerengi Topraklar	Kestanerengi Soils	KSk, LPm, LPq	Calcic Kastanozem, Mollic Leptosol, Lithic Leptosol
D	Kırmızımsı Kestanerengi Topraklar	Reddish Chestnut Soils	CMc, LPk, LPq,	Calcaric Cambisols, Rendzic Leptosol, Lithic Leptosol
T	Kırmızı Akdeniz Toprakları	Red Mediterranean Soils	LPe, LPq, LVx	Eutric Leptosol, Lithic Leptosol, Chromic Luvisol
E	Kırmızı Kahverengi Akdeniz Toprakları	Red Brown Mediterranean Soils	CMx, LPe, LPq	Chromic Cambisol, Eutric Leptosol, Lithic Leptosol
B	Kahverengi Topraklar	Brown Soils	CLh, CMc, LPk, LPq	Haplic Calcisol, Calcaric Cambisol, Rendzic Leptosol, Lithic Leptosol
U	Kireçsiz Kahverengi Topraklar	Non calcareous Brown Soils	CMe, LPe, LPq	Eutric Cambisol, Eutric Leptosol, Lithic Leptosol
F	Kırmızımsı Kahverengi Topraklar	Reddish Brown Soils	CLp, LPk, LPq	Petric Calcisol, Eutric Leptosol, Lithic Leptosol
R	Rendzinalar	Rendzina	LPk, LPq,	Rendzic Leptosol, Lithic Leptosol
V	Vertisoller	Vertisol	LPk, LPq, VRe, VRk,	Rendzic Leptosol, Lithic Leptosol Eutric Vertisol, Calcic Vertisols
Z	Sierozemler	Sierozem	CLh, LPk,	Haplic Calcisol, Rendzic Leptosol

Large soil group (BTG)		USDA	FAO '90	
L	Regosoller	Regosols	LPk, RGc	Rendzic Leptosol, Calcaric Regosol
X	Bazaltik Topraklar	Basaltic Soils	CMe, LPe, LPq	Eutric Cambisol, Eutric Leptosol, Lithic Leptosol
Y	Yüksek Dağ Çayır Topraklar	High Mountain Meadow Soils	CMu, LPm, LPq	Umbric Cambisol, Rendzic Leptosol, Lithic Leptosol
A	Alüvyal Topraklar	Alluvial Soils	FLc, Fle, FLs	Calcaric Fluvisol, Eutric Fluvisol, Salic Fluvisol
H	Hidromorfik Topraklar	Hydromorphic Soils	Gle, GLk,	Eutric Gleysol, Calcic Gleysols
S	Alüvyal Sahil Topraklar	Alluvial Coast Soil	Fle, FLs, LPe	Eutric Fluvisol, Salic Fluvisol, Eutric Leptosol
K	Kolüvyal Topraklar	Colluvial Soils	CMc, CMx, LPk, LPq	Calcaric Cambisols, Chromic Cambisol, Rendzic Leptosol, Lithic Leptosol
C	Tuzlu-Alkali Karışığı Toprakları	Salt-Alkali Soils	SCk, SCn, SNk	Calcic Solonchak, Sodic Solonchak, Calcic Solonetz
O	Organik Topraklar	Organic Soils	HS	Histosol
RK	Bare Rock	-	-	Bare Rock
RV	River bed	-	-	Open Water
DU	Coastal dunes	-	-	Dunes and Shifting Sands
SD	Sand dunes	-	-	Dunes and Shifting Sands
MS	Marsh	-	-	Marshes
SN	Permanent snow	-	-	Glaciers and Permanent Snow
TZ	River delta	-	-	Open Water
WA	Water	-	-	Open Water
BJ	Dam	-	-	Open Water
SA	Settlement	-	-	Urbic Anthrosols
IA	Industrial area	-	-	Urbic Anthrosols
TA	Tourism area	-	-	Urbic Anthrosols
NP	National Park	-	-	Soils to be determined
ND	No data	-	-	No data

Source: Fischer, G. & van Velthuizen, H. 2018. *Climate change Impacts on suitability of main crops in Türkiye for agricultural implications for ecosystems-based adaptation (EBA) to climate change in steppe ecosystem Project (GCP/TUR/063/EC).* Laxenburg, Austria, IIASA and Rome, FAO.

The TURHSD contains 10911 different soil map units, which are linked to harmonized attribute data. Use of a standardized structure (HWSD) allows linkage of the attribute data of topsoil (0–

30 cm) and subsoil (30–100 cm) in terms of soil units and the characterization of selected soil parameters (organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry. The TURHSD is composed of a GIS raster image file linked to an attribute database in Microsoft Access format. There are three blocks of data: (i) General information on the soil mapping unit composition; (ii) Information related to Soil phases, and (iii) Physico-chemical properties of topsoil (0–30 cm) and subsoil (30–100 cm).

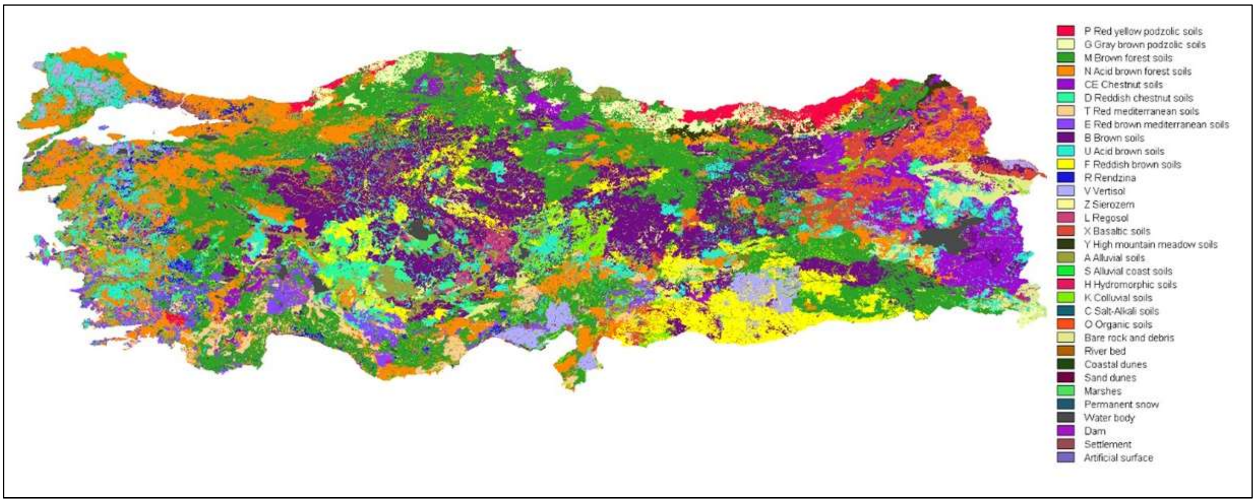
Details of make-up of TURHSD and full descriptions of data used is documented in the IIASA/FAO Report: Climate Change Impacts on Suitability and Yields of Main Crops in Türkiye, Section 2.3.3 Türkiye Harmonized Soil Database (Fischer and van Velthuizen, 2018b).

The resolution of TURHSD is 3 arc-sec, this has been aggregated to the 30 arc-second resolution to match the HWSD resolution. The TURHSD format and soil classification allowed a rather straightforward conversion to HWSD v2.0. Rootable soil depth, AWC of rootable soil depth, Reference soil drainage and Reference bulk density were re-estimated based on available general soil unit information and linked 7-layers attributes of WISE30sec database (Batjes, 2015). The soil units were correlated with the WRB 2022 classification which is included. In this way format and contents of the AFGHSD are harmonized and fully compatible within HWSD v2.0

Basic information layers defining soil associations and soil units are comprising provinces (1–81); BTG soil unit/miscellaneous unit codes (one or two characters) comprising 23 soil unit and 14 miscellaneous unit classes) where for A, H, S, K, C, O the (one) character is followed by FAO texture class number (1–3): slope class (1–6): soil depth class (A–E), and soil phase codes of three soil phases: soil phase 1, salinity/alkalinity (1–5), soil phase 2, stoniness (1–3), soil phase 3, drainage (1–2). The coding is included in HWSD v2.0 under National Soil Information (MU_SOURCE1), see Figure 3.4 and Source: *Fischer, G. & van Velthuizen, H. 2018.* Climate change Impacts on suitability of main crops in Türkiye for agricultural implications for ecosystems-based adaptation (EBA) to climate change in steppe ecosystem Project (GCP/TUR/063/EC). *Laxenburg, Austria, IIASA and Rome, FAO.*

Table 3.4. Full details are provided in (Fischer and van Velthuizen, 2018a).

Figure 3.4. Soils of Türkiye and miscellaneous units



Source: Fischer, G. & van Velthuizen, H. 2018. *Climate change Impacts on suitability of main crops in Türkiye for agricultural implications for ecosystems-based adaptation (EBA) to climate change in steppe ecosystem Project (GCP/TUR/063/EC).* Laxenburg, Austria, IIASA and Rome, FAO.

Table 3.4. Extract soil database for Türkiye

ID	MU_GLOBAL	MU_SOURCE1	MU_SOURCE2	ISSOIL	SHARE	SEQ	SU_SYM90
1	1	01_M_1A_000		1	100	1	CMc

ID: *Record identifier;* ***MU_GLOBAL:*** *Global Mapping Unit Code (1–32000?);* ***MU_SOURCE1:*** *Soil Association Symbol, 01_M_1A_000;* ***MU_SOURCE2:*** *not used;* ***ISSOIL:*** *Soil indicator, indicates whether soil (code 1) or non-soil (code 0);* ***SHARE:*** *Percentage occurrence of soil series within soil association;* ***SEQ:*** *Sequence number of soil series within soil association;* ***SU_SYM90:*** *FAO90 equivalent.*
Soil Association Symbol: 01_M_1A_000

- *01: Province Adana;*
- *M: BTG Soil unit code, Kahverengi Orman Toprakları/Brown Forest Soils;*
- *1: Terrain slope class, 0–2% (Class 1 = 0–2%, Class 2 = 2–6%, Class 3 = 6–12%, Class 4 = 12–20%, Class 5 = 20–30%, Class 6 = >30%);*
- *A: Soil depth, Deep (Class A = deep (>90 cm), Class B = mid deep (50–90 cm), Class C = shallow (20–50 cm), Class D = very shallow (0–20 cm), Class E = Lithosolic);*
- *0: Phase code 1 for salinity/alkalinity, No salinity/alkalinity (Class 0 = No salinity/alkalinity, Class 1 = slightly salty, Class 2 = salty, Class 3 = alkaline, Class 4 = slightly salty and alkaline, Class 5 = salty and alkaline);*
- *0: Phase code 2 for stoniness, No stoniness (Class 0 = no stoniness, Class 1 = stony, Class 2 = rocky, Class 3 = stony/rocky);*
- *0: Phase code 3 for Drainage, No poor or imperfect drainage (Class 0 = No poor or imperfect drainage, Class 1 = imperfect drainage, Class 2= poor drainage).*

Source: Authors' own elaboration.

