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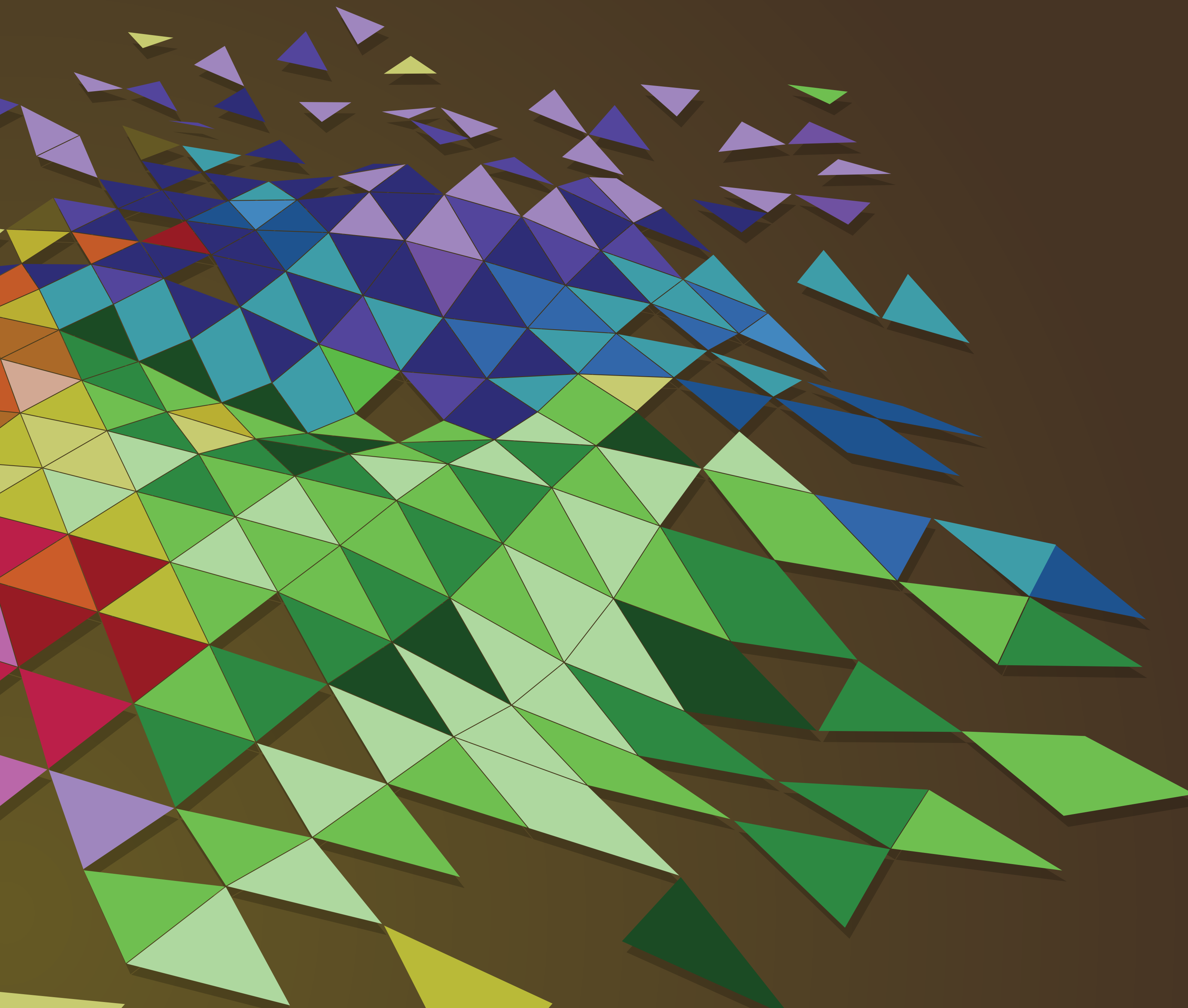
used in Global Agro-Ecological Zoning version 5



SOIL SUITABILITY ASSESSMENT PROCEDURES FOR CONVENTIONAL AND ORGANIC FARMING SYSTEMS

used in Global Agro-Ecological Zoning version 5

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

Rome and Laxenburg, 2026

Required citation:
van Velthuizen, H., Fischer, G. & Nachtergaele, F. 2026. *Soil suitability assessment procedures for conventional and organic farming systems used in Global Agro-Ecological Zoning version 5*. Rome, FAO and Laxenburg, Austria, IIASA. https://doi.org/10.4060/cd8206en

ISBN 978-92-5-140434-8

ABSTRACT

This document describes the update of soil suitability procedures used in the Global Agro-Ecological Zoning version 5 (GAEZ v5).[1] The update was necessitated by and is directly related to the release of the Harmonized World Soil Database version 2.2 (HWSD v2.2),[2] which specifically updates HWSD v2.01 (through HWSD v2.0 [FAO and IIASA, 2023]).[3] The HWSD developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied System Analysis (IIASA) is especially intended for applications in biophysical models and agroecological assessments. The updated v2.2 has been built on the previous versions (HWSD v1.2) (FAO *et al.*, 2012),[4] and then v2.0 and v2.01 (FAO and IIASA, 2023) but with several improvements, including the following:

- The replacement of soil data derived from the International Soil Reference and Information Centre-World Inventory of Soil Emission Potentials (ISRIC-WISE) database (Sombroek, 1984),[5] with soil data of the WISE30sec database (Batjes, 2015),[6] more than doubled the number of soil profiles used, from 10 250 to 21 000.
- In the previous version of HWSD, soil attribute data were limited to two layers: topsoil (0–30 cm) and subsoil (30–100 cm). Version 2.2 uses seven depth layers 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.
- Soil attribute information is expanded, with additional attribute data available from WISE30sec, namely: effective cation exchange capacity (ECEC), total nitrogen (N), carbon to nitrogen ratio (C/N), and aluminium saturation.
- Version 2.2 uses the FAO 1990 Revised Legend (FAO, UNESCO and ISRIC, 1990),[7] as well as correlations with the 2022 version of the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2022).[8]

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[1] **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis).** 2025a. *Global Agro-Ecological Zoning version 5 (GAEZ v5) Model Documentation*. In: *GitHub*. https://github.com/un-fao/gaezv5/wiki

[2] **FAO & IIASA.** 2026. *Harmonized World Soil Database version 2.2.* Rome & Laxenburg, Austria. https://data.apps.fao.org/catalog/iso/ff5c613c-75bb-46a9-a162-bc728059b465

[3] **FAO & IIASA.** 2023. *Harmonized World Soil Database version 2.0*. Rome & Laxenburg, Austria. https://doi.org/10.4060/cc3823en

[4] **FAO, IIASA, ISRIC (International Soil Reference and Soil Information Centre) ISSCAS (Institute of Soil Science, Chinese Academy of Sciences), & JRC (Joint Research Centre of the European Commission).** 2012. *Harmonized World Soil Database (version 1.2)*. Rome, FAO & Laxenburg, Austria, IIASA. https://edepot.wur.nl/197153

[5] **Sombroek, W.** 1984. *Towards a Global Soil Resources Inventory at Scale 1:1 Million*. Wageningen, Kingdom of the Netherlands, ISRIC. https://www.isric.org/sites/default/files/isric_report_1984_04.pdf

[6] **Batjes, N.H.** 2015. *World soil property estimates for broadscale modelling (WISE30sec).* Report 2015/*01*. Waganingen, Kingdom of the Netherlands, ISRIC.

[7] **FAO, UNESCO (United Nations Educational, Scientific and Cultural Organization) & ISRIC**. 1990. *FAO/Unesco Soil Map of the World.* Revised Legend with corrections and updates*.* World Soil Resources Report 60. Wageningen, Kingdom of the Netherlands, ISRIC.

[8] **IUSS (International Union of Soil Sciences) Working Group WRB**. 2022. *World Reference Base for Soil Resources.*

- Error estimates and statistics of individual soil parameters have become accessible through linkage with the WISE30sec database.
- Use has been made of soil phase information globally available in the Digital Soil Map of the World (FAO, 1995)[9] and was accounted for when defining the WRB soil reference groups and WRB soil units (IUSS Working Group WRB, 2022).

In the GAEZ framework, soil suitability procedures estimate yield reductions due to the constraints induced by soil limitations. Crop yield impacts resulting from suboptimum soil conditions are assessed through crop-specific evaluations of seven major agronomic soil qualities estimated from soil attributes available in the HWSD. Soil qualities (SQs) include nutrient availability (SQ1), nutrient retention (SQ2), rooting conditions (SQ3), oxygen availability (SQ4), calcium carbonate and gypsum conditions (SQ5), salinity and sodicity (sodium) conditions (SQ6), and management/workability conditions (SQ7). Limitations depend on the level of inputs and management and are estimated on a crop-by-crop basis and combined into crop and input level specific soil suitability ratings for rainfed cultivation and irrigated water supply systems.

In the present update of soil evaluation procedures, two broadly distinct farming systems were used:

- conventional farming systems as previously covered by the GAEZ v4 agroedaphic procedures; and
- adapted procedures for organic farming systems, a first step toward enabling a GAEZ assessment for spatially explicit potentials of organically produced crops.

International soil classification system for naming soils and creating legends for soil maps. Fourth edition. Vienna, Austria. https://eurasian-soil-portal.info/wp-content/uploads/2022/07/wrb_fourth_edition_2022-3.pdf

[9] **FAO**. 1995. The *Digitized Soil Map of the World and Derived Soil Properties (Version 3.5)*. FAO Land and Water Digital Media Series #1 [CD-ROM]. Rome.

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PREFACE

As part of the revision and enhancement of GAEZ v5 (FAO and IIASA, 2025a),[10] the agroedaphic procedures within the framework were reviewed and updated to incorporate data from HWSD v2.2.

The updated HWSD is based on soil property estimates disaggregated by major climate zones (Peel, Finlayson and McMahon, 2007)[11] for broad-scale modelling applications, derived from WISE30sec (Batjes, 2015)[12].

Compared to HWSD v1.2 (FAO *et al.,* 2012),[13] the updated HWSD v2.2 (FAO and IIASA, 2026)[14] offers enhanced data content – including additional soil attributes and a more detailed vertical resolution – providing up to seven soil depth layers instead of the two used in HWSD v1.2. The revised agroedaphic procedures are adapted to fully utilize these expanded data and the updated database structure.

In addition, this document outlines the updated soil suitability assessment procedures for both conventional and organic farming systems. Although organic farming still constitutes a relatively small share of global agriculture, its importance has been steadily increasing. It offers considerable potential, particularly in regions where sustainable agricultural practices are essential to ensuring long-term food security. The integration of organic farming into the Agro-Ecological Zoning (AEZ) agroedaphic suitability framework marks a significant step toward enabling spatially explicit assessments of crop suitability and production potential for key organically grown crops within appropriate crop rotations.

This document is intended to support AEZ modellers and users of GAEZ v5, particularly in the areas of soil and land evaluation, sustainable agricultural planning, and the responsible management of land and soil resources in the context of food security and agricultural development.

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[10] **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis)**. 2025a. *Global Agro-Ecological Zoning version 5 (GAEZ v5) Model Documentation*. In: *GitHub*. San Francisco, USA, GitHub. [Cited 12 July 2025]. https://github.com/un-fao/gaezv5/wiki

[11] **Peel, M.C., Finlayson, B.L. & McMahon, T.A.** 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences*, 11(5): 1633–1644. https://doi.org/10.5194/hess-11-1633-2007

[12] **Batjes, N.H.** 2015. *World soil property estimates for broadscale modelling (WISE30sec).* Report 2015/*01*. Waganingen, Kingdom of the Netherlands, ISRIC

[13] **FAO, IIASA, ISRIC (International Soil Reference and Soil Information Centre) ISSCAS (Institute of Soil Science, Chinese Academy of Sciences), & JRC (Joint Research Centre of the European Commission).** 2012. *Harmonized World Soil Database (version 1.2)*. Rome, FAO & Laxenburg, Austria, IIASA. https://pure.iiasa.ac.at/id/eprint/17595/

[14] **FAO & IIASA.** 2026. *Harmonized World Soil Database version 2.2.* Rome and Laxenburg, Austria. https://data.apps.fao.org/catalog/iso/ff5c613c-75bb-46a9-a162-bc728059b465

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Eddy De Pauw and Sergio Noce for reviewing an early draft, as well as Sylvia Tramberend and Kahil Taher from IIASA for the support.

The work would not have been possible without the involvement and continued support for HWSD v2.2 and GAEZ v5 by Federica Chiozza, Matieu Henry and Livia Peiser from FAO. Special thanks go to Dario Spiller, Rutendo Mukaratirwa, Shahla Asgharinia, and Filippo Sarvia from the Geospatial Unit of the Land and Water Division for their efforts in implementing the soil evaluation method in the context of PyAEZ. At FAO, we are also grateful for the support provided by colleagues from the Land and Water Division, particularly Ameni Khatteli, Michèle Piraux, Sofia Ramirez Fionda, James Morgan and Andy Murray.

ABBREVIATIONS

AEZ	Agro-Ecological Zoning
AWC	available water capacity
BS	base saturation
CA	conservation agriculture
CCB	calcium carbonate
CEC_{clay}	cation exchange capacity of clay fraction
CEC_{clay+}	cation exchange capacity of clay fraction (adjusted for organic farming)
CEC_{soil}	cation exchange capacity of soil
CEC_{soil+}	cation exchange capacity of soil (adjusted for organic farming)
C/N	carbon to nitrogen ratio
CSA	climate smart agriculture
D1–D7	Harmonized World Soil Database soil depth layers
DRG	soil drainage rating
DRG^{+}	soil drainage rating (adjusted for organic farming)
ECe	electrical conductivity
ECEC	effective cation exchange capacity
ESP	exchangeable sodium percentage
FAO	Food and Agriculture Organization of the United Nations
GAEZ	Global Agro-Ecological Zoning
GRC	soil gravel content
GSP	gelic soil property
GYP	gypsum content
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied System Analysis
ISL	impermeable soil layer
ISRIC	International Soil Reference and Information Centre
IUSS	International Union of Soil Sciences
LUT	land utilization type
OTR	obstacles to roots
pH	potential of hydrogen
RD	Crop rooting depth (a crop-specific property)
SLW	soil layer weight according to crop root mass distribution

RSD	rootable soil depth (a soil-specific property)
SOC	soil organic carbon
SPH	soil phase
SQ	soil quality
SSR	soil suitability rating
TEB	total exchangeable bases
TXT	texture, mineralogy, and structure
VSP	vertic soil property
WISE	World Inventory of Soil Emission Potentials
WR	soil wetness conditions
WRB	World Reference Base for Soil Resources

INTRODUCTION

Historically, the fundaments of the Agro-Ecological Zoning (AEZ) agroedaphic suitability methodology are based on the Food and Agriculture Organization of the United Nations (FAO) framework for land evaluation (FAO, 1976, 1984) , the agroecological zones project (Higgins *et al*., 1978), the land resources of populations of the future (FAO, 1976; Sys and Riquier, 1980; FAO, 1980), land evaluation (Sys, Van Ranst and Debaveye, 1991a, 1991b; Sys *et al.*, 1993; Sys, 1990), and the release of the first Global Agro-Ecological Zoning (GAEZ) version 1 (v1) assessment (FAO and IIASA, 2000). With the global coverage and availability of soil attribute data from the Harmonized World Soil Database (HWSD) version 1.2 (v1.2), the procedures for agroedaphic suitability assessments in the GAEZ modelling environment have been developed over time, as recorded in the documentation of GAEZ v3 of 2012 (Fischer *et al.*, 2012), GAEZ v4 of 2021 (Fischer *et al.*, 2021), and the latest GAEZ v5 of 2025 (FAO and IIASA, 2025a). With advances in the detail and content of digital soil mapping products, soil evaluation in AEZ has been refined, and applied in various national agroecological zoning studies carried out by FAO and the International Institute for Applied Systems Analysis (IIASA), such as in Afghanistan, Bangladesh, China, Ghana, Kenya, Mozambique, Thailand and Türkiye.

The modelling performed by GAEZ estimates yield reductions due to edaphic constraints induced by prevailing soil and terrain slope conditions. Crop yield impacts resulting from suboptimum conditions for soils and for terrain slopes are treated separately. This document deals with soil attributes and their limitations for soil suitability and crop production. The recent update of HWSD from v1.2 to v2.2 serves as a source for spatial distribution of soil units[15] and soil attribute data used for a spatially detailed evaluation of soil qualities for edaphic crop suitability assessments, and includes harmonized soil attribute data for up to seven soil depth layers (D1–D7). A list of soil attributes contained in HWSD v2.2 is given in Table 1.

[15] A soil unit is a distinct body of soil that has specific and recognizable characteristics, which differentiate it from other soils.

Table 1. Soil mapping unit and soil depth layer attributes in the Harmonized World Soil Database version 2.2 (HWSD v2.2)

HWSD v2.2	
HWSD soil mapping unit attributes	**Soil attributes by depth layer (D1–D7)**
Coverage	Depth of top layer (cm)
Soil mapping unit code (SMU)	Depth of bottom layer (cm)
Dominant soil unit (WRB22)	Coarse fragments (% volume)
Dominant soil unit (FAO90)	Sand (% weight)
General soil unit information	Silt (% weight)
Sequence in soil mapping unit (i)	Clay (% weight)
Share in soil mapping unit (%)	Texture class (Soil Survey Division Staff, 1993)
Database ID	Bulk density (g/cm^3)
National soil classification	Reference bulk density (g/cm^3)
Soil unit symbol (WRB22)	Soil organic carbon (SOC) content (% weight)
Soil unit name (WRB22)	pH in water ($-\log(H^+)$)
Soil unit symbol (FAO90)	Total nitrogen content (g/kg)
Soil unit name (FAO90)	Carbon–nitrogen ratio (C/N)
Rootable soil depth (RSD) (class)	Cation exchange capacity of soil (CEC_{soil}) ($cmol_c/kg$)
Soil phase (SPH) 1	Cation exchange capacity of clay fraction (CEC_{clay}) ($cmol_c/kg$)
Soil phase (SPH) 2	Effective cation exchange capacity (ECEC) ($cmol_c/kg$)
Obstacle to roots (OTR) (ESDB)	Total exchangeable bases (TEB) ($cmol_c/kg$)
Impermeable soil layer (ISL) (ESDB)	Base saturation (BS) (% of CEC_{soil})
Soil water regime (ESDB)	Aluminium saturation (% of ECEC)
Soil drainage (DRG) (class)	Exchangeable sodium percentage (ESP) (%)
Available water capacity (AWC) for RSD (mm)	Calcium carbonate (% weight)
Gelic soil properties (GSP)	Gypsum content (% weight)
Vertic soil properties (VSP)	Electrical conductivity (EC) (dS/m)

Note: FAO90 and WRB22 refer to FAO (1990) and IUSS Working Group WRB (2022).

Sources: See References.

Soil suitability is assessed through crop/land utilization type (LUT)-specific evaluations of seven major soil qualities (SQs) relevant for agriculture:[16]

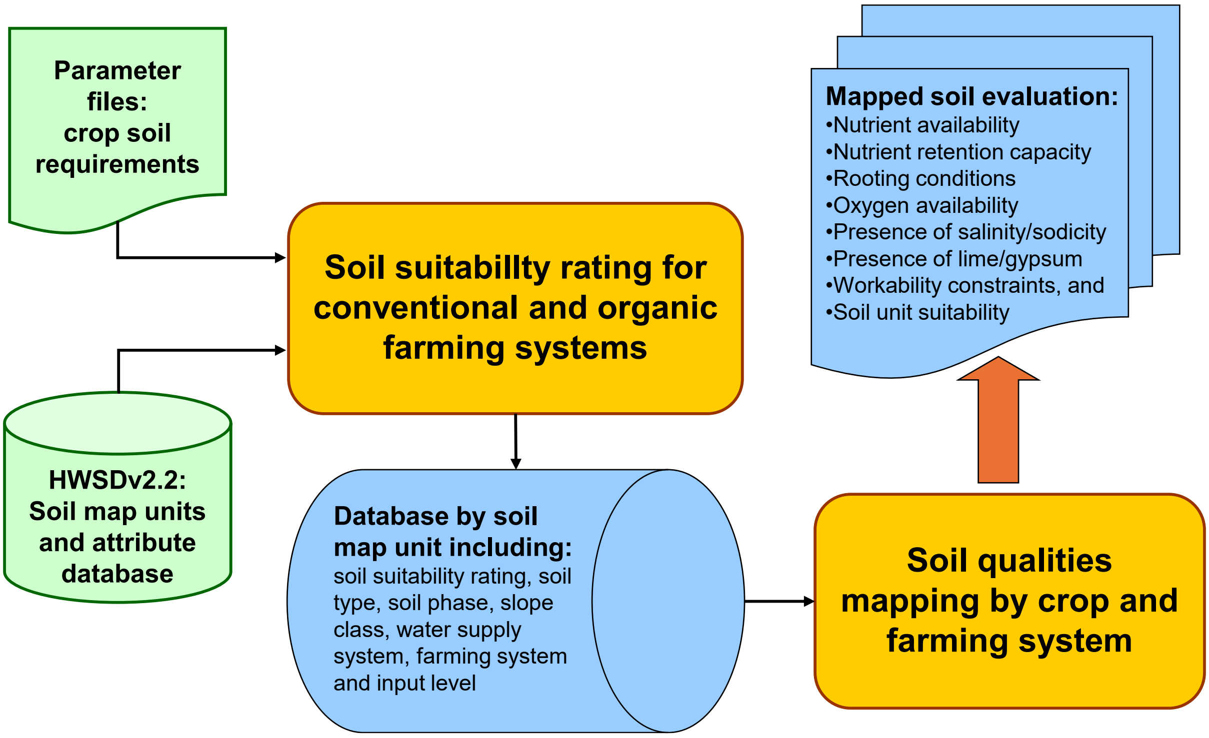
- SQ1: nutrient availability;
- SQ2: nutrient retention;
- SQ3: rooting conditions;

[16] Soil quality (soil health) is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans. The concept of soil quality is here restricted to soil properties relevant for agricultural production.

- SQ4: oxygen availability for roots;
- SQ5: salinity and sodicity conditions;
- SQ6: calcium carbonate and/or gypsum conditions; and
- SQ7: management/workability conditions.

Soil qualities are estimated by comparing relevant soil attributes to the respective crop soil requirements available for each crop and input or management level and water supply systems (rainfed, gravity irrigation, sprinkler irrigation and drip irrigation). Reference crop soil requirements data are available from the GAEZ v5 Platform (FAO and IIASA, 2025b) with some details being provided in Appendix 1. Soil suitability assessments procedures as part of agroedaphic assessments are schematically presented in Figure 1.

Figure 1. Schematic representation of soil suitability assessment procedures within agroedaphic assessments



Source: Authors' own elaboration.

The agroedaphic assessment follows the procedures outlined in the GAEZ v4 documentation (Fischer *et al.*, 2021). In addition to assessing soil unit suitability, it also includes:

- An assessment is carried out to determine the available soil moisture capacity to rootable soil depth (RSD) (determinants include soil texture, soil volume, soil salinity and soil phases).
- An estimate is made of terrain slope suitability according to terrain slope classes and location-specific rainfall amounts and rainfall concentration characteristics by water supply systems, crop groups and levels of input and management.

- Water collecting sites and areas prone to seasonal waterlogging and flood risks are defined and set aside to be assessed separately (accounting for waterlogging and flooding risks and for enhanced soil moisture availability).
- Fallow period requirements are assessed separately based on crop type, input and management level and locally prevailing soil and climate conditions.

Table 2 presents linkages between the soil qualities and soil characteristics available from HWSD v2.2.

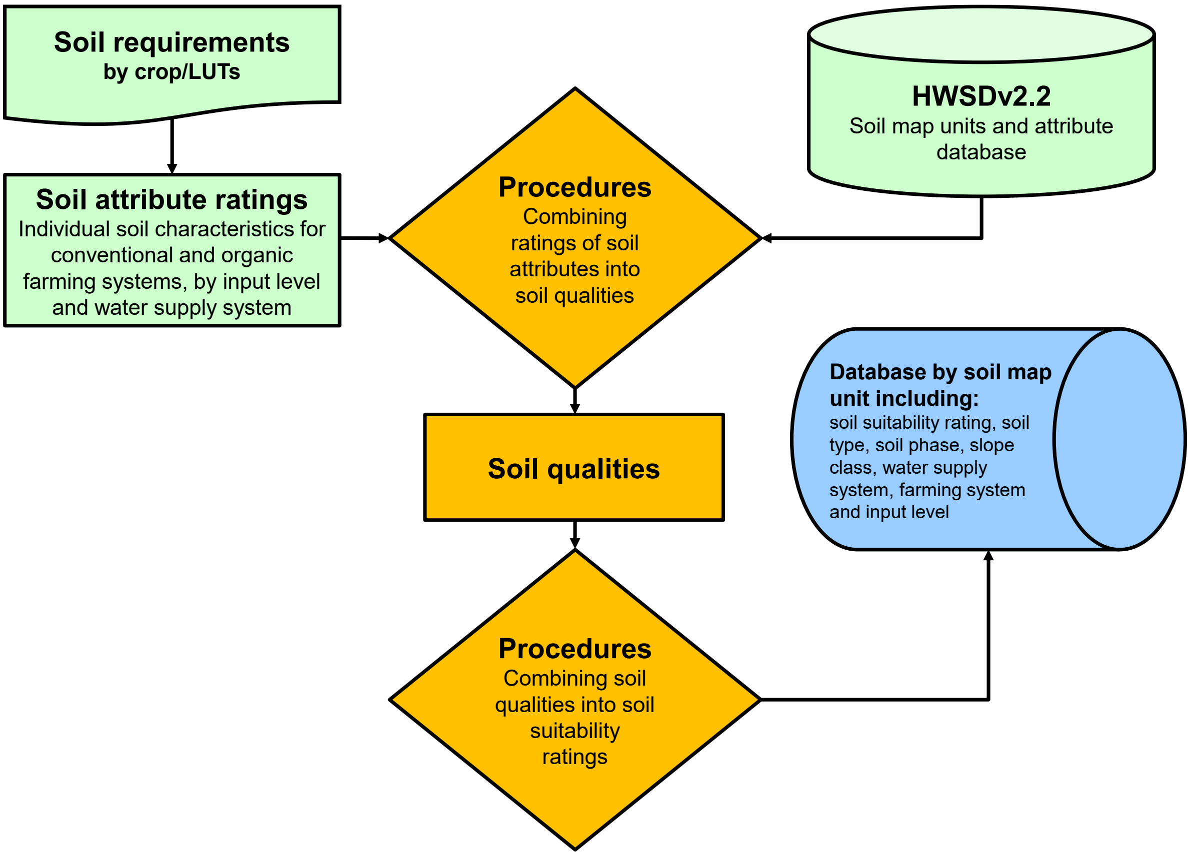
Table 2. Soil qualities and soil characteristics

Soil qualities		Soil quality, related soil physical and chemical characteristics, soil drainage conditions and soil phase
SQ1	Nutrient availability	Soil texture (TXT), soil organic carbon (SOC), soil pH, and total exchangeable bases (TEB).
SQ2	Nutrient retention capacity	Soil texture, base saturation (BS) and cation exchange capacity of soil and clay fraction (CEC_{soil} and CEC_{clay}).
SQ3	Rooting conditions	Soil texture, coarse fragments (GRC), vertic soil properties (VSP) and soil phases (SPHs) causing obstacles to roots, limit rootable soil depth (RSD) and effective soil volume.
SQ4	Oxygen availability to roots	Soil drainage (DRG) and SPHs affecting soil drainage.
SQ5	Salinity and sodicity conditions	Soil salinity, soil sodicity layer attributes and SPHs indicating soil salinity and sodicity conditions.
SQ6	Lime (calcium carbonate) and/or gypsum conditions	Calcium carbonate (CCB) and gypsum content (GYP), and SPHs influencing calcium carbonate and gypsum conditions.
SQ7	Workability (constraining field management)	Soil texture, effective soil depth/volume, and SPHs constraining soil management (soil depth, rock outcrops, stoniness, gravel/concretions, and hardpans).

Source: Authors' own elaboration.

The seven soil qualities (SQ1–SQ7) are estimated from specific soil characteristics, the occurrence of soil phases, soil drainage (DRG) characteristics, and vertic and gelic soil conditions. Procedures and activities employed in the soil suitability assessment are schematically represented in Figure 2.

Figure 2. Soil suitability rating (SSR) procedures



Source: Authors' own elaboration.

Soil suitability estimations are crop/LUT-specific. Procedures were separately parameterized and implemented for conventional and organic farming systems.

SOIL SUITABILITY ASSESSMENT FOR CONVENTIONAL FARMING SYSTEMS

Conventional farming systems cover the full range from traditional smallholder farming to industrial agriculture. The former relies on low inputs and traditional labour-intensive management, while the latter refers to farming systems which may include the use of synthetic chemical fertilizers, pesticides, herbicides and continual inputs, intensive tillage, and monoculture crop rotations. Industrial agriculture is typically highly resource-demanding and energy-intensive, but also highly productive. To cover the range of conventional farming options, three levels of conventional farming are assumed in GAEZ v5:[17]

1. **low level inputs**: high labour intensity and traditional management using local cultivars;
2. **intermediate level inputs:** inputs, medium labour intensity and management using local and improved cultivars; and
3. **high level inputs**: low labour intensity, mechanization and advanced management, using high yielding cultivars.

In all three levels of inputs, the appropriate monocropping rotation requirements and fallow requirements – as appropriate for input levels – are assumed to have been implemented (Fischer *et al.*, 2021).

Procedures to derive soil qualities (SQ1–SQ7) and soil unit suitability from various combinations of soil attributes are based on Liebig's law of the minimum with specified adjustments to account for constraints other than the most limiting[18] (Sys and Riquier, 1980).

To determine SQ3 (rooting conditions), the RSD rating is adjusted with the minimum rating of:

- soil depth/volume limiting soil properties;
- occurrence of soil depth/soil volume limiting soil phases; and
- obstacles to roots or impermeable soil layers (ISLs).

To determine SQ4 (oxygen availability) the minimum rating of soil drainage conditions and specific soil phases impeding soil drainage conditions are used.

To determine SQ5 (soil salinity and sodicity) the minimum rating of the soil salinity and soil sodicity conditions – including occurrence of saline and/or sodic or saline-sodic soil phases – are used.

To determine SQ6 (calcium carbonate and/or gypsum conditions), the most limiting rating of calcium carbonate and gypsum content and occurrence of petrocalcic and petrogypsic soil phases are considered. Calcium carbonate content may affect physiological (growth) aspects, while high gypsum content may cause nutrient imbalances. The prevalence of gypsum may also

[17] Detailed descriptions of LUTs for conventional farming can be found in GAEZ v4 Model Documentation (Fischer *et al.*, 2021) and GAEZ v5 Model Documentation (FAO and IIASA, 2025a).

[18] Constraints ratings of soil profile attributes are obtained by linear interpolation of values specified for six reference rating levels (100 percent, 90 percent, 70 percent, 50 percent, 30 percent and 10 percent).

hinder field and water supply management (Driessen and Dudal, 1991), which is considered in SQ7 (soil workability).

When more complex relationships and multiple factors make up a soil quality – as is the case for SQ1 (nutrient availability), SQ2 (nutrient retention) and SQ7 (soil workability) – the lowest rated attribute is adjusted with the average rating of the remaining attributes, as illustrated by the rating function f_{SQ} (see Equation 1).

Let $(x_1,\ldots,x_m)$ be a vector of soil attributes relevant for a particular soil quality (SQ) and $(\tau(x_1),\ldots,\tau(x_m))$ the vector of respective soil attribute ratings considered in the assessment of SQ, $0 \leq \tau(x_j) \leq 1$.

Further, let j_o denote the soil attribute with the lowest rating, such that $\tau(x_{j_o}) \leq \tau(x_j)$, j = 1,…,m.

Then SQ is defined from the attribute with lowest soil attribute ratings and the average of remaining soil attributes ratings, as follows:

$$SQ = f_{SQ}(x_1,\ldots,x_m) = \tau(x_{j_0}) \times \frac{1}{m-1}\sum_{j \neq j_0} \tau(x_j) \qquad \text{(Equation 1)}$$

Note that the soil attribute ratings are obtained from standards rating classes by linear interpolation of attribute values between respective class limits. An example of the calculation is given in Appendix 4.

Soil qualities are estimated for each individual soil layer: D1 (0–20 cm), D2 (20–40 cm), D3 (40–60 cm), D4 (60–80 cm), D5 (80–100 cm), D6 (100–150 cm), and D7 (150–200 cm) and combined by crop-specific weighing factors according to crop–soil specific rooting patterns and subject to RSDs (Appendix 2). The use of soil attributes of seven soil layers versus the two layers (0–30 cm and 30–100 cm) of the previous HWSD v1.2 markedly improves the suitability estimations for crop/LUTs with varying rooting depths (RDs).

Soil quality rating for conventional farming systems

Nutrient availability (SQ1)

The natural availability of nutrients is essential for successful farming using the following management techniques:

- low inputs and traditional soil and plant or crop management; and
- intermediate inputs and improved soil and plant or crop management.

There are many diagnostics related to nutrient availability. Important soil characteristics of the upper layer are soil texture, mineralogy and structure, soil organic carbon (SOC), soil pH and total exchangeable bases TEB). The soil attributes used for the deeper layers include soil texture, soil pH and TEB. Evaluations of upper and deeper layers are plant- and crop-specific depending on rooting pattern, crop RD and RSD.[19]

[19] Note that rootable depth is a soil property, while rooting depth is a crop characteristic.

The soil profile attributes relevant to soil nutrient availability are interrelated. For SQ1, the attribute with the lowest suitability rating is multiplied with the average of the remaining ones. The relationships shown in Equation 2 and Equation 3 represent the upper soil layer (0–20 cm) and deeper layers (>20 cm) respectively:

$$SQ1_{upper\ soil\ layer} = f_{SQ}\ (TXT, SOC, pH_{Wat}, TEB) \qquad \text{(Equation 2)}$$

$$SQ1_{deeper\ soil\ layers} = f_{SQ}\ (TXT, pH_{Wat}, TEB) \qquad \text{(Equation 3)}$$

where TXT is soil texture, SOC is soil organic carbon, pH_{Wat} is the soil reaction, and TEB is the total exchangeable bases.

Here, SQ1 is evaluated separately for each soil layer. Soil quality ratings of layers are weighted according to the root mass distribution of each plant or crop within the RSD (see Table A2.2, Table A2.3, Table A2.4 and Table A2.5 in Appendix 2).

Nutrient retention capacity (SQ2)

Nutrient retention is of particular importance for the effectiveness of fertilizer applications and is foremost relevant for intermediate and high input farming.

Nutrient retention refers to the capacity of the soil to retain added nutrients against losses caused by leaching. Plant nutrients are held in the soil on the exchange sites provided by the clay fraction, SOC and the clay–humus complex. Losses vary with the intensity of leaching which is determined by the rate of drainage of soil moisture through the soil profile. Soil texture affects nutrient retention in two ways, through its effects on the available exchange capacity of the clay minerals and by soil permeability.

The soil characteristics used for the assessment of the upper soil layer are soil texture, the base saturation (BS) and the cation exchange capacity of soil (CEC_{soil}). For the deeper layers, TXT, BS and the cation exchange capacity of the clay fraction (CEC_{clay}) are used. Soil pH serves as the proxy measure of micronutrient deficiencies.