WISE30sec source data: in WISE30sec there are a small number (about 90) of additional mapping units identified compared to HWSD v1.2, mainly in the Sinai Peninsula and the Namibia desert**.** These have been included in HWSD v2.0.

3.1.3 Verification of soil unit shares in soil associations and textural components

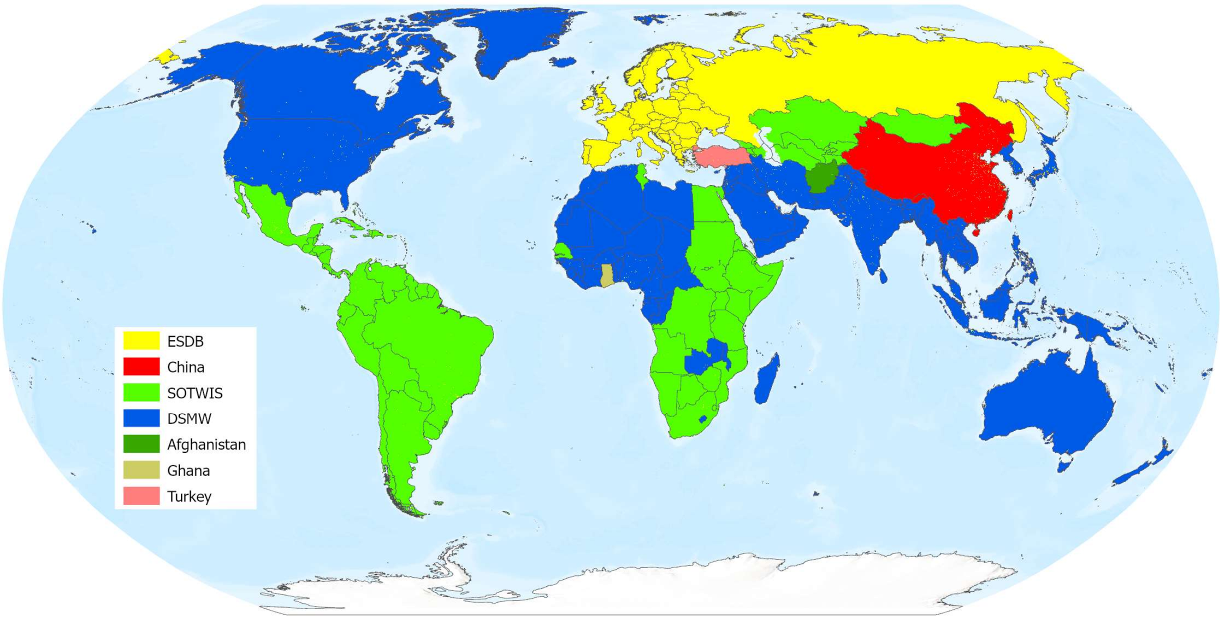
The SHARE and SEQUENCE fields. Data inconsistencies with the sum of SHARES in a soil mapping unit not corresponding to 100 percent have been corrected. When the SHARE was not equal to 100, the shares were adjusted to sum up to 100. In all cases, the sum was close to 100 and the largest share in the soil mapping unit was modified to obtain a sum of 100.

Sum of soil components. The sum of sand, silt and clay fractions in top and subsoil was corrected to 100 percent in the cases where necessary to rounding errors. In general when the sum was less 100, the largest percentage was increased to obtain 100. When the sum exceeded 100, the highest value was reduced to obtain a sum of 100.

3.2 Soil geographical areas

The spatial data layer of HWSD v1.2 databases (Nachtergaele *et al.*, 2012) updated for WISE30sec was used. The WISE30sec update involved individual mapping units in Siberia, the Sinai and Namibia. Further for three countries: Afghanistan, Ghana, and Türkiye the original DSMW soil geographic areas have been replaced by national spatial soil data. All data of HWSD v2.0 is represented in a uniform 30 arc-second lat./lon. grid.

Figure 3.5. Source areas and countries in HWSD v2.0



Source: Authors' own elaboration based on United Nations Geospatial. 2020. Map geodata [shapefiles]. New York, USA, United Nations. Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Country boundaries and coastal boundaries have been updated using the Global Administrative Units Layer (GAUL) (FAO, 2015). Soil coverage sources of the European Soil Bureau Database exclude in the case of France, Spain, and Portugal certain overseas territories not covered by ESDB. These were taken from DSMW, they include Madeira and Azores (Portugal); Canary Islands (Spain). Further Svalbard and Jan Mayen are not covered by any soil database and a missing data value was assigned. The territory of Antarctica is not included in HWSD v2.0. Figure 3.5 presents the regional distribution of the data sources used for HWSD v2.0.

The spatial occurrence of soil mapping units varies by region depending on the data source. The most common resolution represents approximately a 1:1 million map scale and can be found in China, the territory covered by ESDB West and Central Europe, and the SOTWIS database covering Eastern and Southern Africa, Latin America and Northern Eurasia. Source data of Afghanistan, Ghana and Türkiye represent mapping scales between 1:25 000 in Türkiye, 1:250 000 in Ghana and 1:1 million in Afghanistan. The remaining areas, the US, Canada, Australia and parts of Southeast Asia and West Africa are covered by Digital Soil Map of the World (at 1:5 million scale). Spatial reliability is largely relative to original soil map scales. Areas with single soil mapping units (China and Türkiye) are considered less reliable than soil association mapping units consisting of dominant soil units, associated soil units and inclusions.

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ANNEX I: SOIL CLASSIFICATION

To harmonize soil units derived from several different sources, HWSD v2.0 uses a single soil classification, the Revised Legend of the Soil Map of the World (FAO *et al.*, 1990). This classification has been correlated with the present international standard, the World Reference Base for Soil Resources (IUSS Working Group WRB, 2022).

AI.1 Introduction

Although the principles of soil classification have changed little over the last 60 years since the publication of the Seventh Approximation (Soil Survey Staff, 1960), the rules and definitions that have been elaborated within the internationally accepted standard soil taxonomies have changed significantly, for instance in The World Reference Base for Soil Resources (IUSS Working Group WRB, 1998, 2006, 2014, 2022) new Reference Soil Groups were created or renamed and definitions and importance of diagnostic materials, properties and horizons have evolved over time.

Table AI.1. Evolution of the criteria and limits for the Ferralic and Oxic horizons in major soil taxonomies between 1960 and 2022

Taxonomic system	**7th approx. 1960**	**FAO 1974**	**FAO 1988**	**WRB 2014**	**ST2014**	**WRB 2022**
Characteristic name	**Oxic**	**Oxic**	**Ferralic**	**Ferralic**	**Oxic**	**Ferralic**
Texture Class		SL or finer	SL or finer	SL or finer	SL or finer	SL or finer
Thickness		>30cm	>30cm	>30 cm	>30cm	>30cm
CECclay	(<20)	<16	<16	<16	<16	<16
Weatherable minerals	<1%	Traces	<10%	<10%	<10%	<10%
Andic properties			No	No	No	No
Exch Bases+Exch Acidity		<10	<12	<12	<12	
Rock structure	Little or none	<5%	<5%		<5%	
Clay	>15%	>15%				>8%
Argillic/Natric		Not Allowed	Allowed	Allowed	NO clay increase	Allowed
Horizon Boundaries		Gradual/ Diffuse			Diffuse	
Silt/Clay ratio			<0.2			
Sesquioxides/1:1 Clay	<12					
Soil structure	Blocky or many pores					
Coarse fragments				<80%		<80%
Water dispersible clay	Low			<10% or		
Geric properties				YES or		
Organic carbon				>1.4%		

Source: Authors' own elaboration.

One of many examples is illustrated in Table AI.1 where the green areas correspond to criteria that are exactly the same in all classification systems since 1960 and red areas where significant differences occurred.

Consequently, the correlation between classification systems has become more difficult and there is rarely a one-to-one correspondence between the unit names in different taxonomic systems.

The Harmonized World Soil Database (HWSD v1.2, Nachtergaele *et al.,* 2012) used different versions of the FAO legend of the soil map of the world (CEC, 1985; FAO *et al.*, 1990; FAO and UNESCO, 1974) as they were applied in the regional maps and databases used to construct HWSD. In the present approach the FAO 1990 version is used, based on soil correlations undertaken by ISRIC to construct the WISE30sec database (Batjes, 2015). In this version of HWSD a correlation of the soils is made with the latest version of the established international soil classification system, WRB (IUSS Working Group WRB, 2022). This was previously undertaken for Africa (Dewitte *et al*., 2013) but did not cover temperate and boreal soils and used an older version (2006) of WRB.

AI.2 Soil unit correlation between FAO90 and WRB 2022

The correspondence for each of the 152 Soil Units recognized in FAO90 in WRB 2022 terms is given in Table AI.2. In normal script are those units that have hardly changed in name (although their definitions may not be exactly the same), in red are given the units that changed at the highest level of classification. For instance the Greyzems of the FAO90 are no longer used in WRB, while WRB defined new units at the highest level that only existed at a lower level in FAO90 such as Cryosols, Technosols and Stagnosols. Other units at the highest level maintained a similar concept but underwent a name change such as Podzoluvisols renamed as Retisols.