For SQ2, the attribute with the lowest suitability rating is multiplied with the average of the remaining ones. The relationships shown in Equation 4 and Equation 5 represent the upper soil layer D1 (0–20 cm) and the deeper layers D2–D7 (>20 cm) respectively by using weighted values of soil attributes and ratings of the respective soil layers and crop/LUTs:

$$SQ2_{upper\ soil\ layer} = f_{SQ}\ (TXT, BS., CEC_{soil}) \qquad \text{(Equation 4)}$$

$$SQ2_{deeper\ soil\ layers} = f_{SQ}\ (TXT, pH_{Wat}, BS, CEC_{clay}) \qquad \text{(Equation 5)}$$

where TXT is soil texture, BS is the base saturation, CEC_{soil} is the cation exchange capacity of soil, pH_{Wat} is the soil reaction and CEC_{clay} is the cation exchange capacity of the clay fraction.

Note that SQ2 is evaluated separately for each soil layer. Soil quality ratings of layers are weighted according to root mass distribution of each plants or crops within RSDs (see Table A2.2, Table A2.3, Table A2.4 and Table A2.5 in Appendix 2).

Rooting conditions (SQ3)

Rooting conditions depend on the RSD (in cm), considering the presence of an ISL, pans or indurated horizons in the soil, and on effective soil volume (vol. %) accounting for the presence of gravel and stones. Rooting conditions may be affected by soil phases, either limiting the RSD or decreasing the effective volume accessible for root penetration. Rooting conditions influence crop growth in several ways:

- adequacy of foothold (sufficient soil depth for the crop to anchor sufficiently);
- available soil volume and penetrability of the soil for roots to extract nutrients;
- space for root and tuber crops for expansion where the economic yield is produced in the soil; and
- absence of shrinking and swelling properties (vertic), mainly affecting root and tuber crops.

Rootable soil depth and soil volume limitations affect root penetration and constrain yield formation for roots and tubers. Rooting conditions (SQ3) are estimated by combining the rootable soil depth rating τ(RSD) (Sys, 1990a, 1990b, 1990c; Sys, Van Ranst and Debaveye, 1991a, 1991b; Sys *et al.*, 1993), with additional reductions for conditions affecting root development, or root and tuber yield.

Rooting conditions (SQ3) are derived from τ(RSD) and adjusted by the minimum rating of the additional limitation factors, as seen in Equation 6:

$$SQ3 = \tau(RSD) \times \min\left[\tau(TXT), \tau(GRC), \tau(VSP), \tau(GSP), \tau(SPH), \tau(OTR), \tau(ISL)\right] \qquad \text{(Equation 6)}$$

where τ( ) is the respective input level- and crop- specific attribute rating for soil texture (TXT), gravel content (GRC), vertic soil property (VSP) or gelic soil property (GSP). Note that the rootable soil depth (RSD) considers soil depth-limiting soil phases (SPH), obstacles to roots (OTR) and occurrence of an impermeable soil layer (ISL). Soil volume-reducing soil phases are accounted for by τ(SPH).

Oxygen availability (SQ4)

Oxygen availability in soils is largely defined by the drainage characteristics of soils. The determination of soil drainage classes is based on procedures developed at FAO (FAO, 1995). These procedures account for soil type, TXT, SPH and terrain slope.

Assumptions regarding artificial drainage vary with input level. For low and intermediate input farming, drainage ratings assume no artificial drainage. For high input, drainage ratings assume that adequate artificial drainage systems are installed.

Apart from drainage characteristics, oxygen availability may be influenced by soil and terrain characteristics that are defined by the occurrence of specific soil phases and presence of an ISL or prevailing temporal soil wetness conditions (WR).

A specific plant or crop's SQ4 can be defined as the most limiting attribute rating of either soil drainage or soil phase. This soil quality differs between input levels due to the different assumptions regarding artificial drainage, as seen in Equation 7:

$$SQ4 = min[\tau(DRG), \tau(SPH)] \qquad \text{(Equation 7)}$$

where τ(.) is the respective input level specific attribute rating for soil drainage (DRG) and soil phase (SPH).

As the DRG and SPH relate to a soil unit rather than individual soil layers, SQ4 is evaluated for the entire soil unit and the specific plants or crop, limited to RSD.

Salinity and sodicity (SQ5)

Soil salinity refers to an excess of soluble salts in the soil, here measured by the electrical conductivity (ECe) of the saturated soil paste. Soil salinity affects crops through inhibiting the uptake of water. Moderate salinity affects growth and reduces yields, while high salinity levels might prevent the growth of plants or crops.

Soil sodicity is the excess presence of sodium ions (Na^+) in soil relative to other cations, measured by the sodium adsorption ratio (SAR) or exchangeable sodium percentage (ESP). It often occurs in combination with high pH values. Sodicity causes sodium toxicity and affects soil structure, leading to massive or coarse columnar structure with low permeability.

Apart from the ECe and ESP soil layer attributes, saline and sodic soil phases indicate possible limitations for crop growth and yields. In the case of occurrence of saline or sodic soil phases, the EC and ESP attribute values of each soil depth layer are adjusted. According to the definition of these soil phases, the saline soil phase is interpreted to mean that ECe ≥4 dS/m and the sodic soil phase implies ESP ≥6 percent. The impacts of the given levels of soil salinity and soil sodicity are treated of the same for the three conventional farming input levels.

The most limiting rating of the soil salinity and sodicity conditions (after adjustment of attribute values for the occurrence of saline or sodic soil phases) determines SQ5, as seen in Equation 8:

$$SQ5 = min\ [\tau\ (ESP), \tau(EC), \tau(SPH)] \qquad \text{(Equation 8)}$$

where τ( ) is the respective attribute rating function evaluated separately for upper and deeper soil layers, ESP is the exchangeable sodium percentage, the EC is the electrical conductivity and SPH indicates the occurrence of soil phases. The evaluation of SQ5 is for all soil layers within the rooting zone of each plant or crop and is limited to RSD.

Calcium carbonate and gypsum (SQ6)

Calcisols and calcareous soils with high calcium carbonate content, as well as soils with petrocalcic soil phases, may exhibit micronutrient deficiencies, such as of iron, manganese, and zinc and in some cases, toxicity of molybdenum, all of which may affect growth and yield performance of specific crops.

Gypsisols and gypsiferous soils with a high gypsum content (as well as soils with a petrogypsic soil phase), may depress yield performance through nutrient imbalances. High gypsum prevalence may affect field operations and interfere with irrigation water supply and soil drainage. The latter constraints are rated under SQ7 (workability). Tolerance of crops to calcium carbonate and gypsum varies widely (FAO, UNESCO and ISRIC, 1990; FAO, 1984).

In SQ6, the most limiting factor is identified based on of the combined presence of excess calcium carbonate and gypsum in the soil along with the occurrence of petrocalcic and petrogypsic soil phases and SQ6 is assumed to be independent of the level of input and management, as seen in Equation 9:

$$SQ6 = min[\tau(CCB), \tau(GYP), \tau(SPH)] \qquad \text{(Equation 9)}$$

where τ( ) is the respective attribute rating function, CCB is calcium carbonate, GYP is gypsum, and SPH indicates the occurrence of soil phases.

Note that SQ6 is evaluated for all soil layers within the rooting zone of each plant or crop, limited to RSD.

Workability (SQ7)

Diagnostic characteristics that can be related to soil workability vary by type of management applied. Workability or ease of tillage depends on interrelated soil characteristics such as texture, soil structure, organic matter content, soil consistence or bulk density, the occurrence of gravel or stones in the profile or at the soil surface, and the presence of continuous hard rock at shallow depth, as well as rock outcrops. Some soils are easy to work, independent of moisture content, while other soils are only manageable only at a specific moisture status through the use of hand cultivation or light machinery.

Irregular soil depth, gravel and stones in the profile and rock outcrops might prevent the use of farm machinery. Soil constraints related to soil texture and soil structure particularly affect low and intermediate input LUTs, while the constraints related to irregular soil depth and stony and rocky soil conditions mainly affect mechanized land preparation and harvesting operations of high-level input farming LUTs. Workability constraints are therefore assessed separately for low, intermediate and high input farming.

Physical hindrance depends on the crop and specific field management. The AEZ procedures are crop- and management-specific and consider hindrance by limited RSD, soil phases (stony, rudic, lithic, petric, skeletic, petrocalcic, petroferric, fragipan, and duripan), and the prevalence of coarse fragments, TXT, DRG and VSP.

Under high input assumptions, deep ploughing is assumed, and the soil texture ratings and GRC ratings (gravel content) are determined for soil depth layers D1–D5 and then equally weighted. For intermediate and low input assumptions, no deep ploughing is considered to have occurred and only soil depth layers D1–D3 are used in the SQ7 estimation. Rootable soil depth, DRG, soil SPH and VSP apply to entire soil units. Soil workability is evaluated for upper and deeper soil layers within the rooting and tillage zones of each plant or crop LUT, subject to RSD.

The workability soil quality (SQ7) is derived by multiplying the most limiting soil or soil phase attribute rating with the average of the remaining attribute ratings in Equation 10, as follows:

$$SQ7 = f_{SQ}(RSD, GRC, TXT, VSP, DRG, SPH, OTR, ISL) \qquad \text{(Equation 10)}$$

where RSD is the rootable soil depth, GRC is soil gravel content, TXT is soil texture, VSP represents vertic soil properties, DRG is drainage class, SPH indicates the occurrence of soil phases, OTR reflects obstacles to roots, and ISL indicates an impermeable soil layer.

Miscellaneous units in HWSD v2.2 are considered to render land unsuitable for plant or crop production. These include shifting sand, rock debris, rock outcrops, dunes, salt flats, inland water, and ice caps, as well as gelundic, takyric, yermic, desert and gobi units.

Soil suitability rating (SSR) for conventional farming systems

Functional relationships of soil qualities have been formulated to quantify the crop/LUT suitability of soil units. The following guiding principles formed the basis for the way soil qualities by crop/LUT were combined for different levels of input and management:

- Nutrient availability (SQ1) and nutrient retention (SQ2) are key soil qualities, interacting with other limitation factors.
- Nutrient availability is of utmost importance for low level input farming. Nutrient retention capacity is most important for high level inputs. Nutrient availability and nutrient retention capacity are considered of equal importance for farming with an intermediate level of inputs.
- Nutrient availability is strongly related to RD and soil volume available.
- Rooting conditions (SQ3), oxygen available to roots (SQ4), excess salts (SQ5), tolerance to calcium carbonate and gypsum (SQ6), and workability (SQ7) are regarded as equally important soil qualities. The combination of these soil qualities is best achieved by multiplication of the most limiting rating with the average of the ratings of the remaining four soil qualities.

Following these principles, using three levels of inputs and four different water supply systems, a soil unit suitability rating (SSR_{cs}) for conventional farming systems has been estimated by individual crops. The functional relationships for different input levels vary in their use of SQ1 and SQ2, as presented in Equation 11.

Let (SQ_1,….,SQ_m) be a vector of soil quality values, $0 \leq SQ_j \leq 1$ or 100 percent. Further, let j_o denote the soil quality with the lowest value such that: $SQ_{jo} \leq SQ_j$, j = 1,…,m.

Then a combined soil quality function f_{SSR} can be defined as:

$$f_{SSR}(SQ_1, \dots, SQ_m) = SQ_{j_0} \times \frac{1}{m-1} \sum_{j \neq j_0} SQ_j \qquad \text{(Equation 11)}$$

where the most limiting soil quality value is multiplied with the average of the remaining relevant soil qualities values.

The crop and farming system-specific soil unit suitability rating for a conventional farming system *cs* is then specified in Equation 12 as:

$$SSR_{cs} = (\alpha_{cs} \times SQ1_{cs} + \beta_{cs} \times SQ2_{cs}) \times f_{SSR}(SQ3_{cs}, SQ4_{cs}, SQ5_{cs}, SQ6_{cs}, SQ7_{cs}) \qquad \text{(Equation 12)}$$

where *cs* stands for a conventional farming system, with a defined input level (low, intermediate or high).

The results of the soil unit suitability assessment have been tabulated for each crop by the combination of soil unit, slope class, input level and water supply system, so that edaphic suitability[20] can be integrated with the results of the agroclimatic suitability assessment to estimate agroecological suitability and attainable crop yields.

[20] Terrain suitability is estimated according to terrain slope classes and location-specific rainfall amounts and rainfall concentration characteristics. The latter allow to better assess soil erosion risks and to refine the terrain suitability rating scheme. Soil resources and terrain slope conditions are aligned and integrated at grid-cell level (AEZ soil and terrain slope databases) by ranking soil types regarding likely occurrence in different slope classes.

SOIL SUITABILITY ASSESSMENT FOR ORGANIC FARMING SYSTEMS

Organic farming systems encompass agroecological practices as defined for conservation agriculture, organic farming, climate-smart farming and regenerative farming (Box 1). These systems entail specific crop and field management practices (Corsi and Muminjanov, 2019) including the application of organic fertilizers, the use of biostimulants and biological or mechanic pests, and disease and weed control as required to gain biocertification or organic certification.

Box 1. Organic agricultural systems

Agroecological practices: Agroecological practices apply ecological principles to the interactions between human beings and their environment, as well as to their consequences, with the goal of minimizing the negative effects of human (agricultural) activities. It aims at protecting the environment, ensuring the sustainable renewal of the natural resources (such as water, soil and biodiversity) necessary for production, and making sparing use of non-renewable resources *(*Wezel *et al.*, 2020). By gradually eliminating the use of chemicals, it strives toward the implementation of organic farming, thus contributing to improving the health of farmers and consumers alike.

Conservation agriculture (CA): Conservation agriculture is a farming system that can prevent losses of arable land while regenerating degraded lands. It promotes the maintenance of a permanent soil cover, minimum soil disturbance and diversification of plant species. It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improved and sustained crop production (Farooq and Siddique, 2015). Conservation agriculture is based on three principles: including:

1. Continuous minimum mechanical soil disturbance with direct seeding (i.e. no-till).
2. Permanent soil organic cover with crop residues and/or cover crops to the extent allowed by water availability.
3. Species diversification through varied crop rotations, sequences and associations (Corsi and Muminjanov, 2019, p.26).

Organic farming principles: Organic farming denotes agricultural systems that use ecologically based pest control and biological fertilizers derived largely from animal and plant wastes and nitrogen-fixing cover crops. Modern organic farming was developed as a response to the environmental harm caused by the use of chemical pesticides and synthetic fertilizers in conventional agriculture, and it is recognized for its numerous ecological benefits.

Climate-smart agriculture (CSA): Climate-smart agriculture is an approach for developing actions needed to transform and reorient agricultural systems to effectively support development and ensure food security under climate change. Climate-smart agriculture aims to tackle three main objectives:

1. sustainably increasing agricultural productivity and income;
2. adapting and building resilience to climate change; and
3. reducing or avoiding greenhouse gas emissions, where possible.

Box 1 (cont'd)

Regenerative farming (RA): Regenerative farming is an approach that uses soil conservation as the entry point to regenerate and enhance multiple ecosystem services.

Sources: **Wezel, A., Herren, B.G., Kerr, R.B., Barrios, E., Gonçalves, A.L.R. & Sinclair, F.** 2020. Agroecological principles and elements and their implications for transitioning to sustainable food systems. A review. *Agronomy for Sustainable Development*, 40(6): 1–13. https://doi.org/10.1007/s13593-020-00646-z

Farooq, M. & Siddique, K.H.M. 2015. *Conservation Agriculture*. Cham, Switzerland, Springer International Publishing.

Corsi, S. & Muminjanov, H. 2019. *Conservation Agriculture: Training guide for extension agents and farmers in Eastern Europe and Central Asia*. Rome, FAO. https://openknowledge.fao.org/server/api/core/bitstreams/c2ef4bba-a15d-4df2-9326-ed557ab67c92/content

Agroecological practices in organic farming systems (conservation agriculture, organic farming, climate-smart farming, and regenerative farming) are considered very relevant for sustainable agricultural development (FAO, 2016; Atta-Krah *et al.*, 2021; Schreefel *et al.*, 2020; Shiva, 2022). To represent these systems in AEZ, the modelling needs to be extended with organic multicrop rotations, involving the specification of organic farming LUTs based on sustainable field management and appropriately certified organic inputs and produce.

Two distinct input levels are assumed for modelling the suitability and yields of organic farming systems: organic farming with moderate inputs and management, and organic farming with advanced inputs and management (see Box 2).

Organic farming with moderate inputs is a farming method that combines traditional organic farming practices with the use of some modern inputs, such as organic fertilizers and pest management techniques, in a way that is sustainable and minimizes harm to the environment. Organic farming with moderate inputs is here defined as combining the best of traditional and modern techniques for sustainable, organic farming with moderate inputs. Organic farming with advanced inputs is defined as a farming method that uses modern inputs and management, such as precision technologies, sophisticated pest management and specialized fertilizers to maximize yields and improve overall farming efficiency.

Box 2. Organic farming land utilization types

Organic farming systems with moderate inputs: Under the assumption of moderate inputs and improved management, the organic farming system is partly market-oriented. Production for subsistence plus the commercial sale of certified products is a management objective. Production is based on traditional and improved varieties, is partly mechanized, and highly labour intensive.

Organic farming systems with advanced inputs: With an advanced level of inputs, the farming system is mainly market-oriented. Commercial production and the sale of certified products is the main management objective. Production is based on improved and high yielding cultivars and is labour intensive.

Organic farming systems are assumed to follow strict objectives and norms of organic production and processing (e.g. IFOAM - Organics International, 2019). For both moderate and advanced level inputs, the following conditions are assumed:

- no or minimum tillage is applied, stubble and roots are retained in the soil, crop residue is returned, and soil compaction is avoided;
- application of farm compost, farm manure, green manure and/or additional nutrients from commercially available organic fertilizer, biochar and biostimulants (Farooq and Siddique, 2015)
- biological control of pests, diseases and weeds;
- agronomic practices including sole cropping (also sequential), intercropping and mixed cropping;
- cropping patterns and rotations including off-season cover/green manure crops and adequate fallow to maintain nutrient balance and break pest and disease cycles;
- soil conservation practices and the preservation of organic matter in the upper layer to prevent topsoil and soil nutrient losses due to erosion and leaching; and
- upholding agrodiversity and biodiversity on farm fields and adjacent areas to serve as a prerequisite for sustained production.