Table AI.2. Soil correlation between FAO90 and WRB 2022

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
	Acrisols		**Acrisols**
AC	Acrisols	**AC**	Acrisols
ACf	Ferric Acrisols	**ACfr**	Ferric Acrisols
ACg	Gleyic Acrisols	**ACgl**	Gleyic Acrisols
ACh	Haplic Acrisols	**ACha**	Haplic Acrisols
ACp	Plinthic Acrisols	**PTha**	Haplic Plinthosols
ACu	Humic Acrisols	**UMac**	Acric Umbrisols
	Alisols		**Alisols**
AL	Alisols	**AL**	Alisols
ALf	Ferric Alisols	**ALfr**	Ferric Alisols
ALg	Gleyic Alisols	**ALgl**	Gleyic Alisols
ALh	Haplic Alisols	**ALha**	Haplic Alisols
ALp	Plinthic Alisols	**PTha**	Haplic Plinthosols
ALj	Stagnic Alisols	**STal**	Alic Stagnosols
ALu	Humic Alisols	**UMal**	Alic Umbrisols
	Andosols		**Andosols**
AN	Andosols	**AN**	Andosols

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
ANg	Gleyic Andosols	**ANgl**	Gleyic Andosols
ANh	Haplic Andosols	**ANdy**	Dystric Andosols
ANi	Gelic Andosols	**CRan**	Andic Cryosols
ANm	Mollic Andosols	**ANmo**	Mollic Andosols
ANu	Umbric Andosols	**ANum**	Umbric Andosols
ANz	Vitric Andosols	**ANvi**	Vitric Andosols
	Anthrosols		**Anthrosols**
AT	Anthrosols	**AT**	Anthrosols
ATa	Aric Anthrosols	**AT**	Anthrosols
ATc	Cumulic Anthrosols	**AThy**	Hydrargic Anthrosols
ATf	Fimic Anthrosols	**ATht**	Hortic Anthrosols
ATu	Urbic Anthrosols	**TC**	Technosols
	Arenosols		**Arenosols**
AR	Arenosols	**AR**	Arenosols
ARa	Albic Arenosols	**ARcl**	Claric Arenosols
ARb	Cambic Arenosols	**ARbr**	Brunic Arenosols
ARc	Calcaric Arenosols	**ARca**	Calcaric Arenosols
ARg	Gleyic Arenosols	**GLar**	Arenic Gleysols
ARh	Haplic Arenosols	**AR**	Arenosols
ARl	Luvic Arenosols	**ARqg**	Protoargic Arenosols
ARo	Ferralic Arenosols	**ARse**	Sideralic Arenosols
	Chernozems		**Chernozems**
CH	Chernozems	**CH**	Chernozems
CHg	Gleyic Chernozems	**CHgl**	Gleyic Chernozems
CHh	Haplic Chernozems	**CHha**	Haplic Chernozems
CHk	Calcic Chernozems	**CHcc**	Calcic Chernozems
CHl	Luvic Chernozems	**CHlv**	Luvic Chernozems
CHw	Glossic Chernozems	**CHto**	Tonguic Chernozems
	Calcisols		**Calcisols**
CL	Calcisols	**CL**	Calcisols
CLh	Haplic Calcisols	**CLha**	Haplic Calcisols
CLl	Luvic Calcisols	**CLlv**	Luvic Calcisols
CLp	Petric Calcisols	**CLpt**	Petric Calcisols
	Cambisols		**Cambisols**
CM	Cambisols	**CM**	Cambisols
CMc	Calcaric Cambisols	**CMca**	Calcaric Cambisols
CMd	Dystric Cambisols	**CMdy**	Dystric Cambisols
CMe	Eutric Cambisols	**CMeu**	Eutric Cambisols
CMg	Gleyic Cambisols	**CMgl**	Gleyic Cambisols
CMi	Gelic Cambisols	**CRcm**	Cambic Cryosols
CMo	Ferralic Cambisols	**CMfl**	Ferralic Cambisols
CMu	Humic Cambisols	**UMcm**	Cambic Umbrisols
CMv	Vertic Cambisols	**CMvr**	Vertic Cambisols
CMx	Chromic Cambisols	**CMcr**	Chromic Cambisols
	Fluvisols		**Fluvisols**

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
FL	Fluvisols	**FL**	Fluvisols
FLc	Calcaric Fluvisols	**FLca**	Calcaric Fluvisols
FLd	Dystric Fluvisols	**FLdy**	Dystric Fluvisols
Fle	Eutric Fluvisols	**FLeu**	Eutric Fluvisols
FLm	Mollic Fluvisols	**PHfv**	Fluvic Phaeozems
FLs	Salic Fluvisols	**SCfv**	Fluvic Solonchaks
FLt	Thionic Fluvisols	**GLti**	Thionic Gleysols
FLu	Umbric Fluvisols	**UMfv**	Fluvic Umbrisols
	Ferralsols		**Ferrasols**
FR	Ferralsols	**FR**	Ferrasols
FRg	Geric Ferralsol	**FRgr**	Geric Ferralsols
FRh	Haplic Ferrasols	**FRha**	Haplic Ferrasols
FRp	Plinthic Ferrasols	**PTgr**	Geric Plinthosols
FRr	Rhodic Ferrasols	**FRro**	Rhodic Ferrasols
FRu	Humic Ferrasols	**FRum**	Umbric Ferrasols
FRx	Xanthic Ferrasols	**FRxa**	Xanthic Ferrasols
	Gleysols		**Gleysols**
GL	Gleysols	**GL**	Gleysols
GLa	Andic Gleysols	**GLan**	Andic Gleysols
GLd	Dystric Gleysols	**GLdy**	Dystric Gleysols
GLe	Eutric Gleysols	**GLeu**	Eutric Gleysols
GLi	Gelic Gleysols	**CRgl**	Gleyic Cryosols
GLk	Calcic Gleysols	**GLcc**	Calcic Gleysols
GLm	Mollic Gleysols	**GLmo**	Mollic Gleysols
GLt	Thionic Gleysols	**GLsf**	Sulfidic Gleysols
GLu	Umbric Gleysols	**GLum**	Umbric Gleysols
	Greyzems		**Phaeozems**
GR	Greyzems	**PHgz**	Greyzemic Phaeozems
GRg	Gleyic Greyzems	**PHglgz**	Greyzemic Gleyic Phaeozems
GRh	Haplic Greyzems	**PHgz**	Greyzemic Phaeozems
	Gypsisols		**Gypsisols**
GY	Gypsisols	**GY**	Gypsisols
GYh	Haplic Gypsisols	**GYha**	Haplic Gypsisols
GYk	Calcic Gypsisols	**GYcc**	Calcic Gypsisols
GYl	Luvic Gypsisol	**GYlx**	Luvic Gypsisols
GYp	Petric Gypsisols	**GYpt**	Petric Gypsisols
	Histosols		**Histosols**
HS	Histosols	**HS**	Histosols
HSf	Fibric Histosols	**HSfi**	Fibric Histosols
HSi	Gelic Histosols	**HScr**	Cryic Histosols
HSl	Folic Hisols	**HSfo**	Folic Histosols
HSs	Terric Histosols	**HSsa**	Sapric Histosols
HSt	Thionic Histosols	**HSti**	Thionic Histosols
	Kastanozems		**Kastanozems**
KS	Kastanozems	**KS**	Kastanozems

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
KSh	Haplic Kastanozems	**KSha**	Haplic Kastanozem
KSk	Calcic Kastanozems	**KScc**	Calcic Kastanozems
KSl	Luvic Kastanozems	**KSlv**	Luvic Kastanozems
KSy	Gypsic Kastanozems	**KSgy**	Gypsic Kastanozems
	Leptosols		**Leptosols**
LP	Leptosols	**LP**	Leptosols
LPd	Dystric Leptosols	**LPdy**	Dystric Leptosols
LPe	Eutric Leptosols	**LPeu**	Eutric Leptosols
LPi	Gelic Leptosols	**CRlp**	Leptic Cryosols
LPk	Rendzic Leptosols	**LPrz**	Rendzic Leptosols
LPm	Mollic Leptosols	**LPmo**	Mollic Leptosols
LPq	Lithic Leptosols	**LPli**	Lithic Leptosols
LPu	Umbric Leptosols	**LPum**	Umbric Leptosols
	Luvisols		**Luvisols**
LV	Luvisols	**LV**	Luvisols
LVa	Albic Luvisols	**LVab**	Albic Luvisols
LVf	Ferric Luvisols	**LVfr**	Ferric Luvisols
LVg	Gleyic Luvisols	**LVgl**	Gleyic Luvisols
LVh	Haplic Luvisols	**LVha**	Haplic Luvisols
LVj	Stagnic Luvisols	**STlv**	Luvic Stagnosols
LVk	Calcic Luvisols	**LVcc**	Calcic Luvisols
LVv	Vertic Luvisols	**LVvr**	Vertic Luvisols
LVx	Chromic Luvisols	**LVcr**	Chromic Luvisols
	Lixisols		**Lixisols**
LX	Lixisols	**LX**	Lixisols
LXa	Albic Lixisols	**LXab**	Albic Lixisols
LXf	Ferric Lixisols	**LXfr**	Ferric Lixisols
LXg	Gleyic Lixisols	**LXgl**	Gleyic Lixisols
LXh	Haplic Lixisols	**LXha**	Haplic Lixisols
LXj	Stagnic Lixisols	**STlx**	Lixic Stagnosols
LXp	Plinthic Lixisols	**PTli**	Lixic Plinthosols
	Nitisols		**Nitisols**
NT	Nitisols	**NT**	Nitisols
NTh	Haplic Nitisols	**NT**	Nitisols
NTr	Rhodic Nitisols	**NTro**	Rhodic Nitisols
NTu	Humic Nitisols	**NThu**	Humic Nitisols
	Phaeozems		**Phaeozem**
PH	Phaeozems	**PH**	Phaeozems
PHc	Calcaric Phaeozems	**PHcc**	Calcaric Phaeozems
PHg	Gleyic Phaeozems	**PHgl**	Gleyic Phaeozems
PHh	Haplic Phaeozems	**PHha**	Haplic Phaeozems
PHj	Stagnic Phaeozems	**STmo**	Mollic Stagnosols
PHl	Luvic Phaeozems	**PHlv**	Luvic Phaeozems
	Planosols		**Planosols**
PL	Planosols	**PL**	Planosols