Sources: **IFOAM (International Federation of Organic Agriculture Movements)- Organics International**. 2019. *The IFOAM NORMS for Organic Production and Processing.* Edited version of the IFOAM Norms 2014. Bonn, Germany. https://ifoam.bio/sites/default/files/2020-09/IFOAM%20Norms%20July%202014%20Edits%202019.pdf

Farooq, M. & Siddique, K.H.M. 2015. *Conservation Agriculture*. Cham, Switzerland, Springer International Publishing.

The soil evaluation for agricultural productivity of individual crops or plants in organic farming (by an assumed level of inputs) also uses the seven soil qualities (SQ1 to SQ7) previously introduced, albeit with some adaptations, as follows:

- **Nutrient availability ($SQ1^+$).**[21] Organic farming techniques can enhance soil organic carbon status (SOC^+) and the soil structure, which in turn can improve the soil reaction

[21] Throughout this manuscript, modifications of soil attributes and soil qualities induced by organic farming practices are indicated by a "+" sign to differentiate from evaluations for conventional farming.

(pH+), CEC_{soil}^{+} and the total exchangeable bases (TEB+), thereby improving the nutrient status of soils.

- **Nutrient retention (SQ2+)**. Organic farming techniques can improve the soil structure and soil aggregation, which in turn can improve soil pH, the CEC_{soil} and BS, enhancing the CEC_{clay} which together may substantially improve soil nutrient retention.
- **Rooting conditions (SQ3+)**. No changes of soil attributes are assumed or applied.[22]
- **Oxygen availability (SQ4+)**. Organic farming techniques can improve the soil structure and soil aggregation, which in turn can improve the aeration of poorly drained soils, leading to an improvement in soil drainage.
- **Salinity and sodicity (SQ5+)**. Organic farming can alleviate salinity and sodicity levels (ECe+ and ESP+) within the tolerance boundaries for salinity when ECe <25 dS/m and for sodicity when ESP <35 percent.
- **Calcium carbonate and gypsum (SQ6+)**. No changes are assumed or applied.[23]
- **Workability (SQ7+)**. Soil workability constraints in organic farming with moderate and advanced inputs and management are assumed comparable with soil workability constraints as defined for conventional farming with intermediate inputs.[24]

Soil quality rating for organic farming systems

The procedures used to derive SQ1+–SQ7+ from various combinations of soil attributes are formulated according to the procedures applied for conventional farming, with modifications for nutrient availability (SQ1+), nutrient retention (SQ2+), oxygen availability (SQ4+), soil salinity and sodicity (SQ5+), and soil workability (SQ7+).

For organic farming with moderate inputs, both SQ3+ and SQ6+ follow the same procedures as those for conventional farming with intermediate inputs. Organic farming with advanced inputs also follows the same procedures as those for conventional farming with high inputs.

Nutrient availability (SQ1+)

The natural availability of nutrients, along with the use of organic fertilizers, is crucial for successful organic farming with both moderate and advanced inputs.

Soil attributes used for diagnostics related to the nutrient availability for the upper soil layer (0–20 cm) include SOC, pH and TEB as pre-conditions. For the deeper layers (>20 cm) the soil texture, mineralogy and structure , pH and TEB are used.

[22] Increased organic carbon and soil organisms improve rooting conditions to a certain extent, allowing roots to better spread and extend in deeper soil layers. However, at this stage, the extent of improvement that can be attributed to soil organisms has not been quantified nor applied

[23] Research evidence indicates that organic farming practices do alleviate calcium carbonate and gypsum toxicities for field crops. As a conservative estimate of SQ6+, at this stage, potential alleviations were not applied (Brady and Wells, 2017).

[24] Minimum till or no till practices in organic farming may further reduce soil workability constraints.

Additions of organic fertilizer (compost, farm manure, green manure, biochar, and biostimulants) result in a substantial increase of SOC in the upper soil layer[25] which also increases TEB and soil pH (Table 3). Compared to conventional farming, the soil layer attributes of SOC, TEB and soil pH are thus adapted to account for the impacts of organic farming practices, and the ratings (applying the adjusted soil attributes) follow the same procedures used for conventional farming with intermediate inputs.

Table 3. Indicative changes of soil organic carbon (SOC+), soil reaction (pH+) and total exchangeable bases (TEB+) after ten years under organic farming

Attribute and precondition	Adjusted attribute	Organic farming, with moderate inputs	Organic farming with advanced inputs
SOC (%weight) >5%	SOC^+	0	0
SOC (%weight) 3–5%	SOC^+	+1%	+2%
SOC (% weight) 1–3%	SOC^+	+2%	+3%
SOC (% weight) <1%	SOC^+	+3%	+4%
pH (−log[H⁺]) <5.5	pH^+	+ 5%	+10%
pH (−log[H⁺]) 5.5–6.5	pH^+	+2.5%	+5%
pH (−log[H⁺]) 6.5–7.5	pH^+	0	0
pH (−log[H⁺]) >7.5	pH^+	2.5%	-5%
TEB (cmolc/kg) <5	TEB^+	+25%	+50%
TEB (cmolc/kg) 5–15	TEB^+	+17.5%	+35%
TEB ($cmol_c$/kg) 15-25	TEB^+	+10%	+20%
TEB ($cmol_c$/kg) >25	TEB^+	+5%	+10%

Note: the ideal level of soil organic carbon for organic farming ranges between 3 and 5 percent.

SOC = soil organic carbon, pH = soil reaction and TEB = total exchangeable bases.

Sources: **Lal, R**. 2004. Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science*, 304(5677): 1623–1627. https://doi.org/10.1126/science.1097396

Lehmann, J. & Kleber, M. 2015. Perspective The contentious nature of soil organic matter. *Nature*, 528: 60–68. https://doi.org/10.1038/nature16069

Soil profile attributes relevant to soil nutrient availability are interrelated. For $SQ1^+$, the attribute with the lowest suitability rating is multiplied with the average rating of the remaining attributes. The relationships shown in Equation 13 and Equation 14 represent the upper soil layer (0–20 cm) and deeper layers (>20 cm) respectively:

$$SQ1^+_{upper\ soil\ layer} = fSQ\ (TXT, SOC^+, pH_{Wat}^+, TEB^+) \quad \text{(Equation 13)}$$
$$SQ1^+_{deeper\ soil\ layers} = fSQ\ (TXT, pH^+, TEB^+) \quad \text{(Equation14)}$$

[25] The increase of organic carbon takes place through crop residues and organic fertilizer applied to the upper soil layer. Under organic farming conditions, soil organisms improve pH and TEB, including in deeper soil layers (such as through the actions of earthworms), therefore TEB+ and pH+ are also applied for deeper soil layers.

where TXT is soil texture, SOC is soil organic carbon, pH_{Wat} is the soil reaction, and TEB is the total exchangeable bases.

Nutrient availability ($SQ1^+$) is evaluated separately for all soil layers. Layer results are weighted according to root mass distribution of each plant or crop, subject to RSD.

Nutrient retention capacity ($SQ2^+$)

Nutrient retention refers to the capacity of the soil to retain added nutrients against losses caused by leaching. As previously noted, losses vary with the intensity of leaching, which is determined by the rate of drainage of soil moisture through the soil profile. Soil texture affects nutrient retention in two ways: through its effects on available exchange sites on the clay minerals and by soil permeability. Nutrient retention is of particular importance for the effectiveness of nutrient applications.

Soil profile attributes used for the estimation of $SQ2^+$ of the upper layer of soil (0–20 cm) under organic farming systems are soil TXT, BS and CEC_{soil}.

For the deeper layers (>20 cm), soil TXT, pH, BS, and CEC_{clay} are used. Additions of organic fertilizer (compost, farm manure, green manure, biochar and biostimulants) result in substantial increases of upper layer soil organic carbon (SOC),[26] which in turn in deeper layers increases BS, pH, CEC_{soil} and CEC_{clay} (Table 4) (i.e. adjusted soil layer attributes BS^+, pH^+, CEC_{soil}^+, and CEC_{clay}^+). Soil attribute ratings for organic farming systems with moderate and advanced inputs and management use adapted attributes and follow the same rating procedures that are applied to conventional farming with intermediate inputs.

Table 4. Indicative changes of BS+, soil reaction (pH+), cation exchange capacity of soil (CECsoil+) and cation exchange capacity of the clay fraction (CECclay+) after ten years under organic farming

Attribute and precondition	Adjusted attribute	Organic farming with moderate inputs	Organic farming with advanced inputs
BS (%) <30%	BS^+	+25%	+40%
BS (%) 30–50%	BS^+	+15%	+25%
BS (%) 50–80%	BS^+	+5%	+10%
BS (%) >80%	BS^+	0	0
pH (−log[H^+]) <5.5	pH^+	+ 5%	+10%
pH (−log[H^+]) 5.5–6.5	pH^+	+2.5%	+5%
pH (−log[H^+]) 6.5–7.5	pH^+	0	0
pH (−log[H^+]) >7.5	pH^+	−2.5%	−5%
CEC_{soil} ($cmol_c$/kg) <10	CEC_{soil}^+	+25%	+40%
CEC_{soil} ($cmol_c$/kg) <10–20	CEC_{soil}^+	+15%	+25%

[26] Increase of organic carbon takes place through crop residues and organic fertilizers applied to the upper soil layer. Under organic farming conditions the increase of SOC improves BS and CECsoil in the upper layer, and pH, BS, CECclay in deeper layers. For estimating nutrient retention in deeper layers under organic farming (>ten years), soil texture is assumed to remain largely unchanged.

Table 4 (Cont.)

CEC_{soil} ($cmol_c$/kg) <20–30	CEC_{soil}^+	+5%	+10%
CEC_{soil} ($cmol_c$/kg) >30	CEC_{soil}^+	0	0
CEC_{clay} ($cmol_c$/kg) <15	CEC_{clay}^+	+5%	+10%
CEC_{clay} ($cmol_c$/kg) 15–40	CEC_{soil}^+	+5%	+7.5%
CEC_{clay} ($cmol_c$/kg) 40–80	CEC_{soil}^+	+2.5%	+5%
CEC_{clay} ($cmol_c$/kg) >80	CEC_{soil}^+	0	+2.5%

Sources: **Brady, N.C. & Weil, R.R.** 2017. *The Nature and Properties of Soils.* Fifteenth edition. London, Pearson Education.

Lal, R. & Stewart, B.A. 2018. *Soil and Climate*. Boca Raton, USA, CRC Press.

Magdoff, F. & Van Es, H. 2021. *Building Soils for Better Crops. Ecological Management for Healthy Soils.* College Park, USA, University of Maryland, Sustainable Agriculture Research and Education (SARE) Outreach. https://www.sare.org/wp-content/uploads/Building-Soils-for-Better-Crops.pdf

Sumner, M.E. & Miller, W.P. 1996. Cation Exchange Capacity and Exchange Coefficients. In: D.L. Sparks (ed). *Methods of Soil Analysis, Part 3. Chemical Methods,* pp. 1201–1229. Madison, USA, Soil Science Society of America (SSSA).

For the estimation of SQ2$^+$, the attribute with the lowest suitability rating is multiplied with the average of the remaining ones. The relationships shown in Equation 15 and Equation 16 represent the upper soil layer (0–20 cm) and the deeper layers (>20 cm) respectively:

$$SQ2^+_{upper\ soil\ layer} = f_{SQ}\ (TXT,\ BS^+,\ CEC_{soil}^+) \qquad \text{(Equation 15)}$$

$$SQ2^+_{deeper\ soil\ layers} = f_{SQ}\ (TXT,\ pH^+,\ BS^+,\ CEC_{clay}^+) \qquad \text{(Equation 16)}$$

where TXT is soil texture, BS is base saturation, CEC_{soil} is the cation exchange capacity of soil, pH is the soil reaction, and CEC_{clay} is the cation exchange capacity of the clay fraction.

Note that SQ2$^+$ is evaluated separately for all soil layers. Layer results are weighted according to root mass distribution of each plant or crop, subject to RSD.

Rooting conditions (SQ3$^+$)

The evaluation of SQ3 for organic farming with moderate inputs follows the same rating procedures used for conventional farming with intermediate inputs. Organic farming with advanced levels of inputs uses the same procedures used for conventional farming with high inputs.

Oxygen availability (SQ4$^+$)

Oxygen availability in soils is in part defined by the soil drainage characteristics of soils. The determination of soil drainage classes is based on procedures developed at FAO (FAO, 1995). These procedures account for soil type, soil texture, soil phases and terrain slope.

Assumptions regarding artificial drainage vary with input level. Organic farming with moderate inputs assumes no artificial drainage, while organic farming with advanced inputs assumes adequate artificial drainage.

Apart from drainage characteristics, oxygen availability may be influenced by soil and terrain characteristics caused by the occurrence of specific soil phases and the presence of ISLs or temporally prevailing WR.

For conventional farming the LUT definition in AEZ assumes regular tillage. No till and minimum till are assumed for organic farming LUTs only (see Box 2). Overall, when compared to conventional farming, organic farming improves SOC status, which enhances soil structure and biological activity, and therefore the aeration of poorly drained soils. To account for these ameliorations, the drainage of poor, imperfectly and moderately well-drained soils improves due to organic farming practices by one class (soil drainage conditions) compared to drainage conditions for conventional farming.

On the other hand, organic farming tends to reduce excessive drainage. Organic farming adds more compost, manure and crop residues to the soil, causing less leaching and slower drainage, keeping moisture available to plants longer (Panagea *et al*., 2021). Hence, under organic farming systems, somewhat excessively drained soils improve towards well drained and excessively drained soils improve towards somewhat excessively drained.

In Equation 17, $SQ4^+$ has been defined as the most limiting rating for a specific plant or crop of either soil drainage or soil phase-related limitations:

$$SQ4^+ = min[\tau(DRG^+), \tau(SPH)] \qquad \text{(Equation 17)}$$

where τ( ) is the respective (crop- and input level-specific) attribute rating for drainage and soil phases with regard to $SQ4^+$. DRG describes the drainage conditions and SPH is the soil phases.

Note: Due to the characteristics of these soil attributes, $SQ4^+$ is evaluated for the entire soil unit and not differentiated by soil depth layers.

Salinity and sodicity ($SQ5^+$)

Soil salinity (excess soluble salts) and sodicity (high sodium, affecting soil structure) can be significantly reduced over ten years with organic amendments, better drainage and improved soil structure. Organic farming increases soil organic matter through compost, manure, biochar, and green manures. Higher organic matter enhances soil aggregation, water infiltration and leaching of excess salts, contributing to the reduction of soil salinity over time. Organic amendments stimulate microbial diversity and activity, contribute to the breakdown of harmful salts, enhance nutrient cycling, and facilitate sodium leaching, thereby reducing sodicity levels. (Table 5).

Organic farming can improve soil salinity and sodicity conditions, but the extent of improvement depends on various factors including climate, soil drainage, crop management practices, and the duration of organic management. (Guo *et al*., 2022).

Table 5. Soil salinity and sodicity dynamics under organic farming over time

Years under organic farming	Salinity (ECe)	Sodicity (ESP)	Main changes	Rate of change
1–3	Slight reduction	Initial stability/slight reduction	Increased organic matter and microbial activity	Slow initial improvement
4–7	Moderate reduction	Noticeable decline	Improved soil structure, enhanced water movement	Relative rapid improvement
8–10	Significant reduction	Stabilized at low levels	Healthy soil, reduced compaction, better drainage	Substantial improvement until new balance is reached

Improvements of soil salinity and sodicity are assumed to vary in organic farming with moderate and with advanced inputs. Organic farming with advanced inputs and with installed artificial drainage is considered more effective in reducing salinity and sodicity.

The main factors contributing to an improvement of soil salinity and sodicity are initial salinity and sodicity levels, and initial soil drainage conditions. The greatest benefits seen using organic farming practices can be achieved in soils that are moderately saline or alkaline (sodic) and well-drained. Under these conditions, given a ten-year period of organic farming practices, the reported improvements of salinity levels are about 60 percent. Sodicity levels are reported dropping by 50 percent (Table 6). However, high sodicity levels (ESP >35 percent) as well as high salinity levels (ECe >25 dS/m) in poorly drained soils prevent the rapid establishment of organic farming and hamper significant soil salinity and sodicity improvements.[27]

Table 6. Indicative percentage changes of soil salinity (ECe^+) and soil sodicity (ESP^+) after ten years under organic farming

Attribute and precondition	Adapted attribute	Organic farming with moderate inputs *	Organic farming with advanced inputs *
Soil salinity (ECe >25 dS/m)	ECe^+	0%	0%
Soil salinity (ECe 16–25 dS/m)	ECe^+	−15–0%	−20%
Soil salinity (ECe 8–16 dS/m)	ECe^+	−40–0%	−45%
Soil salinity (ECe 2–8 dS/m)	ECe^+	−50–0%	−60%
Soil salinity (ECe <2 dS/m)	ECe^+	−50–0%	−60%
Soil sodicity (ESP >35%)	ESP^+	0%	0%
Soil sodicity (ESP 25–35%)	ESP^+	−15–0%	−20%
Soil sodicity (ESP 15–25%)	ESP^+	−35–0%	−40%
Soil sodicity (ESP 8–15%)	ESP^+	−40–0%	−50%
Soil sodicity (ESP <8%)	ESP^+	−45–0%	−50%

[27] Organic systems alone may not suffice in severely saline and sodic soils. A combination of reclamation techniques may also be required (such as artificial drainage, biosubsoiling with deep rooted crops, planting salt-tolerant crops and gypsum applications)

* Organic farming with moderate inputs does not assume artificial drainage and changes will depend on salinity/sodicity preconditions as well as the prevailing soil drainage class. For organic farming with advanced inputs, artificial drainage is assumed and the results depend on ECe and ESP preconditions only.