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
PLd	Dystric Planosols	**PLdy**	Dystric Planosols
PLe	Eutric Planosols	**PLeu**	Eutric Planosols
PLi	Gelic Planosols	**CRap**	Abruptic Cryosol
PLm	Mollic Planosols	**PLmo**	Mollic Planosols
PLu	Umbric Planosols	**PLum**	Umbric Planosols
	Plinthosols		**Plinthosols**
PT	Plinthosols	**PT**	Plinthosols
PTa	Albic Plinthosols	**PTab**	Albic Plinthosols
PTd	Dystric Plinthosols	**PTdy**	Dystric Plintohsols
PTe	Eutric Plinthosols	**PTeu**	Eutric Plinthosols
PTu	Humic Plinthosols	**PTum**	Humic Plinthosols
	Podzols		**Podzols**
PZ	Podzols	**PZ**	Podzols
PZb	Cambic Podzol	**PZet**	Entic Podzol
PZc	Carbic Podzols	**PZcb**	Carbic Podzols
PZf	Ferric Podzol	**PZrs**	Rustic Podzol
PZg	Gleyic Podzols	**PZgl**	Gleyic Podzols
PZh	Haplic Podzols	**PZal**	Albic Podzols
Pzi	Gelic Podzol	**CRsd**	Spodic Cryosol
	Podzoluvisols		**Retisols**
PD	Podzoluvisols	**RT**	Retisols
PDd	Dystric Podzoluvisols	**RTdy**	Dystric Retisols
PDe	Eutric Podzoluvisols	**RTeu**	Eutric Retisols
PDg	Gleyic Podzoluvisols	**RTgl**	Gleyic Retisols
PDi	Gelic Podzoluvisol	**CRrt**	Retic Cryosols
PDj	Stagnic Podzoluvisols	**STrt**	Retic Stagnosols
	Regosols		**Regosols**
RG	Regosols	**RG**	Regosols
RGc	Calcaric Regosols	**RGca**	Calcaric Regosols
RGd	Dystric Regosols	**RGdy**	Dystric Regosols
RGe	Eutric Regosols	**RGeu**	Eutric Regosols
RGi	Gelic Regosols	**CRha**	Haplic Cryosols
RGu	Umbric Regosols	**UMha**	Haplic Umbrisols
RGy	Gypsiric Regosols	**RGgp**	Gypsiric Regosols
	Solonchaks		**Solonchaks**
SC	Solonchaks	**SC**	Solonchaks
SCg	Gleyic Solonchaks	**SCgl**	Gleyic Solonchaks
SCh	Haplic Solonchaks	**SCha**	Haplic Solonchaks
SCi	Gelic Solonchaks	**CRsz**	Salic Cryosols
SCk	Calcic Solonchaks	**SCcc**	Calcic Solonchaks
SCm	Mollic Solonchaks	**SCmo**	Mollic Solonchaks
SCn	Sodic Solonchaks	**SCso**	Sodic Solonchaks
Scy	Gypsic Solonchaks	**SCgy**	Gypsic Solonchaks
	Solonetz		**Solonets**
SN	Solonetz	**SN**	Solonetz

FAO90		WRB 2022	
Code	**Name**	**Code**	**Name**
SNg	Gleyic Solonetz	**SNgl**	Gleyic Solonetz
SNh	Haplic Solonetz	**SNha**	Haplic Solonetz
SNj	Stagnic Solonetz	**SNst**	Stagnic Solonetz
SNk	Calcic Solonetz	**SNcc**	Calcic Solonetz
SNm	Mollic Solonetz	**SNmo**	Mollic Solonetz
SNy	Gypsic Solonetz	**SNgy**	Gypsic Solonetz
	Vertisols		**Vertisols**
VR	Vertisols	**VR**	Vertisols
VRd	Dystric Vertisols	**VRha**	Haplic Vertisols
VRe	Eutric Vertisols	**VRha**	Haplic Vertisols
VRk	Calcic Vertisols	**VRcc**	Calcic Vertisols
Vry	Gypsic Vertisols	**VRgy**	Gypsic Vertisols

Source: Authors' own elaboration.

The soil that is classified within the World Reference Base is the epiderm of the Earth (Nachtergaele, 2005) and is "*any material within 2 m of the Earth's surface that is in contact with the atmosphere, excluding living organisms, areas with continuous ice not covered by other material, and water bodies deeper than 2 m*". This has implications for areas that formerly were mapped as non-soils such as Salt Flats (Hypersalic Solonchaks). Urban areas and infrastructure considered as Technosols and Dunes and Shifting Sands that would be mapped in WRB as Aeolic and Protic Arenosols (see Table AI.3).

Table AI.3. Miscellaneous units in HWSD and their WRB 2022 classification

Symbol	Miscellaneous unit	WRB 2022	WRB 2022 name
DS	Dunes and Shifting Sands	ARpr and ARay	Protic and Aeolic Arenosols
FP	Fishponds	AT	Undifferentiated Anthrosols
GG	Glaciers	GG	Glaciers
HD	Human disturbed	AT	Undifferentiated Anthrosols
IS	Small Islands	IS	Small Islands
RK	Bare Rock	LPnt	Nudilithic Leptosols
ST	Salt flats	SCjz	Hypersalic Solonchaks
UR	Urban	TC	Undifferentiated Technosols
WR	Open Water	WR	Open Water

Source: Authors' own elaboration.

AI.3 Soil phases affecting the classification in WRB

A special problem for the classification is the effect of soil phases that are properties of importance to soil management, and are not necessarily related to the main pedogenetic processes used to classify a soil. Thirty soil phases were considered in HWSD v1.2, based on information present in the source mapping material. Since 1990, there has been a clear evolution in WRB to incorporate soil phases in soil names. For instance the petrocalcic phase of FAO74 was recognized as a specific soil unit, a Petric Calcisol in FAO90. This process has accelerated in the development of WRB that gives as much attention to the classification of individual profiles as to the extent and global importance of certain soil types. Consequently, the presence of a phase inventoried in HWSD v1.2 does affect the WRB soil name. An overview of the phases as mapped in HWSD v1.2 and their equivalent in WRB is given in Table AI.4.

The most widespread phases that affect the WRB classification are: stony, lithic and gravelly, or in WRB terms Akroskeletic (stony and gravelly) and Leptic (lithic). These phases are relevant for many WRB Reference Soil Groups (Table AI.5).

There are a number of objections to use the phase information: (a) phases have not been mapped consistently in the source material (b) in the correlation from FAO74 to FAO90 in WISE30sec phases were not taken into account (c) the SOTWIS area has not included phase information (d) in WISE30sec the statistics to estimate soil unit characteristics were based on soil unit names and climate.

Table AI.4. Soil phases and their equivalent name and use in WRB

Phase name	Equivalent WRB qualifier	SRG	Phase name	Equivalent WRB qualifier	SRG
Stony	Akroskeletic (kk)	Many	Sodic	Protosodic (qs)	Some
Lithic	Leptic (lp)	Many	Anthraquic	Anthraquic (aq)	Some/ Anthrosols
Petric	Plinthic (pl)	Some/ Plinthosols	Placic	Placic (pi), Ortsteinic (os)	Some/ Podzols
Petrocalcic	Petrocalcic (pc)	Some/ Calcisols	Rudic	Akroskeletic (kk)	Many
Petrogypsic	Petrogypsic (pg)	Some/ Gypsisols	Skeletic	Skeletic (sk)	Many
Petroferric	Petroplinthic (pp)	Some/ Plinthosls	Takyric	Takyric (ty)	Some
Fragipan	Fragic (fg)	Some	Yermic	Yermic (ye)	Some
Duripan	Duric (du)	Some/ Durisols	Gravelly	Skeletic (sk)/ Coarsic (cs)	Some
Salic	Protosalic (supp.qualif)	Not used	Concretionary	Akroskeletic (kk)	Some

Source: Authors' own elaboration.

Table AI.5. Soil phases used as principal qualifier in reference soil groups (WRB 2022)

Phase linked RSG / principal qualifier	**Reference soil group (WRB 2022)**																														
	HI	**AT**	**TC**	**CR**	**LP**	**SN**	**VR**	**SC**	**GL**	**AN**	**PZ**	**PT**	**PL**	**ST**	**NT**	**FR**	**CH**	**KS**	**PH**	**UM**	**DU**	**GY**	**CL**	**RT**	**AC**	**LX**	**AL**	**LV**	**CM**	**FL**	**AR**	**RG**
Leptic	X		X	X			X	X		X	X		X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Plinthic									X																							
Petrocalcic							X	X									X	X	X		X	X	X									
Petrogypsic								X										X			X	X										
Plinthosols / Plinthic												X																				
Fragic																				X				X	X	X	X	X	X			
Durisols / Duric							X			X			X				X	X	X		X											
Anthraquic		X					X		X	X			X	X	X				X						X	X	X	X	X			
Turbic				X																												
Ortsteinic / Placic											X																					
Skeletic	X			X	X					X	X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Takyric					X	X		X													X	X	X			X		X	X	X		X
Yermic				X	X	X		X													X	X	X			X		X	X	X	X	X
Coarsic	X		X	X	X						X	X									X	X	X									

Source: Authors' own elaboration.

However, an overriding consideration to maintain soil phases in HWSD is the fact that they are used extensively in the Global Agroecological Zoning edaphic evaluation (Fischer *et al*., 2021).

The following was undertaken to reflect the phases in the WRB soil unit codes.

- Stony, Skeletic and Lithic Soil phases were re-introduced in the SOTWIS area on the basis of information contained in the original SMW material. Phases in all other source material were maintained;
- The WRB soil unit name, correlated with the FAO90 soil unit name as given in Table AI.2 was maintained without taking into account the presence of phases. However the WRB soil code, given between brackets after the soil unit name, does take into account the phases;
- When two phases were present both phases were included in the WRB soil code;
- There may be a contradiction between the WRB soil unit name and the name that would correspond with the one given in the code, because of the phase information;
- Only the Primary Qualifiers of the WRB classification were retained in the soil code (with as exceptions accepting claric in Arenosols as a primary qualifier (for albic Arenosols in FAO90 and Arenic in Gleysols), and
- The sequence of primary qualifiers as given in WRB was retained. The stony and rudic phase correspond with akroskeletic (kk) in WRB, therefore Akroskeletic was used in the same place as skeletic in the primary qualifiers.

Some examples are given in Table AI.6.

Table AI.6. Examples of correlations between FAO90 and WRB 2022 soil classification

FAO90	WRB2022	Phase1	Phase2	WRB final	WRB name
ACf	ACfr			ACfr	Ferric Acrisol
ACf	ACfr	6 (petroferric)	PTac	Acric Plinthosol	
ACh	ACha	1 (stony)	2 (lithic)	AClekk	Akroskeletic Leptic Acrisol

Source: Authors' own elaboration.

AI.4 Supplementary qualifiers

In HWSD v2.0 the WRB supplementary qualifiers are not explicitly mentioned in the soil names. They can however easily be deduced from the attributes, in particular those qualifiers related to textural class (arenic, loamic, siltic and clayic), organic carbon content (humic/ochric), base saturation (eutric/dystric), or $CaCO_3$ content (calcaric) in the Reference Soil Groups where they are relevant.

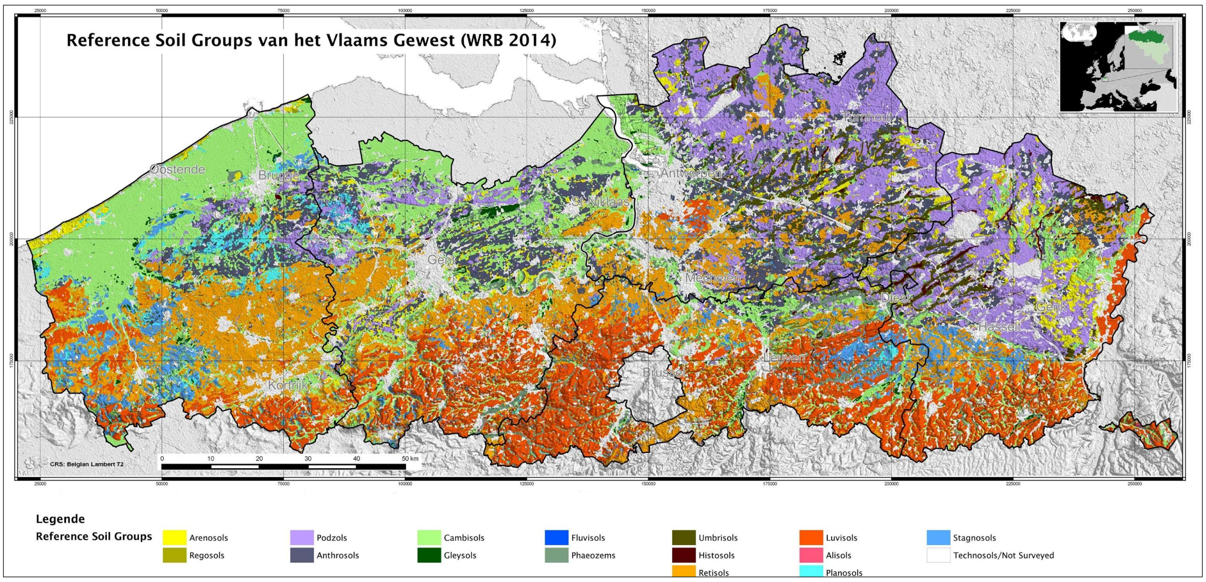
AI.5 Technosols and urban areas

Urban environments, mining areas and places where infrastructure is in place have man-made soils that are very different from the original soil present in those places. These soils are characterized by artefacts, a higher content of coarse material, disturbed soil horizons and sometimes heavy metal concentrations. This is captured in WRB by the Reference Soil Group of Technosols. As these soils were not systematically mapped until two decades ago, their global distribution can only be estimated from urban/artificial land cover.

Thanks to advances in technology, particularly remote sensing and GIS, areas covered by artificial surfaces can be mapped with great precision and their proportion in mapping units can be estimated. However if this information is systematically incorporated in WISE30sec, it will result in an exponential increase of soil mapping units (even if only a limited number Technosol classes are retained). Another problem is the fact that the most recent land cover maps have a very high resolution (10 m) that needed to be simplified into a 30 arc-second grid.

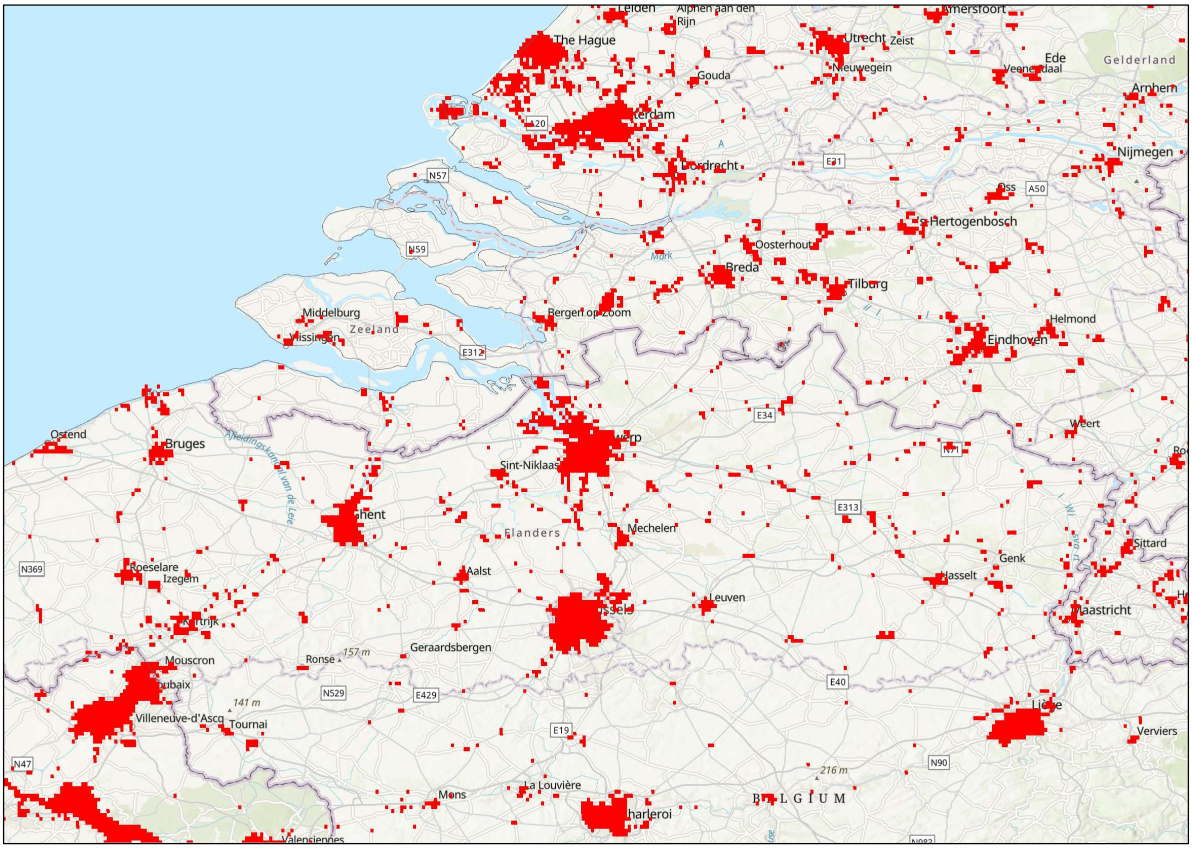
The results from WorldCover2020 (Zanaga *et al.*, 2021) “sharpens” the map because it tends to inflate the densely built areas (at 10 m pixels is classified as built up if the actual built-up area is 50 percent or more) and may under-represent built land in areas of low building density, e.g. rural areas. The GHS land cover data set (Pesaresi and Politis, 2022) count built and paved areas, etc. but even in densely built cities the built-up share can be well below 100 percent because of trees, parks, lawns, etc. However, as most non-artificial covered areas in an urban environment contain Technosols, a treshhold of 50 percent was retained in Worldcover 2020 to identify these soils. This considers that when a 30 arc-second pixel has more than half the area as paved or built-up, the whole pixel is considered to contain Technosols. A test was carried out comparing mapped Technosols in Flanders, Belgium (Dondeyne *et al.*, 2014) with results obtained with the HWSD v2.0 procedure (Figure AI.1 and Figure AI.2).

Figure AI.1. Soil map of Flanders 1:250 000 - urban areas (Technosols) in white based on city limits



Source: Dondeyne, S., Vanierschot, L., Langohr, R., Van Ranst, E. & Deckers, J. (2014). The soil map of the Flemish region converted to the World Reference Base for Soil Resources.

Figure AI.2. Map of Flanders extracted from HWSD v2.0 viewer urban areas (Technosols) in red, based on WorldCover 2020 (built-up class with 50% threshold)



Source: Authors' own elaboration.

ANNEX II: USING HWSD v2.0 IN GIS SOFTWARE

AII.1 Technical specifications

This section describes the HWSD image raster file format, which is provided in .BIL format (band interleaved by line) and can be read or imported by most GIS and spatial data processing software. Header files and specifications of the HWSD raster are provided for use with the QGIS, ESRI ArcGIS, TerrSet (formerly IDRISI), and R. BIL is the standard method of organizing image data and is rather a scheme for storing the actual pixel values of an image in a file. The BIL format consists of several different files. Each file of an image will have the same name but a different file extension. The first is a binary file that actually holds the image data. This file will have a .BIL extension. The second file is an ASCII file that holds descriptive information that describes the image data. This file will have an .HDR file extension.

The world file *.BLW (in ASCII format) provides the image to world information including details on grid cell size and x and y map coordinates of the centre of the upper-left pixel. Below is the format for the world file for HWSD raster.

0.00833333333333
0.00000000000000
0.00000000000000
-0.00833333333333
-179.99583333333334
89.99583333326137

The next two files are optional. They are both ASCII files. The color map file describes the image color map for single-band pseudo-color images and will have a .CLR file extension. The statistics file describes image statistics for each spectral band in a grayscale or multi–band image and has a .STX file extension. In an ArcGIS environment a minimum of three files (*.bil; *.blw; and *.hdr) are required as input for the IMAGEGRID command, which can be used to import the .bil file into an ArcGIS Grid format.

The data in HWSD is stored in 1 image band as unsigned 16 bit integer. The image consists of 21 600 rows and 43 200 columns. This information is stored in the header file with extension *.HDR.

```
BYTEORDER   I
LAYOUT    BIL
NROWS    21600
NCOLS    43200
NBANDS    1
NBITS    16
BANDROWBYTES  86400
TOTALROWBYTES 86400
```

```
PIXELTYPE   UNSIGNEDINT

ULXMAP    –179.9958333335

ULYMAP    89.9959554038125

XDIM     0.008333333

YDIM     0.008333333

NODATA    65535
```

AII.2 Loading the data in ArcGIS and QGIS

The HWSD is composed of a raster image file and a linked attribute database. The raster image file is in ESRI BIL format and can be directly read by ArcGIS, ArcGIS PRO and QGIS. It is often recommended to convert the BIL format to another more common format such as GeoTIFF. The attribute data is stored in Microsoft Access 2003 format (MDB). Since there is a 1-n relation between the raster image pixels and the attributes, it is necessary to prepare a query in Microsoft Access in order to visualize the data in GIS.