Sources: See References.

The changes expected over ten years of organic farming practices have been synthesized from various studies examining the long-term effects of organic farming on soil salinity and sodicity. While no single study provides systematic improvements (considering various initial salinity and sodicity levels combined with different initial soil drainage conditions), it has been repeatedly demonstrated that organic farming practices – through increased organic matter, improved soil structure, enhanced microbial activity, and better water infiltration– significantly contribute to the remediation of salinity and sodicity, especially in well-drained or moderately drained soils (including Sys, Van Ranst and Debaveye, 1991a, 1991b; Sys *et al*., 1993; Tejada *et al*., 2006; Vargas *et al*., 2018; Allen *et al*., 1998; Rengasamy, 2006; Leogrande and Vitti, 2018).

As seen in Equation 18, the most limiting rating of the soil salinity and soil sodicity conditions (after adjusting attributes for the occurrence of saline and sodic soil phases) determines $SQ5^+$:

$$SQ5^+ = min\,[\tau\,(ESP^+),\,\tau(ECe^+)] \qquad \text{(Equation 18)}$$

where τ( ) is the respective attribute rating function separately evaluated for both adjusted electrical conductivity (ECe^+) and exchangeable sodium percentage (ESP^+) values of upper and deeper soil layers. All soil layers within the rooting zone of each plant or crop are evaluated for $SQ5^+$ and aggregation over soil layers is limited to RSD.

It is important to note and acknowledge that published research results of organic farming impact on soil salinity and sodicity conditions are scarce. Therefore, the GAEZ v5 soil evaluation model can be run with or without indicative changes of soil salinity (ECe) and soil sodicity (ESP) due to organic farming.

Calcium carbonate and gypsum ($SQ6^+$)

The evaluation of $SQ6^+$ for organic farming with moderate inputs follows the same procedures used. for conventional farming with intermediate inputs. Organic farming with advanced inputs uses the same procedures applied to conventional farming with high inputs.

Workability ($SQ7^+$)

Success of both conventional and organic farming may be affected by soil workability constraints. Conventional farming with high inputs and advanced field management relies on conventional tillage and large-scale mechanized harvesting. In contrast, organic farming – which employs zero or minimum tillage along with environmentally and scale-adapted harvesting technologies – is likely to be less affected by soil workability constraints than field management of conventional farming.

In the current model implementation, a conservative estimate of soil workability constraints is used for organic farming LUTs, for both moderate and advanced levels of inputs and management ($SQ7^+$ for organic systems follows the soil workability constraints applicable for respective LUTs in conventional farming under intermediate level inputs and management). For soil attributes – which are available per depth layer and applied in estimating $SQ7^+$ (TXT and GRC) – the D1 to D3 soil depth layers are used and equally weighted to derive $SQ7^+$.

When more information is available for assessing organic farming LUTs with specific characteristics, model users may choose to adapt soil workability constraint ratings as is most appropriate in their specific applications.

Soil unit suitability rating (SSR^+) for organic farming systems

As for conventional farming systems, functional relationships of soil qualities have been formulated to quantify crop/LUT suitability of soils for organic farming. The following guiding principles formed the basis for the way soil qualities were combined for organic farming systems under different levels of inputs and management:

- Nutrient availability and nutrient retention are key soil qualities, interacting with other limitation factors.
- Nutrient availability is of crucial importance for organic farming with moderate inputs, and of high importance to organic farming with advanced inputs.
- Nutrient retention is important for moderate and highly important for organic farming with advanced inputs.
- Nutrient availability is strongly related to RD and soil volume.
- Rooting conditions, oxygen available to roots, excess salts, tolerance to calcium carbonate and gypsum, and workability are regarded as equally important soil qualities. The combination of these soil qualities (SQ3+ to SQ7+) is best achieved by multiplication of the most limiting rating with the average of the ratings of the remaining four soil qualities.

Following these principles for individual crops (with two levels of inputs and management and four different water supply systems), each soil unit suitability rating for organic farming systems can be estimated. The procedures used to derive the soil unit ratings from various combinations of soil qualities can be described in Equation 19 as:

$$SSR^+_{cs} = (\alpha_{cs} \times SQ1^+_{cs} + \beta_{cs} \times SQ2^+_{cs}) \times f_{SSR}(SQ3^+_{cs}, SQ4^+_{cs}, SQ5^+_{cs}, SQ6^+_{cs}, SQ7^+_{cs}) \qquad \text{(Equation 19)}$$

where SSR^+ is the soil unit suitability rating and *cs* defines an organic farming system (by level of inputs and farm management [moderate or advanced]). Coefficient α is an input level specific weighting factor for $SQ1^+$ and β the weighting factor for $SQ2^+$, with $\alpha + \beta = 1$. Weighting factors α_{cs} and β_{cs} applied for different conventional and organic farming systems in the current GAEZ v5 soil evaluation are shown in Table 7. . The function f_{SSR} used in Equation 19 is defined as in Equation 11 for conventional systems.

Table 7. Weighting factors for combining soil qualities SQ1 and SQ2 in soil unit suitability rating

Input level and farm management	Weighting factor for SQ1α	Weighting factor for SQ2β
Conventional farming (low inputs)	1.0	0.0
Conventional farming (intermediate inputs)	0.5	0.5
Conventional farming (high inputs)	0.0	1.0
Organic farming (moderate inputs)	0.33	0.67
Organic farming (advanced inputs)	0.25	0.75

Note: The table shows parameters α_{cs} and β_{cs} used for weighting soil qualities SQ1 and SQ2 in Equation 12 and SQ1+ and SQ2+ in Equation 19 when calculating soil suitability ratings.

The results of the soil unit suitability assessment have been tabulated for each combination of (crop, soil unit, slope class, input level, water supply system) for further integration in GAEZ v5 with the results of the agroclimatic crop suitability assessment.

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Appendix 1. Crop soil requirement tables (GAEZ v5)

Crop soil requirements are listed in GAEZ v5 for 76 crops under rainfed and sprinkler irrigation systems, assuming high, intermediate and low levels of inputs and management conditions. In addition, soil requirements are presented for 61 crops producing under gravity irrigation systems and for 20 crops producing under drip irrigation systems, assuming high and intermediate levels of input and management conditions. The crop soil requirement tables are also valid for organic farming LUTs under moderate and advanced levels of input and management. As discussed in the main text, organic farming interpretations for $SQ1^+$, $SQ2^+$, $SQ4^+$, $SQ5^+$ and $SQ7^+$ deviate from conventional farming.

Soil requirement ratings are presented separately by water supply type and input level (where relevant) for chemical and physical soil characteristics, soil textures, soil drainage and various soil phases.

A1.1. Chemical and physical soil characteristics

Suitability ratings of soil characteristics are empirical coefficients that reflect the effect the value of the soil characteristic has on the yield potential of a specific crop. In the GAEZ v5 soil evaluation routines, the ratings are obtained by interpolation using piecewise linear functions of expected crop yield responses to different soil attribute levels. Soil attribute rating functions are monotonically increasing or monotonically decreasing relationships. The response functions are specified using six attribute levels, which correspond with rating factors of 100 percent (no constraint), 90 percent (slight constraint), 70 percent (moderate constraint), 50 percent (severe constraint), 30 percent (very severe constraint) and 10 percent (not suitable). For pH, where the crop response can be characterized by an inverse u-shaped function, the rating function is split into two monotonic components, with one being evaluated when soil pH is less than the crop-specific optimal pH range, and the other evaluated for soil pH greater than the optimal range.

A1.2. Soil textures

Soil texture conditions influence various soil qualities (SQ1, SQ2, SQ3 and SQ7) and ratings differ by input level. Soil texture ratings have been compiled for 13 texture classes (Soil Survey Division Staff, 1993).

A1.3. Soil drainage

Soil drainage ratings vary by crop and may also vary by the prevalent soil texture conditions. Assumptions for artificial soil drainage differ by input levels. Conventional farming with high inputs and organic farming with advanced inputs assume that full and adequate artificial drainage systems are installed, while conventional farming with low and intermediate inputs and organic farming with moderate inputs do not assume artificial drainage.

A1.4. Soil phase

The soil phase ratings have been compiled for conventional farming by input level (high, intermediate and low). For organic farming – depending on field management specifications – values as presented for conventional farming with intermediate inputs are currently proposed.

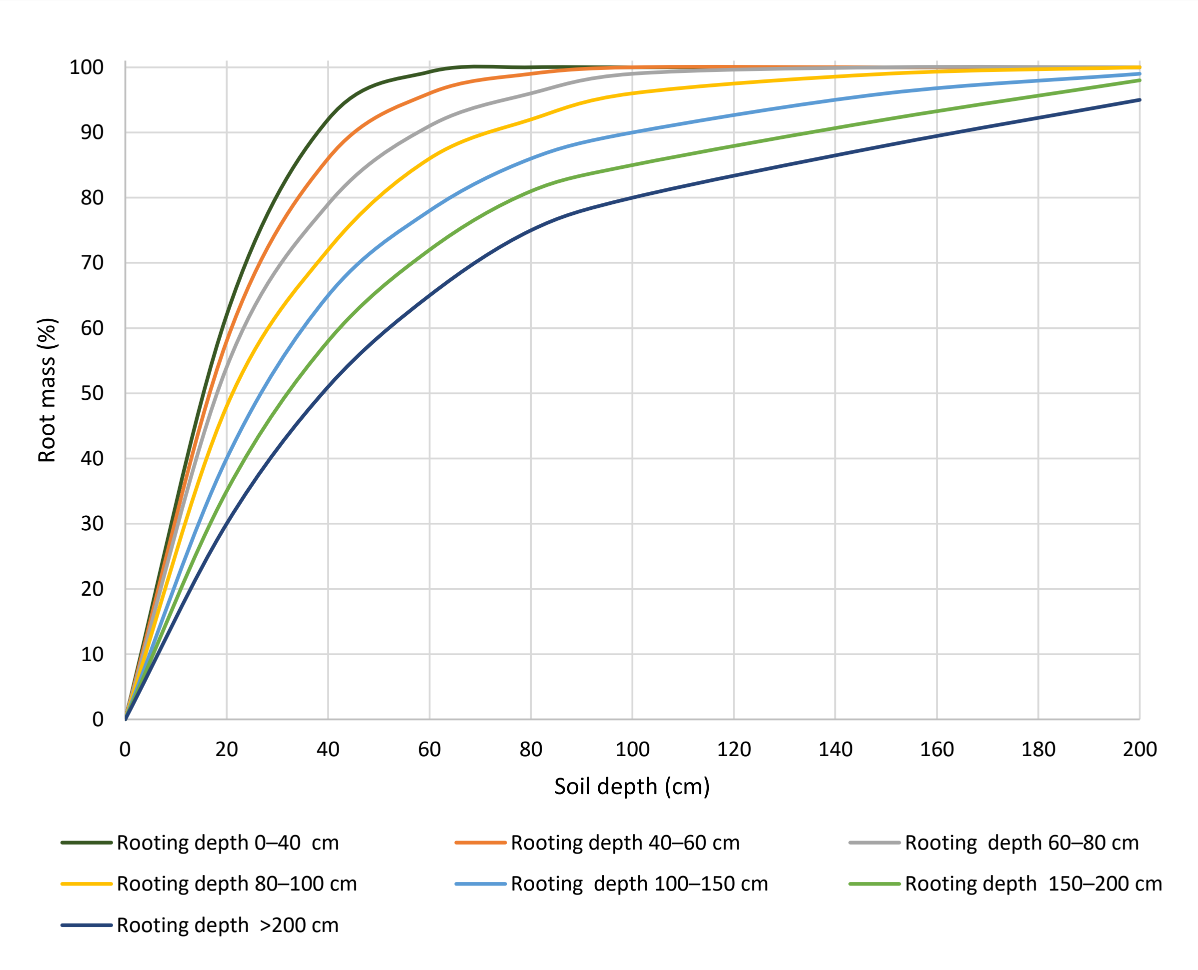
The ratings represent constraints implied by the occurrence of soil phases in the percentage of yield achievement, where 100 percent rating means no yield reduction and 0 percent rating renders a soil entirely unsuitable for growing a crop.

Soil phases are organized by the soil quality to which they apply, by the level of input and management, and by water supply system.

Appendix 2. Deriving weight for the Harmonised World Soil Database (HWSD) soil layers for application in soil suitability assessments

Version 5 of GAEZ uses relationships between crop RD (cm) and crop root mass distribution (percentage) obtained from literature, as shown in Figure A2.1. The resulting root mass distribution parameters depend on crop RD (a crop characteristic) and RSD (a soil property). A summary of the extracted distribution parameters by RD class is provided in Table A2.1.

Figure A2.1. Cumulative root mass (percentage) by rooting depth (RD) (cm)



Source: Authors’ own elaboration.

Table A2.1. Cumulative root mass (percentage) by rooting depth (RD) (cm)

Rootable soil depth (cm)	Rooting depth classes						
	1	2	3	4	5	6	7
	0–40 cm (%)	40–60 cm (%)	60–80 cm (%)	80–100 cm (%)	100–150 cm (%)	150–200 cm (%)	>200 cm (%)
0	0	0	0	0	0	0	0
20	62	58	54	48	40	35	30
40	92	86	79	72	65	58	51
60	100	96	91	86	78	72	65
80	100	99	96	92	86	81	75
100	100	100	99	96	90	85	80
150	100	100	100	99	96	92	88
200	100	100	100	100	99	98	95

Sources: **Fan, J., Mcconkey, B.G., Wang, H. & Janzen, H.** 2016. Root distribution by depth for temperate agricultural crops. *Field Crops Research*, 189: 68–74. https://doi.org/10.1016/j.fcr.2016.02.13

Jackson, R.B., Canadell, J., Ehleringer, J.R., Mooney, H.A., Sala, O.E. & Schulze, E.D. 1996. A global analysis of root distributions for terrestrial biomes. *Oecologia*, 108(3): 389–411. https://doi.org/10.1007/BF00333714

Kemper, R., Bublitz, T.A., Müller, P., Kautz, T., Döring, T.F. & Athmann, M. 2020. Vertical Root Distribution of Different Cover Crops Determined with the Profile Wall Method. *Agriculture*, 10(11): 503. https://doi.org/10.3390/agriculture10110503

Perkons, U., Kautz, T., Uteau, D., Peth, S., Geier, V., Thomas, K., Lütke Holz, K. *et al.* 2014. Root-length densities of various annual crops following crops with contrasting root systems. *Soil and Tillage Research*, 137: 50–57. https://doi.org/10.1016/j.still.2013.11.005

When the RSD is limited, this then affects root distribution and hence the relationship between root mass and RD. Table A2.2, Table A2.3, Table A2.4 and Table A2.5 summarize root distribution parameters used in the GAEZ v5 edaphic assessment in terms of six crop RD classes, by HWSD soil depth layers, and for four broad soil crop RSD classes (deep soils, moderately deep soils, shallow soils and very shallow soils).

Table A2.2. Root mass by soil layer, for deep soils (>100 cm)

Rooting depth		HWSD soil depth layer D1–D7							
Class	cm	0–20 cm (%)	20–40 cm (%)	40–60 cm (%)	60–80 cm (%)	80–100 cm (%)	100–150 cm (%)	150–200 cm (%)	Total
1	**0–40**	62	30	8	0	0	0	0	100
2	**40–60**	58	28	10	3	1	0	0	100
3	**60–80**	54	25	12	5	3	1	0	100
4	**80–100**	48	25	13	6	4	3	1	100
5	**100–150**	42	24	14	8	4	6	2	100
6	**>150**	35	23	14	9	5	8	6	100

Note: Rootable soil depth is a soil property, here representing RSD class 1 (>100 cm). Crop RD is a crop property, here represented in six classes, starting with 0–40 cm (class 1) to >150 cm (class 6).

Source: Authors' own elaboration.

Table A2.3. Root mass by soil layer, for moderately deep soils (50–100 cm)

RD		HWSD soil depth layer D1–D7							
Class	**cm**	**0–20 cm (%)**	**20–40 cm (%)**	**40–60 cm (%)**	**60–80 cm (%)**	**80–100 cm (%)**	**100–150 cm (%)**	**150–200 cm (%)**	**Total**
1	**0–40**	62	30	8	0	0	0	0	100
2	**40–60**	58	28	10	3	1	0	0	100
3	**60–80**	54	25	12	5	4	0	0	100
4	**80–100**	50	25	15	6	4	0	0	100
5	**100–150**	47	24	16	8	5	0	0	100
6	**>150**	45	23	17	9	6	0	0	100

Note: Rootable soil depth is a soil property, here representing RSD class 2 (50–100 cm). Crop RD is a crop property, here represented in six classes, from 0–40 cm (class 1) to >150 cm (class 6).

Source: Authors' own elaboration.

Table A2.4. Root mass by soil layer, for moderately deep soils (10–50 cm)

RD		HWSD soil depth layer D1–D7*							
Class	**cm**	**0–20 cm (%)**	**20–40 cm (%)**	**40–60 cm (%)**	**60–80 cm (%)**	**80–100 cm (%)**	**100–150 cm (%)**	**150–200 cm (%)**	**Total**
1	**0–40**	62	38	0	0	0	0	0	100
2	**40–60**	58	42	0	0	0	0	0	100
3	**60–80**	54	46	0	0	0	0	0	100
4	**80–100**	50	50	0	0	0	0	0	100
5	**100–150**	48	52	0	0	0	0	0	100
6	**>150**	46	54	0	0	0	0	0	100

Note: Rootable soil depth is a soil property, here representing RSD class 3 (10–50 cm). Crop RD is a crop property, here represented in six classes, from 0–40 cm (class 1) to >150 cm (class 6).

* For soils in crop RSD class 3 (shallow soils) only soil depth layers D1 and D2 are generally available.

Source: Authors' own elaboration.

Table A2.5. Root mass by soil layer, for moderately deep soils (<10 cm)

Rooting depth		HWSD soil depth layer D1–D7*							
Class	**cm**	**0–20 cm (%)**	**20–40 cm (%)**	**40–60 cm (%)**	**60–80 cm (%)**	**80–100 cm (%)**	**100–150 cm (%)**	**150–200 cm (%)**	**Total**
1	**0–40**	100	0	0	0	0	0	0	100
2	**40–60**	100	0	0	0	0	0	0	100
3	**60–80**	100	0	0	0	0	0	0	100
4	**80–100**	100	0	0	0	0	0	0	100
5	**100–150**	100	0	0	0	0	0	0	100
6	**>150**	100	0	0	0	0	0	0	100

Note: Rootable soil depth is a soil property, here representing RSD class 4 (<10 cm). Crop RD is a crop property, here represented in six classes, from 0–40 cm (class 1) to >150 cm (class 6).

* For soils in crop RSD class 4 (very shallow soils) only soil depth layer D1 is considered.

Source: Authors' own elaboration.

Soil qualities are separately estimated for individual soil layers: D1 (0–20 cm), D2 (20–40 cm), D3 (40–60 cm), D4 (60–80 cm), D5 (80–100 cm), D6 (100–150 cm), and D7 (150–200 cm) and combined by crop-specific weighing factors according to crop and soil-specific rooting patterns which are subject to RSD.

Appendix 3. Rooting depth (RD) of crops in GAEZ v5

Table A3.1 presents the crop RD in GAEZ v5. The data was taken from two main sources: FAO56 (Allen *et al*., 1998) and ECOCROP (FAO, 1999). For the remaining crops various sources were consulted. In case of differences of reported crop RDs, judgements were made by the authors. GAEZ users may want to review and update the crop RDs presented in Table A3.1, as better or region-specific data comes available.

Table A3.1. Rooting depth (RD) of crops in GAEZ v5.

GAEZ crop types (name)	Rooting depth – range (m)	Rooting depth – minimum (m)	Minimum value of maximum rooting depth (m)***	Rooting depth suggested for AEZ applications (m)	Rooting depth (RD) class
Cereals					
Barley, hibernating *(Hordeum vulgare)*	1.5-1.8	1.5	1.0	1.5	5
Barley, other (*Hordeum vulgare)*	1.0-1.5*	1.0	1.0	1.0	4
Buckwheat *(Fagopyrum esculentum)*	0.9-1.2**	0.9		0.9	4
Finger millet *(Eleusine coracana)*	0.5-1.5°			1.0	4
Fonio (*Digitaria exilis*)	0.5-1.5°			1.0	4
Foxtail millet *(Setaria italica)*	1.0-2.0*	1.0	1.0	1.0	4
Oat *(Avena sativa)*	1.0-1.5*	1.0		1.0	4
Grain maize (*Zea maize*)	1.0-1.7*	1.0	0.9	1.0	4
Silage maize (*Zea maize)*	1.0-1.7	1.0	0.9	1.0	4
Pearl millet *(Pennisetum glaucum)*	1.0-2.0*	1.0	1.0	1.0	4
Dryland rice (*Oryza sativa* subsp. *Indica)*	0.85-1.05**	0.85		0.85	4
Wetland rice (*Oryza sativa* subsp. *indica and japonica*)	0.5-1.0*	0.5	0.5	0.5	3
Rye, hibernating (*Secale cereale)*	1.5-1.8	1.5		1.5	5
Rye, other (*Secale cereale)*	1.0-1.5	1.0		1.0	4
Grain sorghum *(Sorghum bicolor)*	1.0-2.0*	1.0	1.0	1.0	4
Biomass sorghum *(Sorghum bicolor)*	1.0-2.0*	1.0	1.0	1.0	4
Teff (*Eragrostic tef)*	0.2-0.5°			0.5	2
Triticale *(Triticosecale*)	1.0-1.5	1.0	1.0	1.0	4

Wheat, hibernating *(Triticum* spp.*)*	1.5-1.8*	1.5	1.0	1.5	5
Wheat, other *(Triticum spp.)*	1.0-1.5*	1.0	1.0	1.0	4
Roots and tubers					
Cassava, short duration *(Manihot esculenta)*	0.5-0.8*	0.5	0.6	0.5	3
Cassava, long duration *(Manihot esculenta)*	0.7-1.0*	0.7	0.6	0.7	4
Sweet potato *(Ipomoea batatas)*	1.0-1.5*	1.0	1.0	1.0	4
White potato *(Solanum tuberosum*)	0.30-0.45	0.3	0.4	0.4	3
Tannia (cocoyam) *(Xanthosoma sagittifolium)*	0.30-0.40 (in mounds)	0.3		0.5	3
Taro (cocoyam) (*Colocasia esculenta)*	0.30-0.40 (in mounds)	0.5		0.5	3
White yam (*Dioscorea rotundata*)	0.30-0.40** (in mounds)	0.3		0.5	3
Greater yam (*Dioscorea alate)*	0.30-0.40 (in mounds)	0.3		0.5	3
Yellow yam (*Dioscorea cayenensis)*	0.30-0.40 (in mounds)	0.3		0.5	3
Yams, no mounds *(Dioscorea spp.)*	0.5-1.5°			1.0	3
Pulses					
Phaseolus bean (*Phaseolus vulgaris and Phaseolus lunatus*)	0.5-0.7*	0.5		0.5	3
Chickpea (*Cicer arietinum)*	0.6-1.0*	0.6		0.6	3
Cowpea *(Vigna unguiculata)*	0.6-1.0*	0.6		0.6	3
Dry pea (*Pisum sativum* L.*)*	0.6-0.9*	0.6		0.6	3
Green Gram (*Vigna radiata*)	0.6-1.0*	0.6		0.6	3
Lentil (*Lens culinaris*)	0.5-1.0	0.5		0.5	3
Pigeon pea *(Cajanus cajan)*	1.0-2.0	1.0		1.0	5
Oil crops					
Camelina *(Camelina sativa)*	1.0-1.5*	1.0		1.0	4
Carinata (*Brassica carinata*)	1.0-1.5*	1.0		1.0	4
Castor bean *(Ricinus communis)*	1.0-2.0*	1.0		1.0	5
Groundnut *(Arachis hypogaea)*	0.5-1.0*	0.5	0.5	0.5	3
Jatropha (*Jatropha curcas*)	1.15-1.45	1.15		1.15	5
Macauba palm (*Acrocomia aculeata*)	1.0-2.0	1.0		1.0	4
Oil palm (*Elaeis oleifera*)	1.0-2.0	1.0	1.0	1.0	5
Olive (*Olea europaea*)	1.2-1.7*	1.2		1.2	6
Rape, hibernating (*Brassica napus)*	1.5-1.8*	1.0		1.0	4

Table A3.1 (Cont.)

Rape, other (*Brassica napus)*	1.0-1.5*	1.0		1.0	4
Sesame *(Sesamum indicum)*	1.0-1.5*	1.0	1.0	1.0	4
Soybean *(Glycine max)*	0.6-1.3*	0.6	0.6	0.6	3
Sunflower *(Helianthus anuus)*	0.8-1.5*	0.8	0.8	0.8	3
Sugar crops					
Sugarcane (*Saccharum officinarum*)	1.2-2.0*	1.2	1.2	1.2	5
Sugar beet (*Beta vulgaris*)	0.7-1.2*	0.7		0.7	3
Industrial crops					
Cotton (*Gossypium hirsutum*)	1.0-1.7*	1.0	1.0	1.0	4
Flax (*Linum usitatissium*)	1.0-1.5*	1.0		1.0	4
Rubber (*Hevea brasiliensis*)	1.0-1.5*	1.0	1.0	1.0	6
Narcotics and stimulants					
Cacao (*Theobroma cacao*)	0.7-1.0*	0.7	0.7	0.7	6
Arabica Coffee (*Coffea arabica*)	0.9-1.5*	0.9	0.9	0.9	6
Robusta Coffee (*Coffea canephora*)	0.9-1.5*	0.9	0.9	0.9	6
Sinensis tea (*Camellia sinensis* var. *sinensis*)	0.9-1.5*	0.9	1.0	0.9	5
Assam tea (*Camellia sinensis* var. *assamica*)	0.9-1.5*	0.9	1.0	0.9	5
Hybrid tea (*Sinensis* x *assamica*)	0.9-1.5*	0.9	1.0	0.9	5
Tobacco (*Nicotiana tabacum*)	0.8[o]	0.8	0.7	0.8	4
Fruits					
Banana and plantain (*Musa* spp.)	0.5-0.9	0.5	0.5	0.5	3
Cashew (*Anacardium occidentale*)	>1.5[o]			>1.0	6
Citrus (*Citrus sinensis*)	0.8-1.5*	0.8	1.1	0.8	6
African tall coconut (*Cocos nucifera*)	0.7-1.1*	0.7	1.0	0.7	4
Dwarf coconut (*Cocos nucifera*)	0.7-1.1*	0.7	1.0	0.7	4
Hybrid coconuts (*Cocos nucifera*)	0.7-1.1*	0.7	1.0	0.7	4
Mango (*Mangifera indica*)	< 6.0 **			>1.0	6
Watermelon (*Citrullus lanatus*)	0.8-1.5*			1.0	5

Table A3.1 (Cont.)

Bioenergy feedstocks					
Energy cane (*Saccharum spontaneum* x *Saccharum officinarum*)	1.2-2.0*	1.2		1.2	5
Miscanthus (*Miscanthus* spp.)	> 2.5**			>1.0	4
Reed canary grass (*Phalaris arundinacea*)	>3.0**			>1.0	4
"Solaris" tobacco (*Nicotiana solanifolia*)	1.0-1.5*	1.0	0.7	1.0	4
Switchgrass (*Panicum virgatum*)	0.5-1.5º			1.0	4
Vegetables					
Cabbage (*Brassica oleracea*)	0.5-0.8*	0.5		0.5	2
Carrot (*Daucus carota*)	0.5-1.0*	0.5		0.5	3
Okra (*Abelmoschus esculentus*)	0.2-0.5º			0.5	3
Onion (*Allium cepa*)	0.3-0.6*	0.3		0.4	3
Tomato (*Lycopersicon lycopersicum*)	0.7-1.5*	0.7		0.7	4
Fodder crops					
Alfalfa (*Mediago sativa*)	1.0-2.0*	1.0		1.0	4
Brachiaria (*Brachiaria* spp.)	0.6-0.9**	0.6		0.6	3
Napier grass (*Cenchrus pupureus*)	>1.5º			>1.0	4
Pasture legumes	0.6-0.9*	0.6		0.6	3
Pasture grasses	0.5-1.5*	0.5		0.5	3

Note: * Allen *et al.* (1998). º FAO (2022). ** Fischer *et al.* (2021), Kemper *et al.* (2020), Perkons *et al.* (2013), Allen *et al.* (1998), Vargas *et al.* 2018, FAO (2022) and *** FAO (2004).

Sources: See References.

Appendix 4. Calculation examples of soil suitability ratings of rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

The general soil unit information extracted from HWSD v2.2 and used in the GAEZ v5 edaphic evaluation includes the following items:

- soil mapping unit (SMU) number;
- soil mapping unit sequence number in SMU;
- soil unit classification (FAO90 [FAO, 1990] andWRB22 [IUSS Working Group WRB, 2022]);
- percentage share of soil unit in SMU;
- soil phases (SPH);
- rootable soil depth (RSD);
- obstacle to roots (OTR);
- impermeable soil layer (ISL);
- soil water regime (WR);
- soil drainage (DRG) (class);
- gelic soil properties (GSP); and
- vertic soil properties (VSP).

Table A4.1 shows general soil information for an example from HWSD v2.2, namely soil mapping unit (SMU) 27116, located near Ilonga in Tanzania. This SMU comprises of four soil units. For this example, the dominant soil unit was selected and classified as Humic Acrisols (ACu) in FAO (1990) and Acric Umbrisols (UMackk) in IUSS Working Group WRB (2022) soil classifications. The dominant soil unit accounts for 55 percent of the SMU and has a stony soil phase, which indicates the presence (>35 percent) of gravel, stones, boulders or rock outcrops in the surface layers or at the surface.

Table A4.1. Soil unit characteristics and suitability for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

Soil unit characteristics		Soil quality	Attribute rating	
			Conventional (high inputs)	Organic farming (advanced inputs)
Soil mapping unit (SMU)	27116	–	–	–
Soil unit sequence number	1	–	–	–
Soil unit (WRB22)*	Akroskeletic Acric Umbrisols (UMackk)	–	–	–
Soil unit (FAO90)**	Humic Acrisols (ACu)	–	–	–
Share in SMU (%)	55	–	–	–
Rootable soil depth (RSD) (class)	Deep (>100 cm)	SQ3, SQ7	100	100
Soil phase (SPH) 1	Stony	SQ3	75	75
Soil phase (SPH) 1	Stony	SQ7	50	75
Soil phase(SPH) 2	None	–	–	–
Obstacle to roots (OTR)	None	SQ3, SQ4,	100	100
Impermeable soil layer (ISL)	None	SQ3, SQ4	100	100
Soil water regime	None	SQ4	100	100
Soil drainage class (DRG)	Moderately well (MW)	SQ4	100	100
Gelic soil properties (GSP)	None	SQ3, SQ7	100	100
Vertic soil properties (VSP)	None	SQ3, SQ7	100	100

Note: FAO90 and WRB22 refer to FAO (1990) and IUSS Working Group WRB (2022).

Source: Authors' own estimation apart from ***IUSS (International Union of Soil Sciences) Working Group WRB**. 2022. *World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps*. Fourth edition. Vienna, Austria. https://eurasian-soil-portal.info/wp-content/uploads/2022/07/wrb_fourth_edition_2022-3.pdf

**** FAO**. 1990. *Guidelines for Soil Description*. Rome.

Soil attributes extracted by soil depth layer (D1–D7) include:

- depth of soil layer (cm);
- coarse fragments (>2 mm) (volume percentage);
- texture class (Soil Survey Division Staff, 1993);
- organic carbon content (weight percentage);
- pH in water (-log(H^+));
- cation exchange capacity of soil (cmol/kg);

- cation exchange capacity of the clay fraction (cmol/kg);
- total exchangeable bases (sum of Na^+, Ca^{++}, Mg^{++}, and K^+ exchangeable cations);
- base saturation (percentage);
- exchangeable sodium percentage (percentage);
- calcium carbonate (weight percentage);
- gypsum content (weight percentage); and
- electrical conductivity (dS/m).

Table A4.2 lists soil attribute values by soil depth layer extracted for the selected ACu soil unit and indicates for which of the seven soil qualities each attribute is assessed and rated.

Table A4.2. Soil attributes of Humic Acrisol soil unit (ACu) in the Harmonized World Soil Database (HWSD) v2.2 soil mapping unit (SMU 27116), by depth layers

Soil layer attribute	Soil quality	Soil attribute value by depth layers						
		D1 0–20 cm	D2 20–40 cm	D3 40–60 cm	D4 60–80 cm	D5 80–100 cm	D6 100–150 cm	D7 150–200 cm
Coarse fragments (GRC) (% volume)	SQ3, SQ7	2	4	3	4	5	9	24
Texture class (TXT) (Soil Survey Division Staff, 1993)	SQ1, SQ2, SQ3, SQ7	Clay loam	Clay loam	Clay loam	Clay loam	Clay	Clay	Clay loam
Soil organic carbon (SOC) content (% weight)	SQ1	3.03	1.75	1.04	0.71	0.44	0.36	0.29
pH in water (−log[H^+])	SQ1, SQ2	5.1	5.2	5.2	5.3	5.3	5.4	5.5
Cation exchange capacity of soil (CEC_{soil}) (cmol/kg)	SQ2	18	16	14	13	13	13	15
Cation exchange capacity of clay fraction (CEC_{clay}) (cmol/kg)	SQ2	22	22	21	24	21	21	45
Total exchangeable bases (TEB) (cmol/kg)	SQ1	5	5	5	3	5	8	7
Base saturation (BS) (% CEC_{soil})	SQ2	37	38	40	38	42	45	41
Exchangeable sodium percentage (ESP) (%)	SQ5	1	1	1	2	1	1	1
Calcium carbonate (CCB) (% weight)	SQ6	0	0	0	0	0	0	0

Table A4.2 (Cont.)

Gypsum content (GYP) (% weight)	SQ6	0	0	0	0	0	0	0
Electrical conductivity (EC) (dS/m)	SQ5	0	0	0	0	0	0	0

Source: Authors' own elaboration apart from * **Soil Survey Division Staff**. 1993. *Soil Survey Manual*. *U.S. Department of Agriculture Handbook 18*. Washington, DC, United States Department of Agriculture (USDA). https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf

Table A4.3 lists adjusted soil attribute values, reflecting ten consecutive years of organic farming practices under advanced inputs and management.