Using the HWSD database in a GIS is straightforward, ideally, the full map unit composition should be considered and not only the dominant soil unit. One or more queries should be prepared in Access in order to implement a customized attribute table and to increase the GIS software performance. In many cases, however, the aim will be to obtain an attribute table that has a "one to one" relation between the GRID value and the unique Soil Mapping Unit (SMU) identifier (HWSD2_SMU_ID) in the database. As documented in the main report, one soil mapping unit (polygon in the raster layer) will have a dominant soil with up to 10 associated soils each with seven depth layers. Each depth layer represents one row in the database which means that an SMU with a dominant soil and 4 associated soils has 1+4 * 7 equals 35 rows in the database. This needs to be presented to the GIS in query form, though MS Access, MS Excel or in dbf/text format. This operation will thus simplify the soil map itself, and the user needs to assess the implications of such simplifications for derived applications.

At this stage, the HWSD2_SMU_ID attribute can be joined to the GRID value. The basic steps to start using the database are:

- implement appropriate query in Access, Excel or via any other supported format by your GIS;
- if necessary, realize the appropriate calculations (e.g. after exporting from Access to Excel);
- convert the final attributes table to a compatible GIS format;
- join the HWSD2_SMU_ID attribute and the GRID value (dbf or txt formats), and
- convert the attribute to a new GRID (in the case it is needed).

The extraction from MS Access is straightforward when attributes are available only once for each as HWSD2_SMU_ID code value, in case there is only a dominant soil and no associated soils. In case of numerical attributes, it is necessary to select the sequence to which the attribute refers to. Nevertheless, it is often necessary to calculate derived values for the entire profile (seven layers) in case of attributes measured (or simulated) in each series, and convert it back to a univocal HWSD2_SMU_ID code. Here is a numerical example of calculation to extract Total Exchangeable Bases (TEB) from the database (sum of TEB multiplied by the share of each soil unit in the mapping unit)[3]:

$$TEB = \sum SEQ(SHARE * TEB/100)$$

[3] This kind of formula works fine when total content of a substance in an area is determined (total exchangeable bases, organic carbon pool), but it may lead to less useful results where average values for an area are determined. For example, a soil mapping unit comprising of 50 percent of soils with a topsoil (0–20 cm) OC content of 1.1 percent, 40 percent with a topsoil OC content of say 3.9 percent, and 10 percent with a topsoil OC content of 30 percent (e.g. Histosols) would be assigned a value of 5.1 percent if the above formula were used, which is misleading. Alternative ways of expressing include presenting estimates for the spatially dominant soil unit or the spatially dominant class value in the area (Arrouays *et al.*, 2017).

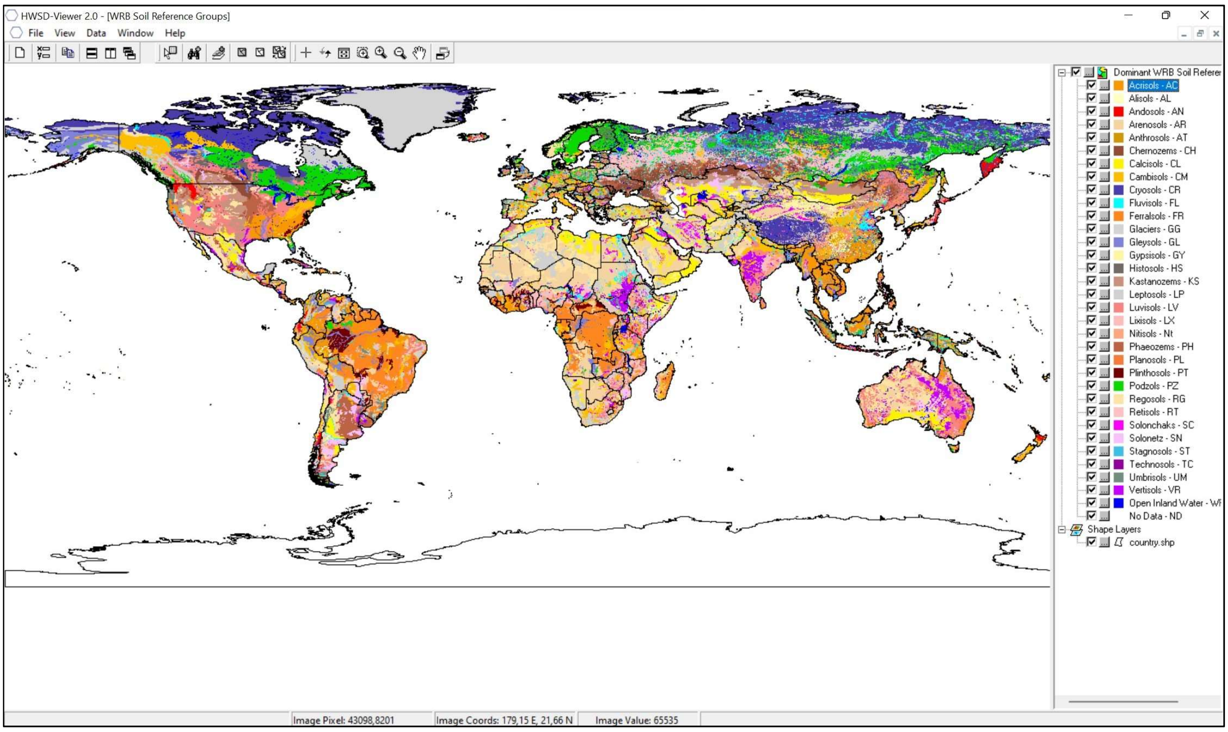
ANNEX III: THE HWSD V2.0 VIEWER

AIII.1 Introduction

The objective of the HWSD v2.0 viewer is to provide a simple tool to consult the data contained in the Harmonized World Soil database version 2.0. The HWSD consists of a 30 arc-second (or ~1 km) raster image and a soil attribute database in Microsoft Access format. The raster image file is stored in binary format (ESRI Band Interleaved by Line - BIL) which can directly be read or imported by most commercial GIS and Remote Sensing software. The viewer is optimized for viewing soil compositions and properties only. For more advanced data extraction or data analysis, it is recommended to use GIS software tools (QGIS, ArcGIS), or spatial analysis tools such as R or Python.

AIII.2 System requirements

The HWSD v2.0 viewer requires a Windows computer with a recommended minimum processor speed of 1.5 GHz and 8 GB or RAM. Windows 98 up to Windows 11 is required as operating system. A minimum of 2 GB of free hard disk space is required for installing and running the software.

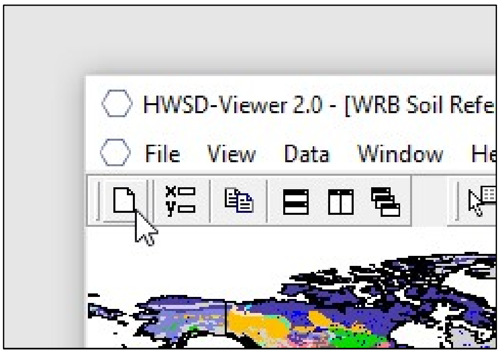


Source: Authors' own elaboration based on United Nations Geospatial. 2020. Map geodata [shapefiles]. New York, USA, United Nations.
Notes: Final boundary between the Sudan and South Sudan has not yet been determined. Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

AIII.3 First-time use of HWSD viewer

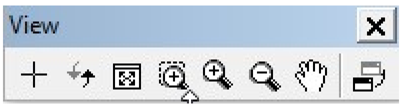
When launching the viewer, the soil map will open automatically. The first time, it will decompress the HWSD raster image, and this may take a while but is required only once (unless you select to delete the image file after closing the viewer).

Use the *File>New Window* menu option or use the icon to load another window with the HWSD raster map and related attribute data.



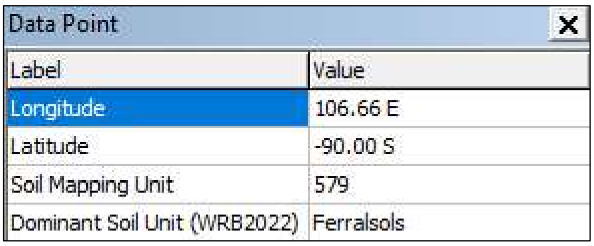
AIII.4 Basic operations

You open a new map window from the icon in the toolbar of the *File>New Window*. The HWSD map will be loaded showing the soil classification groups. Simple map viewing operations are accessed from the View menu or the View toolbar, and include redrawing, zooming in, zooming out and moving the map.



The icons in the View toolbar have the following functionality: (1) reset the view operation, (2) redraw the map, (3) fit the complete map in the window, (4) zoom in on the map by drawing a rectangle, (5) zoom in on the map by a fixed zoom percentage, (6) zoom out with fixed zoom percentage, and (7) pan or move around the map.

The Data Point tool shows coordinates of the mouse cursor, the global SMU identifier (HWSD2_SMU_ID) and the Dominant Soil Unit in a floating Window.

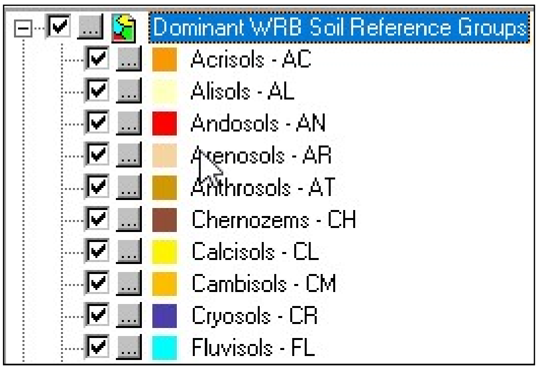


AIII.5 Manipulating the legend

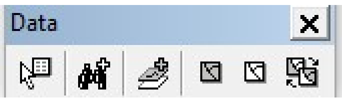
The legend shows the main soil groups in the raster map, as well as the vector layers. Manipulating the legend includes showing or hiding entries, and changing their appearance.

The legend entries can be manipulated one by on using the  and  icons, to hide or display the entry on the map, or to change the color of the entry. You can also hide the complete soil raster layer from the 

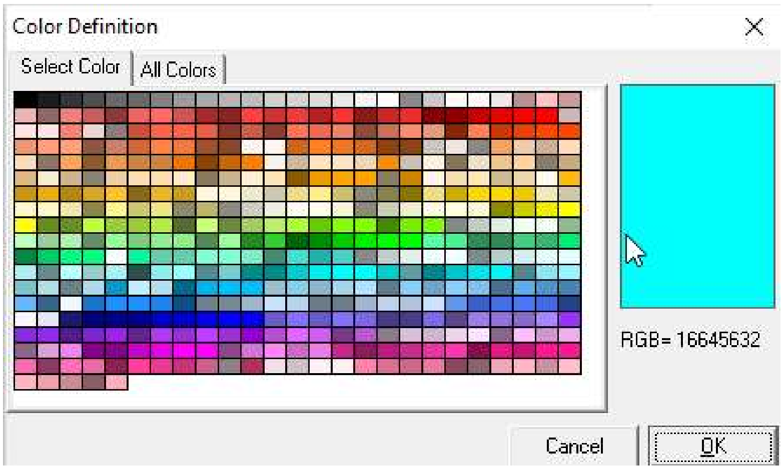
checkbox. In this case, only the vector overlays will be shown.



You can also manipulate the legend from the three rightmost icons in the Data Toolbar. The first will activate (display) all legend entries; the second will clear them all. The third will switch the selection. These tools allow to quickly select one or a few soil groups.



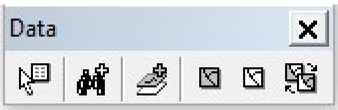
Colors can be changed from the  entries in the legend. A dialog box gives a number of predefined colors or you can set the RGB numbers given access to all possible colors supported by your computer.



AIII.6 Accessing HWSD attribute data

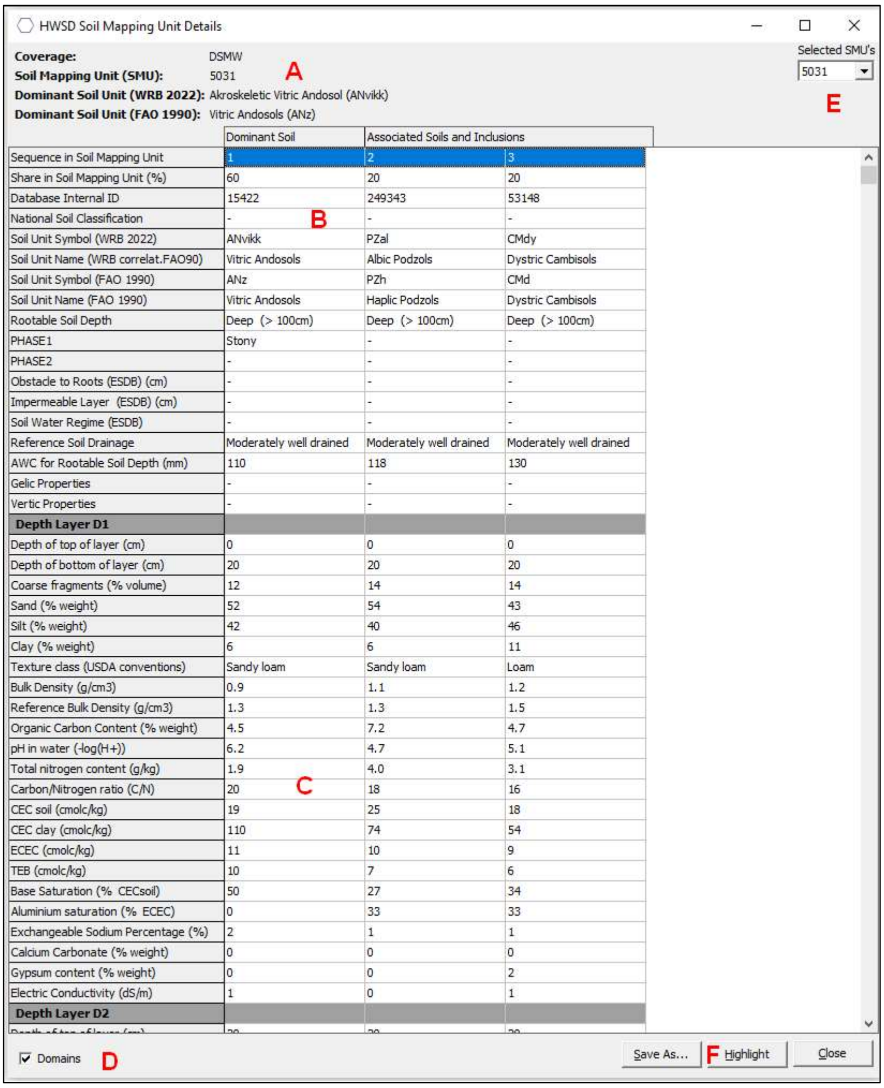
Soil attribute data is linked to the raster map via the pixel value, and soil properties are loaded from the Microsoft Access database. Data are displayed in spreadsheet-like format. The data can be copied to the clipboard and directly copied into Microsoft Excel.

Use the left-most icon in the Data toolbar to display the HWSD soil mapping unit details of the selected SMU. The clicked area will be indicated with a small cross; if you want to highlight the clicked area, use the Highlight button explained below.



AIII.7 The HWSD soil mapping unit details

The View lists the soil properties in table format, one column for each share in the soil mapping unit.

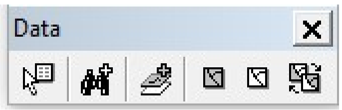


The most important properties of the selected SMU are: the coverage, the SMU identifier (HWSD2_SMU_ID) and the soil mapping unit code (A). In the first column (B) information about the data area, listed by share, with the dominant soil is visualized. Scrolling down the table soil physic-chemical properties are displayed (C). At the bottom left corner the *Display* tick (D) displays the option to visualize the domain values of data or the numerical entries from the database. The drop-down list (E) on the top right corner of the window lists the selected SMU's. You can return here to a previously selected unit and display its properties. The *Highlight* button (F) highlights the selected SMU on the map.

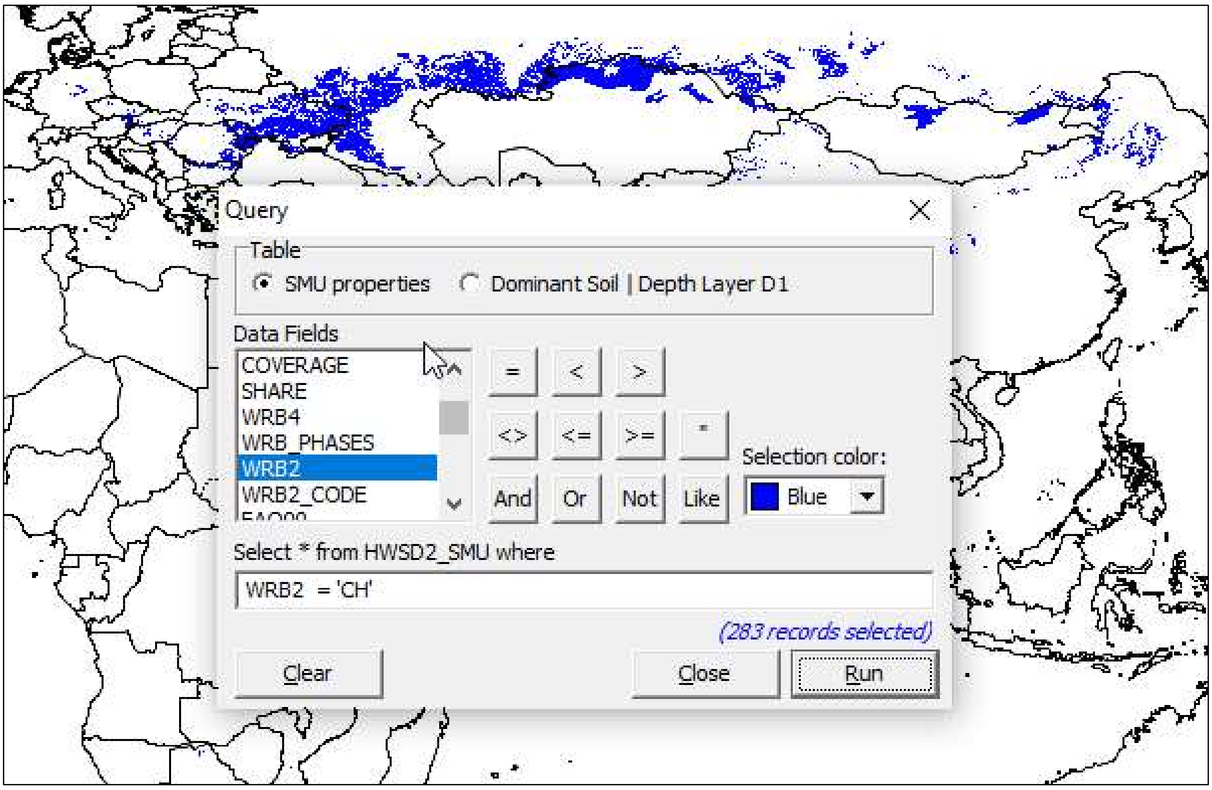
In order to find the selected SMU, you might need to use the legend manipulation tools. The selection colour can be changed from the *HWSD Query Tool*.

AIII.8 HWSD data query

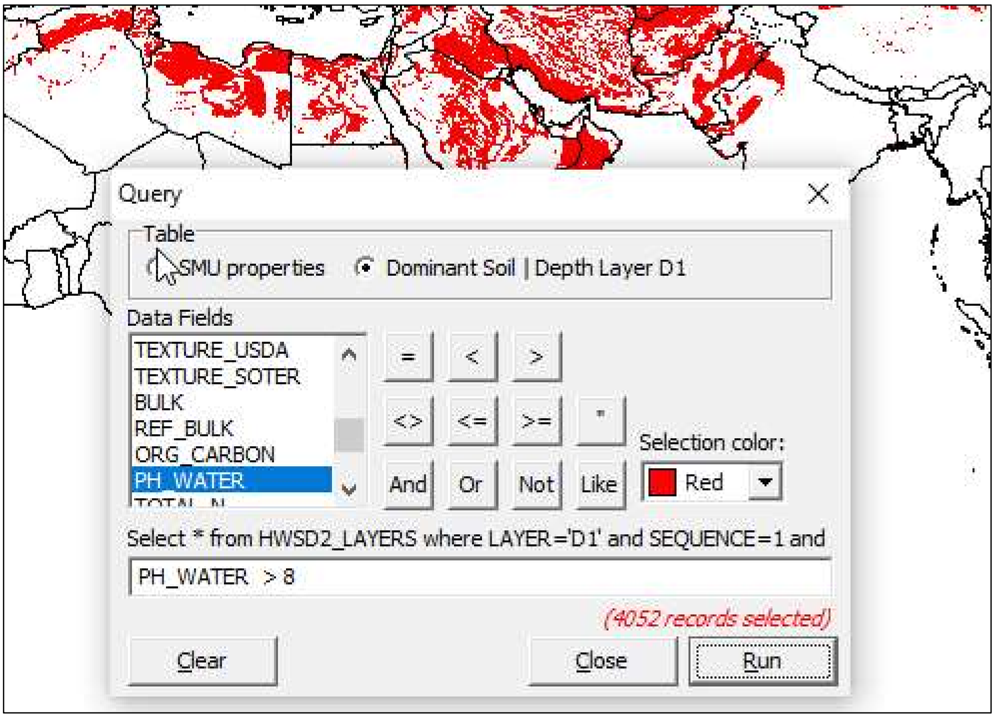
The HWSD Query Tool can perform any Microsoft Access SQL compatible query on the HWSD database. You will need to select the SMU properties or properties of the "Dominant soil|Depth Layer D1" as illustrated in the Figures below.