Table A4.3. Soil attributes of Humic Acrisol soil unit (ACu) in the Harmonized World Soil Database version 2.2 (HWSD v2.2) (SMU 27116) by depth layers, adjusted for ten consecutive years of organic farming practices with advanced inputs

Soil layer attribute	Soil quality	Soil attribute value by depth layers						
		D1 0–20 cm	D2 20–40 cm	D3 40–60 cm	D4 60–80 cm	D5 80–100 cm	D6 100–150 cm	D7 150–200 cm
Coarse fragments (GRC) (% volume)	SQ3+, SQ7+	2	4	3	4	5	9	24
Texture class (TXT) (Soil Survey Division Staff, 1993)*	SQ1+, SQ2+, SQ3+, SQ7+	clay loam	clay loam	clay loam	clay loam	clay	clay	clay loam
Soil organic carbon (SOC) content (% weight)	SQ1+	5.00	5.00	5.00	4.71	4.44	4.36	4.29
Soil pH in water (-log(H+))	SQ1+, SQ2+	5.6	5.7	5.7	5.8	5.8	5.9	6.1
Cation exchange capacity of soil (CEC_{soil}) (cmol/kg)	SQ2+	22.3	20.5	18.5	17.4	17.4	17.4	19.5
Cation exchange capacity of clay fraction (CEC_{clay}) (cmol/kg)	SQ2+	24.0	24.0	23.0	26.2	23.0	23.0	47.9
Total exchangeable bases (TEB) (cmol/kg)	SQ1+	7.5	7.5	7.5	4.5	7.5	11.5	10.2
Base saturation (BS) (% CEC_{soil})	SQ2+	49.7	50.8	52.8	50.8	54.8	57.6	53.8
Exchangeable sodium percentage (ESP) (%)	SQ5+	0.5	0.5	0.5	1	0.5	0.5	0.5
Calcium carbonate (CCB) (% weight)	SQ6+	0	0	0	0	0	0	0
Gypsum content (GYP) (% weight)	SQ6+	0	0	0	0	0	0	0
Electrical conductivity (EC) (dS/m)	SQ5+	0	0	0	0	0	0	0

Source: Authors' own elaboration apart from * **Soil Survey Division Staff**. 1993. *Soil Survey Manual. U.S. Department of Agriculture Handbook 18*. Washington, DC, United States Department of Agriculture (USDA). https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf

The soil quality rating procedure compares each attribute value from the soil database to the rating function thresholds representing 0 percent, 10 percent, 30 percent, 50 percent, 70 percent and 90 percent reduction respectively. Rating function values for the attributes of the soil in this example are listed in Table A4.4 and Table A4.5 for conventional farming with high inputs and organic farming with advanced inputs respectively.

Table A4.4. Soil attribute rating for rainfed maize (conventional farming with high inputs)

Soil layer attribute	Soil quality	Soil attribute rating function values					
		100%	90%	70%	50%	30%	10%
Coarse fragments (GRC) (% volume)	SQ3	≤15	35	55	65	70	≥75
Coarse fragments (% volume)	SQ7	≤10	15	25	40	55	≥65
Soil organic carbon (SOC) content (% weight)	SQ1	≥1.2	0.8	0.5	0	–	–
Soil pH in water (-log(H^+)), low	SQ1, SQ2	≥5.8	5.5	5.35	5.2	5.1	≤5.0
Soil pH in water (-log(H^+)), high	SQ1, SQ2	≤7.0	7.8	8.2	8.5	8.55	≥8.6
Cation exchange capacity of soil (CEC_{soil}) (cmol/kg)	SQ2	≥8	4	2	0	–	–
Cation exchange capacity of clay fraction CEC_{clay}) (cmol/kg)	SQ2	≥16	0	–	–	–	–
Total exchangeable bases (TEB) (cmol/kg)	SQ1	≥5	3.5	2	0	–	–
Base saturation (BS) (% CECsoil)	SQ2	≥50	35	20	0	–	–
Exchangeable sodium percentage (ESP) (%)	SQ5	≤8	15	20	25	–	>25
Calcium carbonate (CCB) (% weight)	SQ6	≤6	15	25	35	–	>35
Gypsum content (GYP) (% weight)	SQ6	≤2	4	10	20	–	>20
Electrical conductivity (EC) (dS/m)	SQ5	≤ 2	4	6	8	12	>12
Rootable soil depth (RSD) (cm)	SQ3	≥ 80	70	50	35	15	≤10
Rootable soil depth (cm)	SQ7	≥ 100	75	50	30	-	<30

Table A4.5. Soil attribute rating for rainfed maize (organic farming with advanced inputs)

Soil layer attribute	Soil quality	Soil attribute rating function values					
		100%	90%	70%	50%	30%	10%
Coarse fragments (GRC) (% volume)	SQ3+	≤15	35	55	65	70	≥75
Coarse fragments (% volume)	SQ7+	≤15	25	45	55	65	≥75
Soil organic carbon (SOC) content (% weight)	SQ1+	≥1.2	0.8	0.5	0	–	–
Soil pH in water (-log(H^+)), low	SQ1+, SQ2+	≥6.2	5.8	5.5	5.35	5.2	≤5.1
Soil pH in water (-log(H^+)), high	SQ1+, SQ2+	≤7.0	7.8	8.2	8.5	8.55	≥8.6
Cation exchange capacity of soil (CEC_{soil}) (cmolc/kg)	SQ2+	≥10	8	4	2	0	–
Cation exchange capacity of clay fraction (CEC_{clay}) (cmol/kg)	SQ2+	≥24	16	0	–	–	–
Total exchangeable bases (TEB) (cmol/kg)	SQ1+	≥8	5	3.5	2	0	–
Base saturation (BS) (% CECsoil)	SQ2+	≥80	50	35	20	0	–
Exchangeable sodium percentage (ESP) (%)	SQ5+	≤8	15	20	25	–	>25
Calcium carbonate content (CCB) (% weight)	SQ6+	≤6	15	25	35	–	>35
Gypsum content (GYP) (% weight)	SQ6+	≤2	4	10	20	–	>20
Electrical conductivity (EC) (dS/m)	SQ5+	≤2	4	6	8	12	>12
Rootable soil depth (RSD) (cm)	SQ3 +	≥80	70	50	35	15	≤10
Rootable soil depth (cm)	SQ7+	≥75	60	40	25	–	<25

For instance, the rating function parameters used for the coarse fragments soil attribute when assessing soil suitability for maize under conventional high input farming suggests that up to a gravel content of 15 percent (volume %) there is no yield reduction expected. Beyond 65 percent of coarse fragments, the soil is considered unsuitable for maize cultivation (see values regarding SQ7). The coarse fragment rating τ(GRC) (where GRC is soil gravel content) is obtained by a linear interpolation of soil rating classes. For instance, rating GRC with regard to SQ3, a GRC attribute value of 20 percent would result in $\tau(GRC = 20) = 100 - (100 - 90) \times (20 - 15)/(35 - 15) = 97.5$ and with regard to SQ7 the GRC rating value would be $90 - (90 - 70) \times (20 - 15)/(25 - 15) = 80$.

As previously explained, the soil attributes listed in Table A4.3 are available for each of the seven soil depth layers and are evaluated separately for each layer's SQ calculation. Attributes of the general soil unit information apply to the entire soil unit and are evaluated at the soil unit level. In the example of soil unit ACu with a stony phase, this applies to the presence of a stony phase. The soil phase rating factor with respect to rooting conditions (SQ3) is estimated at 75 percent, with respect to workability (SQ7) it is 50 percent for conventional farming with high inputs and 75 percent for organic farming with advanced inputs[28] (Table A4.1). Table A4.6 and

[28] Differences in workability constraints due to a stony soil phase between conventional and organic farming are mainly related to soil tillage constraints.

Table A4.7 show soil attribute ratings for rainfed maize obtained for the range of attributes considered by soil depth layers.

Table A4.6. Soil attributes rating by depth layer for rainfed maize (conventional farming with high inputs)

Soil layer attribute	Soil quality	Soil attribute ratings by depth layers (%)						
		D1	D2	D3	D4	D5	D6	D7
Coarse fragments (GRC) (% volume)	SQ3	100	100	100	100	100	100	95.5
Coarse fragments (% volume)	SQ7	100	100	100	100	100	–	–
Texture class (TXT) (Soil Survey Division Staff, 1993)*	SQ1, SQ2, SQ3, SQ7	100	100	100	100	100	100	100
Soil organic carbon (SOC) content (% weight)	SQ1	100	–	–	–	–	–	–
Soil pH in water (-log(H^+))	SQ1, SQ2	30	50	50	63.3	63.3	76.7	90
Cation exchange capacity of soil (CEC_{soil}) (cmol/kg)	SQ2	100	–	–	–	–	–	–
Cation exchange capacity of clay fraction (CEC_{clay}) (cmol/kg)	SQ2	–	100	100	100	100	100	100
Total exchangeable bases (TEB) (cmol/kg)	SQ1	100	100	100	83.3	100	100	100
Base saturation (BS) (% CEC_{soil})	SQ2	91.3	92.0	93.3	92.0	94.7	96.7	94.0
Exchangeable sodium percentage (ESP) (%)	SQ5	100	100	100	100	100	100	100
Calcium carbonate (CCB) (% weight)	SQ6	100	100	100	100	100	100	100
Gypsum content (GYP) (% weight)	SQ6	100	100	100	100	100	100	100
Electrical conductivity (EC) (dS/m)	SQ5	100	100	100	100	100	100	100

Source: Authors' own elaboration apart from * **Soil Survey Division Staff**. 1993. *Soil Survey Manual. U.S. Department of Agriculture Handbook 18*. Washington, DC, United States Department of Agriculture (USDA). https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf

Table A4.7. Soil attribute rating by depth layer for rainfed maize (organic farming with advanced inputs)

Soil layer attribute	Soil quality	Soil attribute ratings by depth layers (%)						
		D1	D2	D3	D4	D5	D6	D7
Coarse fragments (GRC) (% volume)	$SQ3^+$	100	100	100	100	100	100	95.5
Coarse fragments (% volume)	$SQ7^+$	100	100	100	–	–	–	–
Texture class (TXT) (Soil Survey Division Staff, 1993)*	$SQ1^+$, $SQ2^+$, $SQ3^+$, $SQ7^+$	100	100	100	100	100	100	100
Soil organic carbon (SOC) content (% weight)	$SQ1^+$	100	–	–	–	–	–	–
Soil pH in water (-log(H^+))	$SQ1^+$, $SQ2^+$	77.3	84.7	84.7	90.8	90.8	93.5	96.3
Cation exchange capacity of soil (CEC_{soil}) (cmol/kg)	$SQ2^+$	100	–	–	–	–	–	–
Cation exchange capacity of clay fraction (CEC_{clay}) (cmol/kg)	$SQ2^+$	–	100	98.7	100	98.7	98.7	100
Total exchangeable bases (TEB) (cmol/kg)	$SQ1^+$	98.3	98.3	98.3	83.3	98.3	100	100
Base saturation (BS) (% CECsoil)	$SQ2^+$	89.6	90.3	90.9	90.3	91.6	92.5	91.3
Exchangeable sodium (%)	$SQ5^+$	100	100	100	100	100	100	100
Calcium carbonate (CCB) (% weight)	$SQ6^+$	100	100	100	100	100	100	100
Gypsum content (GYP) (% weight)	$SQ6^+$	100	100	100	100	100	100	100
Electrical conductivity (EC) (dS/m)	$SQ5^+$	100	100	100	100	100	100	100

Source: Authors' own elaboration apart from * **Soil Survey Division Staff**. 1993. *Soil Survey Manual. U.S. Department of Agriculture Handbook 18*. Washington, DC, United States Department of Agriculture (USDA). https://www.nrcs.usda.gov/sites/default/files/2022-09/The-Soil-Survey-Manual.pdf

A4.1. Nutrient availability ($SQ1^+$) for rainfed maize (organic farming with advanced inputs)

The soil attributes (Table A4.3) used for the SQ1 assessment of the upper soil layer are TXT^+, SOC^+, pH^+, and TEB^+, and for the deeper layers, TXT, pH^+, and TEB^+. Attribute ratings are obtained from Table A4.5.

As can be seen in Table A4.8, soil reaction (pH^+)[29] is the most limiting attribute considered for SQ1, namely in upper soil layer D1 (78 percent) and in deeper layers D2–D6 (ranging from 83 to 94 percent). The other attributes used for determining SQ1 are TXT^+, SOC^+ and TEB^+.

Table A4.8. Nutrient availability ($SQ1^+$) soil attribute rating by soil depth layer for organic farming with advanced inputs

Soil attribute	Soil attribute rating (%) for soil unit ACu by soil depth layer						
	D1	D2	D3	D4	D5	D6	D7
Texture class (TXT^+)	100	100	100	100	100	100	100
Soil organic carbon (SOC^+)	100	–	–	–	–	–	–
Soil reaction (pH^+)	77.3	84.7	84.7	90.8	90.8	93.5	96.3
Total exchangeable bases (TEB^+)	98.3	98.3	98.3	83.3	98.3	100	100

Note: ACu = Humic Acrisol.

The results of $SQ1^+$ calculation using Equation 13 and Equation 14 for upper and deeper soil layers and aggregation to soil unit level are presented in Table A4.9. The results for $SQ1^+$ by soil depth layer are obtained by taking the most limiting attribute rating and multiplying by the average of the remaining attribute ratings.

The $SQ1^+$ soil unit rating is obtained by adding up soil layer ratings weighted with crop specific root mass distribution factors. As shown in Table A4.9, a $SQ1^+$ rating of 81 percent was estimated for organic farming with advanced inputs.

[29] Nutrient availability is considered for organic farming and low and intermediate inputs for conventional farming, low and intermediate inputs. Conventional farming with high inputs relies solely on fertilizer use and soil nutrient retention capacity.

Table A4.9. Weighted $SQ1^+$ soil attribute rating for organic farming with advanced inputs

Soil depth layer	SQ1 by layer (%)	Soil layer weight (SLW)*	Weighted rating
D1 (0–20 cm)	76.9	0.48	36.9
D2 (20–40 cm)	84.0	0.25	21.0
D3 (40–60 cm)	84.0	0.13	10.9
D4 (60–80 cm)	79.5	0.06	4.8
D5 (80–100 cm)	90.0	0.04	3.6
D6 (100–150 cm)	93.5	0.03	2.8
D7 (150–200 cm)	96.3	0.01	1.0
$SQ1^+$ of soil unit ACu in SMU 27116			81.0

** Soil layer weights are according to the root mass distribution of maize (RD class 4). See information in Appendix 2 and Appendix 3.*

A4.2. Nutrient retention (SQ2) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

The soil characteristics used for the SQ2 assessment of the upper soil layer are TXT, BS, CEC_{soil}, and for the deeper layers, TXT, pH, BS, and CEC_{clay} respectively.

The results of the SQ2 calculation (Equation 4 and Equation 5) for conventional farming and organic farming (Equation 15 and Equation 16) for the upper and lower soil layer ratings are presented in Table A4.10 and Table A4.11, showing that pH is the most limiting attribute considered for SQ2. Note that soil attribute ratings by soil depth layer for conventional farming with high inputs and organic farming with advanced inputs are derived respectively from Tables A4.7 and A4.8. Attribute ratings for pH range from 50 percent (for D2) to 90 percent (D7) for conventional farming with high inputs and from 85 to 96 percent for organic farming with advanced inputs. Note that pH is used for deeper layers only (D2–D7). Results by soil depth layer are obtained by taking the most limiting attribute rating and multiplying with the average of the remaining attribute ratings.

Table A4.10. Nutrient retention (SQ2) soil attribute ratings by soil depth layer for conventional farming with high inputs

Soil attribute	Soil attribute rating (%) by soil depth layer						
	D1	D2	D3	D4	D5	D6	D7
Soil reaction (pH)	–	50	50	63.3	63.3	76.7	90
Cation exchange capacity of clay fraction (CEC_{clay})	–	100	100	100	100	100	100
Base saturation (BS)	91.3	92.0	93.3	92.0	94.7	96.7	94.0
Cation exchange capacity of soil (CEC_{soil})	100	–	–	–	–	–	–
Texture class (TXT)	100	100	100	100	100	100	100

Table A4.11. Nutrient retention ($SQ2^{+}$) soil attribute ratings by soil depth layer for organic farming with advanced inputs

Soil attribute	Soil attribute rating (%) by soil depth layer						
	D1	D2	D3	D4	D5	D6	D7
Soil reaction (pH^{+})	–	84.7	84.7	90.8	90.8	93.5	96.3
Cation exchange capacity of clay fraction (CEC_{clay}^{+})	–	100	98.7	100	98.7	98.7	100
Base saturation (BS^{+})	89.6	90.3	90.9	90.3	91.6	92.5	91.3
Cation exchange capacity of soil (CEC_{soil}^{+})	100	–	–	–	–	–	–
Texture class (TXT)	100	100	100	100	100	100	100

In the examples for SQ2 shown in Table A4.12 and Table A4.13, a soil unit rating of 71.7 percent was estimated for conventional farming with high inputs, and a SQ2 rating of 86.5 percent was estimated for organic farming with advanced inputs. An aggregate SQ2 soil unit rating can be obtained by adding up soil layer ratings multiplied by crop-specific root mass distribution weights. Soil layer weights in maize (RD class 4) are taken from Table A2.2, Table A2.3, Table A2.4 and Table A2.5.

Table A4.12. Soil attribute rating used for SQ2 estimation of Humic Acrisol soil unit (ACu) by soil depth layer (conventional farming with high inputs)

Soil depth layer	SQ2 by layer (%)	Soil layer weight (SLW)*	Rating by depth layer
D1 (0–20 cm)	91.3	0.48	43.8
D2 (20–40 cm)	48.7	0.25	12.2
D3 (40–60 cm)	48.9	0.13	6.4
D4 (60–80 cm)	61.6	0.06	3.7
D5 (80–100 cm)	62.2	0.04	2.5
D6 (100–150 cm)	75.8	0.03	2.3
D7 (150–200 cm)	88.2	0.01	0.9
SQ2 of soil unit ACu in SMU 27116			71.7

Note: ACu = Humic Acrisol.

* Soil layer weights are according to the root mass distribution of maize (RD class 4). See information in Appendix 2 and Appendix 3.

Table A4.13. Soil attribute rating used for $SQ2^+$ estimation of Humic Acrisol soil unit (ACu) by soil depth layer (organic farming with advanced inputs)

Soil depth layer	$SQ2^+$ by layer (%)	Soil layer weight (SLW)*	Rating by depth layer
D1 (0–20 cm)	89.6	0.48	43.0
D2 (20–40 cm)	81.9	0.25	20.5
D3 (40–60 cm)	81.7	0.13	10.6
D4 (60–80 cm)	87.5	0.06	5.3
D5 (80–100 cm)	87.8	0.04	3.5
D6 (100–150 cm)	90.1	0.03	2.7
D7 (150–200 cm)	90.1	0.01	0.9
$SQ2^+$ of soil unit ACu in SMU 27116			86.5

Note: ACu = Humic Acrisol.

* Soil layer weights are according to the root mass distribution of maize (RD class 4). See information in Appendix 2 and Appendix 3.