The simple query below illustrates the highlighting of all dominant soils as Chernozem from the query WRB2="CH"

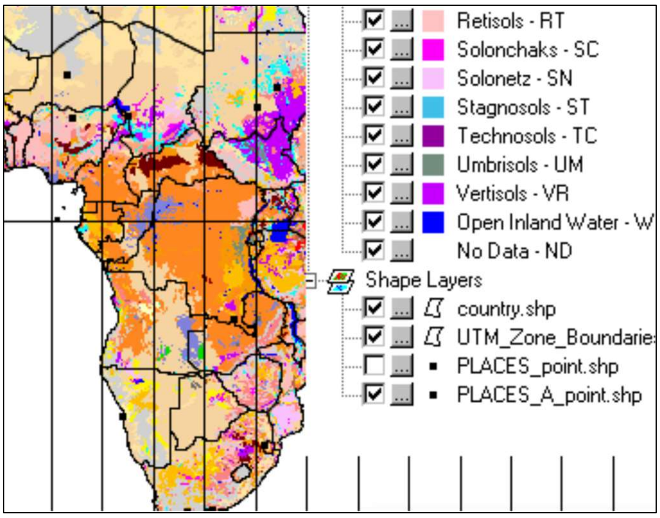


Another example below illustrates the query on the top layer of the dominant soil with PH > 8.



AIII.9 Adding shapefile overlays

A shape file with national boundaries (United Nations Geospatial, 2020) is included with the installation and is loaded as overlay on the HWSD image. Any additional Shape file (point, line, and polygon) can be loaded as overlay, and its properties can be changed from the legend. The figure below illustrates Shape overlays with major towns and a reference UTM grid.



AIII.10 Preferences

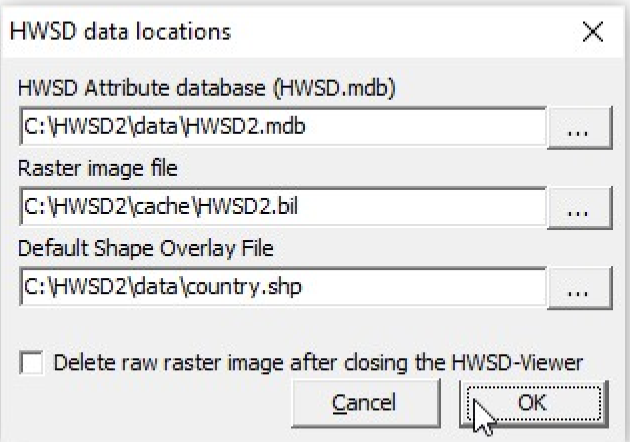
There are a few program preferences available from the *View* and *Data* Menu:

- *Persistent view operation*: this setting retains the ongoing operations (zooming in or panning etc...) without the need to re-select the operation (this preference is on by default);
- *Synchronize views*: when you have different windows open, zoom and pan operations will be synchronized over the different windows (this preference is on by default), and
- *Open new window*: opens a new window when selecting a new soil map window (this preference is on by default).

If you want to delete the 2GB raster image after closing the HWSD viewer, activate here the "*Delete raster image after closing the HWSD-viewer*". This will however require the lengthy process of decompressing the raster image every time when the viewer is started (this preference is off by default, the option can be found in the *Data > Data Location menu*).

AIII.11 Loading other databases

From the *Data Location* menu item, you can select other HWSD databases, if new versions come available. You can also select a different default shape file overlay. If you want to delete the 2GB raster image after closing the HWSD viewer, activate here the "*Delete raw raster image after closing the HWSD-viewer* ". This will however require the decompressing the raster image every time when stating the viewer.



ANNEX IV: GUIDELINES TO INCORPORATE NATIONAL SOILS DATA IN HWSD V2.0

In nearly every country national soil studies were carried out over many years for different purposes with different survey scales and analytical methods while using different soil classification systems. These legacy soil data and maps may form a sound basis for a harmonized inventory of soil information that can be used for national digitized soil mapping (Arrouays *et al*., 2017; Sulaeman *et al.*, 2013) or to support global soil data sets that are necessary to investigate global issues, such as climate change or determining global hotspots of constraints and potentials for agriculture in support of food security, as is the purpose of the present HWSD approach.

HWSD was developed to reflect quantified spatial representations of soil conditions in the best possible way at national, regional, continental, and global level. This was achieved by using quantified soil composition within delineated soil association map units. Such information is best derived from soil survey data, based on eco-environmental field investigations and backed by remote sensing interpretations. Therefore, the first and most important data sets to be acquired are digital soil survey inventories preferably in polygon (shape) formats with a quantification of composition of distinctly different soil occurrences, within delineated soil association or soil and terrain (SOTER) units (Van Engelen and Wen, 2002).

The next step is the quantification of soil attributes of individual soil units, for which in the first-place typifying soil profile descriptions and laboratory analysis are used.

To characterize the soils and soil series at national level, a statistical approach may be followed, calculating mean values and standard deviations for soil attributes, taking into account climatic differences that affect soil profile development that result in variations of attribute values. For HWSD the widely used Köppen/Geiger classification is applied. Underlying statistical methods are well explained in the WISE30sec Document (Batjes, 2015) providing a quantitative measure of uncertainty (and outlier detection). Wise30sec document provides taxo-transfer schemes to be used for incidental missing values.

In summary, a systematic approach to collect and harmonize soil data for HWSD involves:

- **Soil Inventory:**
    - Documenting national soil legacy data (location, scale, year, number of soil profiles and analytical data, surveyor, report reference and quality rating);
    - Soil map coverage screening and selection of most suitable national mapping scale;
    - Identifying soil mapping units characterized by one or more soil units (series) with statistical determined attributes and levels of uncertainty;
    - Soil units preferably correlated with an international soil classification system (FAO et al., 1990; IUSS Working Group WRB, 2022; Soil Survey Staff, 2014), and
    - Such soil (association) inventory (with quantified soil series composition) is then converted in digital (GIS) format (polygons/shape units).

- Collate soil association mapping unit information: (see this document) for each soil association mapping unit consisting of:
    - Coverage;
    - Soil Mapping Unit (SMU);
    - Dominant soil unit (WRB 2022), and
    - Dominant Soil unit (FAO90).
- Formulate general soil information: (see procedures outlined in this document) for each soil entity (unit/series) consisting of:
    - Share in soil association;
    - Soil classifications, National, FAO90 and WRB 2022;
    - Rootable soil depth (see this document);
    - Soil phase 1;
    - Soil phase 2;
    - Reference Drainage class;
    - Available Water capacity (AWC) for rootable soil depth, and
    - Occurrence of Gelic and or Vertic soil properties.

- **Soil profile attributes:**
    - Analytical and morphological data screening and quality control (data checks pH/BS, $CaCO_3$/pH, distribution with depth, granulometry adds up to 100 etc…);
    - Identification of missing or scant data as well geographically as for specific soil units or within the profile sampled to insufficient depth ranges. Consultation of International regional and global soil studies (WISE, SoilGrid, HWSD) to fill these gaps;
    - Creation of representative soil attributes by soil unit and climate class;
    - Recalculate the distribution of soil attributes by depth layer are 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–150 cm, 150–200 cm (weighted average approach from soil horizon sequences);
    - Required analytical data include 20 soil properties that are commonly required for global agroecological zoning, land evaluation, crop growth simulation, modelling of soil gaseous emissions, and analyses of global environmental change: organic carbon content, total nitrogen, C/N ratio, pH(H_2O), CECsoil, CECclay, effective CEC, total exchangeable bases (TEB), base saturation, aluminum saturation, calcium carbonate content, gypsum content, exchangeable sodium percentage (ESP), electrical conductivity, particle size distribution (content of sand, silt and clay), proportion of coarse fragments (> 2 mm), bulk density;
    - Integration of the national data in HWSD this involves several technical issues related to down or up-scaling of the data to the 30 arc-second standard of HWSD, the land/see mask, international boundaries (GAUL), urban areas etc., and

- Across-border correlation of soil information with neighboring countries.

- **Shortcut:**
  - A major shortcut when a high-quality national soil association inventory with quantified soil composition data exists but sufficient soil profile attribute data is lacking, is to use the corresponding WISE30sec attribute values for each FAO90/Köppen-Geiger unit.

- **Data review:**
  - A review of national soil data readily available and in a format close to that required by HWSD v2.0 are:
    - At IIASA: Mauritius, Ukraine, and Thailand;
    - At ISRIC: Malawi, Nepal. and 14 Donau States accessible at https://data.isric.org/geonetwork;
    - At the GSP, numerous countries with inventories of national georeferenced soil properties. Their inclusion in HWSD v2.0 requires availability and linkage of these point data to soil (association) maps with quantified soil morphology (taxonomy) composition and scrutinizing availability and quality of about twenty different soil attributes, and
    - A major outstanding task remains the inclusion of the existing more up-to-date soil Information obtained by digital soil mapping in the United States, Canada and Australia.

Harmonized World Soil Database
version 2.0

The Harmonized World Soil Database version 2.0 (HWSD v2.0) is a unique global soil inventory providing information on the morphological, chemical and physical properties of soils at approximately 1 km resolution. Its main objective is to be useful for modelers and to serve as a basis for prospective studies on agro-ecological zoning, food security and the impacts of climate change. HWSD v2.0 also serves an educational function, illustrating the geographical distribution of soils as well as their properties globally. HWSD v2.0 is easily accessible and user-friendly.

ISBN 978-92-5-137499-3

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CC3823EN/1/01.23