A4.3. Rooting condition (SQ3) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

Rooting conditions (SQ3) are estimated by combining the rootable soil depth rating *τ(RSD)* with additional soil ratings for conditions affecting root development and root and tuber yield. These include TXT, GRC, VSP, GSP, SPH, OTR and ISL. Soil phases that are considered for SQ3 are stony, rudic, lithic, petric, skeletic, petrocalcic, petroferric, fragipan and duripan. Texture, mineralogy, and structure class and GRC are evaluated by soil depth layer (Equation 6). Table A4.14 indicates that a stony soil phase is the only limitation,[30] impacting on SQ3, which results in a SQ3 rating of 75 percent for both high input conventional farming and advanced input organic farming.

Table A4.14. Rooting condition (SQ3) soil attribute ratings for conventional farming with high inputs and organic farming with advanced inputs

Soil attribute	Rating (%) of soil attributes used for SQ3 estimation							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Rootable soil depth (RSD)				>100 cm				100
Texture class (TXT)	100	100	100	100	100	100	100	
Coarse fragments (GRC)	100	100	100	100	100	100	95.5	
Vertic soil properties (VSP)				None				100
Gelic soil properties (GSP)				None				100
Soil phase (SPH)				Stony				75
Obstacles to roots (OTR)				None				100
Impermeable soil layers (ISL)				None				100

A4.4. Oxygen availability (SQ4) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

Oxygen availability in soils is largely determined by drainage characteristics of soils. Apart from drainage characteristics, oxygen availability may be influenced by soil and terrain characteristics such as the occurrence of specific soil phases and soil characteristics affecting soil hydrological conditions. These include soil phases that indicate phreatic or anthraquic soil conditions and the presence of ISLs or temporal WR. Oxygen availability for roots (SQ4) ratings are defined by the most limiting attribute rating. Drainage classes are based on information on soil type, terrain slope, soil texture, and occurrence of petrocalcic, petrogypsic, petroferric, duripan, placic, lithic or anthraquic soil phases. The presence of an ISL within the rooting zone or other specific soil hydrological conditions which affect soil drainage or oxygen availability directly, are dealt with separately. Equation 7 applies for conventional farming with high inputs,

[30] Coarse fragments in layer D7 are beyond the reach of maize roots.

while Equation 17 applies for organic farming with advanced inputs. The soil quality rating SQ4 is 100 percent in both cases, meaning that no limitations occur (Table A4.15 and Table A4.16 respectively).

Table A4.15. Oxygen availability for roots (SQ4) soil attribute ratings (conventional farming with high inputs)

Soil attribute	Rating (%) of soil attributes used for SQ4 estimation							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Drainage class (DRG)	MW (moderately well)							100
Impermeable soil layers (ISL)	None							100
Soil wetness conditions (WR)	None							100

Table A4.16. Oxygen availability for roots ($SQ4^+$) soil attribute ratings (organic farming with advanced inputs)

Soil attribute	Rating (%) of soil attributes used for $SQ4^+$ estimation							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Drainage class (DRG^+)*	W (well)							100
Impermeable soil layers (ISL)	None							100
Soil wetness conditions (WR)	None							100

** Shifted by one class due to the assumed impact of ten years of organic farming.*

A4.5. Salinity and sodicity (SQ5) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

Apart from soil salinity (ECe) and soil sodicity (ESP), the presence of saline and sodic soil phases may affect crop growth and yields. The most limiting rating of the soil salinity and sodicity conditions and the occurrence of saline and sodic soil phases determines SQ5 (Equation 8).

Note, when a saline soil phase occurs, it is assumed – in accordance with the saline soil phase definition – that ECe ≥4 dS/m prevails for D1 to D5 soil layers. Hence, when a saline soil phase is indicated for a soil unit, the maximum value of 4 dS/m and the original layer salinity attribute is used for D1 to D5 soil layers when evaluating each layer for a soil salinity rating. The same applies for the sodic phase, where the ESP threshold is set to 6 percent. In this example, virtually no salinity or sodicity occurs, so SQ5 and $SQ5^+$is set to 100 percent.

A4.6. Calcium carbonate and gypsum (SQ6) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

Calcisols and calcareous soils with high calcium carbonate content – as well as soils with petrocalcic soil phases – may exhibit micronutrient deficiencies, which can affect growth and yield performance of some crops. Gypsisols and gypsiferous soils with a high gypsum content and soils with a petrogypsic soil phase may depress yield performance through nutrient imbalances and may affect field operations and interfere with irrigation water supply and soil drainage. [31] Tolerance of crops to calcium carbonate and gypsum varies widely.

The most limiting soil rating for specific crop/LUTs (due to calcium carbonate content, gypsum content or the occurrence of petrocalcic or petrogypsic soil phases) is selected to represent the SQ6 and SQ6+ rating value. The soil unit under consideration in this example contains no calcium carbonate and only 1 percent gypsum and therefore no limitations are indicated concerning SQ6 (Table A4.5 and Table A4.6). The evaluation of SQ6 (Equation 9) for this soil unit ACu therefore equates to 100 percent (Table A4.17).

Table A4.17. Calcium carbonate and gypsum (SQ6) soil attribute ratings (conventional farming with high inputs and organic farming with advanced inputs)

Soil attribute	Rating (%) of soil attributes used for SQ6 estimation							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Calcium carbonate	100	100	100	100	100	100	100	100
Gypsum	100	100	100	100	100	100	100	100
Petrocalcic phase (SPH)	None							100
Petrogypsic phase (SPH)	None							100

A4.7. Workability (SQ7) (conventional farming with high inputs and organic farming with advanced inputs)

Physical hindrance depends on the crop and specific field management. Agro-Ecological Zoning procedures consider hindrance by limited RSD, soil phases (stony, rudic, lithic, petric, skeletic, petrocalcic, petroferric, fragipan, and duripan) and the prevalence of GRC, TXT and VSP.

Soil texture ratings and gravel content ratings are determined for each soil depth layer (D1–D7). In this example, however, TXT and GRC are not causing limitations for either conventional or organic farming. (Equation 10 is applicable to conventional farming with high inputs, and organic farming with advanced inputs).

Table A4.18 and Table A4.19 suggest that a stony soil phase is the only limiting factor impacting on SQ7, resulting in a SQ7soil unit rating of 50 percent for conventional farming with high

[31] Petrocalcic and petrogypsic ratings (SQ6) for rainfed and sprinkler irrigation are crop specific. Note that there is no differentiation by input level or farming system. Workability constraints caused by petrocalcic or petrogypsic horizons (phases) are dealt with separately by SQ7 (soil workability).

inputs and a less severe SQ7 soil unit rating of 75 percent for organic farming with advanced inputs.

Table A4.18. Workability (SQ7) soil attribute ratings by soil depth layer (conventional farming with high inputs)

Soil attribute	Rating (%) of soil attributes used for SQ7 estimation of soil unit ACu							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Rootable soil depth (RSD)				Deep				100
Coarse fragments (GRC)	100	100	100	100	100	–	–	100
Texture class (TXT)	100	100	100	100	100	–	–	100
Soil phase (SPH)				Stony				50
Vertic properties (VSP)				None				100
Soil drainage (DRG)				MW (moderately well)				100
Obstacles to roots (OTR)				None				100
Impermeable soil layers (ISL)				None				100

Table A4.19. Workability ($SQ7^+$) soil attribute ratings by soil depth layer (organic farming with advanced level inputs and management)

Soil attribute	Rating (%) of soil attributes used for $SQ7^+$ estimation of soil unit ACu							
	D1	D2	D3	D4	D5	D6	D7	Soil unit
Rootable soil depth (RSD)				Deep				100
Coarse fragments (GRC)	100	100	100	–	–	–	–	100
Texture class (TXT)	100	100	100	–	–	–	–	100
Soil phase (SPH)				Stony				75
Vertic properties (VSP)				None				100
Soil drainage (DRG^+)				Well				100
Obstacles to roots (OTR)				None				100
Impermeable soil layers (ISL)				None				100

A4.8. Soil suitability rating (SSR) for rainfed maize (conventional farming with high inputs and organic farming with advanced inputs)

The soil quality ratings are combined into a soil suitability rating (SSR) for the combination of soil unit, crop type and input level. In this example, the soil unit ACu, characterized by a stony soil phase, is assessed for rainfed maize production under conventional farming (high inputs) and organic farming (advanced inputs) conditions.

The calculation applies rating function f_{SSR} (Equation 11) and combines soil quality ratings SQ1 to SQ7 for conventional farming with high inputs (as shown in the main text) according to Equation 12 and uses Equation 19 for organic farming with advanced inputs.

Table A4.20 lists the soil quality ratings SQ2 to SQ7 obtained in the previous steps of this example. Limitations occur for SQ3 and especially SQ7 due to a stony soil phase, and for SQ2 due to suboptimal pH and BS values. Using the values in Table A4.20 and applying Equation 12, then an overall SSR is obtained for rainfed maize under conventional farming with high inputs:

$$SSR_{conventional,\ high} = SQ2 \times SQ7 \times ((SQ3 + SQ4 + SQ5 + SQ6)/4) = 0.717 \times 0.50 \times ((0.75 + 1 + 1 + 1)/4) = 0.336$$

The edaphic evaluation concludes that the chosen ACu soil unit with a stony soil phase has substantial limitations for rainfed maize cultivation under high input conventional farming, with an adjudged rating of 33.6 percent.

Table A4.20. Soil ratings of Humic Acrisol soil unit (ACu) for rainfed maize (conventional farming with high inputs)

Soil quality (%)	SQ1	SQ2	SQ3	SQ4	SQ5	SQ6	SQ7	SSR
	Nutrient availability	Nutrient retention	Rooting conditions	Oxygen availability	Salinity and sodicity	Calcium carbonate /gypsum	Workability	Soil unit suitability
Rating	n/a	71.7	75.0	100	100	100	50.0	33.6

Table A4.21 shows the soil quality ratings obtained for maize under organic farming with advanced inputs. Limitations occur for $SQ3^+$ and $SQ7^+$ due to a stony soil phase, and some restrictions for $SQ1^+$ and $SQ2^+$ are found due to low pH^+ values and suboptimal BS values. Using the results in Table A4.21 and applying Equation 19, then an overall soil unit suitability rating is obtained for rainfed maize under organic farming with advanced inputs:

$$SSR^+_{organic,\ advanced} = (\alpha \times SQ1^+ + \beta \times SQ2^+) \times SQ7^+ \times ((SQ3^+ + SQ4^+ + SQ5^+ + SQ6^+)/4) = (0.25 \times 0.810 + 0.75 \times 0.865) \times 0.75 \times (1 + 1 + 1 + 0.75)/4) = 0.598$$

Where SSR^+ is the soil unit suitability rating, α is the input specific weighting factor for $SQ1^+$, β is the respective weighting factor for $SQ2^+$. In the calculation example for organic farming with advanced inputs, α has been set to 0.25 and β to 0.75 (see Table 7. in main text).

The edaphic evaluation of the given soil map unit (SMU 27116) concludes that the chosen ACu dominant soil unit has some limitations, foremost related to rooting conditions and workability, for rainfed maize cultivation. This also affects suitability under organic farming systems with advanced level inputs and management, with an adjudged rating of 59.8 percent. Yet, the evaluation for the organic system is nearly twice as good compared to the rating obtained for conventional farming with high inputs (note the value of 33.6 percent in Table A4.20).

Table A4.21. Soil ratings of Humic Acrisol soil unit (ACu) for rainfed maize (organic farming with advanced inputs)

Soil quality (%)	$SQ1^+$	$SQ2^+$	$SQ3^+$	$SQ4^+$	$SQ5^+$	$SQ6^+$	$SQ7^+$	SSR^+
	Nutrient availability	**Nutrient retention**	**Rooting conditions**	**Oxygen availability**	**Salinity and sodicity**	**Calcium carbonate /gypsum**	**Workability**	**Soil unit suitability**
Rating	81.0	86.5	75.0	100	100	100	75.0	59.8

Appendix 5. Estimation of soil available water capacity (AWC)

The 21 000 soil profiles used for WISE30sec and subsequently in HWSD v2.2 and classified according to FAO classification (FAO90 [FAO, 1990]) are representing typical soil characteristics by soil unit, within defined climatic zones (Koeppen-Geiger first level classification, [Peel*,* Finlayson and McMahon, 2007]). It is assumed that the soil profiles are representing locally typical profiles by soil unit without considering soil phases.

Therefore, in soil suitability classifications, for the determination of available water-holding capacity and soil drainage, relevant soil phases, where indicated for an SMU, must also be considered in the GAEZ procedures for estimating the available water capacity (AWC) for RSD.

The AWC for RSD represents the amount of water that the soil can hold and 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. The AWC depends on effective depth and volume of the soil as well as the physical and chemical characteristics (FAO, 1995).

The presence of a root-restricting layer reduces the rootable depth and therefore the available water capacity. The AWC calculation in GAEZ uses soil phase information to determine rootable depth and computes AWC values by layer. The procedure consists of six steps. Intermediate AWC results of each step are sequentially numbered from $AWC^{(1)}$ to $AWC^{(5)}$, with $AWC^{(5)}$ representing the final result.

Step 1: Determine reference available water capacity (AWC*)* from the United States Department of Agriculture (USDA) texture class per layer (D1–D7) => $AWC^{(1)}$

Reviewing various texture-based estimates of AWC in the literature (Allen *et al.*, 1998; Saurette, Warren and Heck, 2022;, Sys *et al.*, 1993; USDA, 1997) and following the reasoning in USDA (1997), the reference AWC values per textural class are set up (Table A5.1).

Table A5.1. Soil texture-based available water capacity (AWC) used in the Global Agro-Ecological Zoning version 5 (GAEZ v5)

Texture classes[1]		AWC
No.	**USDA texture[1]**	**mm/m**
1	Heavy clay	160
2	Silty clay	175
3	Clay	175
4	Silty clay loam	190
5	Clay loam	190
6	Silt	175
7	Silt loam	175
8	Sandy clay	160
9	Loam	160
10	Sandy clay loam	160
11	Sandy loam	125
12	Loamy sand	85
13	Sand	65

[1] Soil Survey Division Staff (1993).

Sources: See References.

Step 2: Adjust available water capacity (AWC) for soil parent material: AWC$^{(1)}$ + soil parent material adjustments => AWC$^{(2)}$

Soil parent material influences soil classification and affects available water capacity. Adjustments of AWC for soil parent material are adapted from the Digital Soil Map of the World and derived soil properties version 3.5 (FAO, 1995) as follows:

- **Andosols:** Due to specific parent materials, Andosols have a higher AWC (except Vitric Andosols).
- **Vertisols:** Specific clay mineralogy (montmorrilonite) reduces AWC from reference AWC.
- **Tropical soils:** Tropical soils may have a specific mineralogy and AWC. The prevalence of kaolinitic clay minerals cause low or very low CEC_{clay} (<24 $cmol_c$/kg), resulting in substantial lower AWC than the reference AWC. Suspect soils are Ferralsols, Acrisols, Nitisols, Plinthosols, and Lixisols.
- **Histosols:** These soils are primarily composed of organic materials and have exceptionally high AWC, set to 250 mm/m.

The reference AWC is increased by 10 percent for Andosols, reduced by 20 percent for Vertisols and reduced by 10 percent for tropical soils with low CEC_{clay}. In the latter case, the reduction is only applied when values of CEC_{clay} <24 $cmol_c$/kg occur in the D3 layer (40–60 cm depth).

Step 3: Reduce available water capacity (AWC*)* for coarse material fraction and volume reducing soil phases: AWC$^{(2)}$ + coarse fragment reduction => AWC$^{(3)}$

The presence of GRC in the soil profile (gravel, concretions, and stones and boulders larger than 2 mm) reduces AWC. An adjustment factor is estimated from the coarse materials attribute information available for individual soil layers (D1–D7) in HWSD v2.2 (Table A5.2). The AWC reduction is estimated at about 1 percent for each volume percentage of GRC.

Table A5.2. Available water capacity (AWC) adjustment for coarse fragments (GRC)

USDA texture class	Coarse fragments (%)								
	0	10	20	30	40	50	60	65	70
Clay	1.000	0.867	0.767	0.633	0.567	0.433	0.367	0.3	0.233
Silty clay	1.000	0.875	0.75	0.656	0.563	0.469	0.406	0.344	0.281
Sandy clay	1.000	0.875	0.813	0.656	0.531	0.469	0.406	0.281	0.25
Silty clay loam	1.000	0.9	0.8	0.7	0.6	0.5	0.425	0.325	0.3
Clay loam	1.000	0.9	0.8	0.7	0.6	0.5	0.425	0.325	0.3
Sandy clay loam	1.000	0.867	0.8	0.7	0.6	0.5	0.433	0.367	0.3
Silt loam	1.000	0.9	0.8	0.7	0.6	0.5	0.425	0.325	0.3
Loam	1.000	0.882	0.794	0.706	0.618	0.5	0.441	0.324	0.294
Sandy loam	1.000	0.917	0.792	0.667	0.625	0.5	0.458	0.375	0.292
Loamy sand	1.000	0.857	0.786	0.714	0.643	0.5	0.429	0.357	0.286
Sand	1.000	0.917	0.833	0.667	0.583	0.5	0.417	0.333	0.25

Sources: **Fischer, G., Nachtergaele, F., Van Velthuizen, H., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D. & Tramberend, S**. 2021. *Global Agro-Ecological Zones v4 – Model documentation*. Rome, FAO. https://doi.org/10.4060/cb4744en

USDA (United States Department of Agriculture). 1997. *Irrigation Guide*. Washington, DC, Natural Resources Conservation Service (NRCS). https://www.nrcs.usda.gov/sites/default/files/2023-01/7385.pdf

Soil volume-reducing soil phases (stony, rudic, petric, concretionary, gravelly, and skeletic) decrease AWC. These soil phases occur between 0 and 50 cm or between 0 and 100 cm of the soil surface and restrict AWC. It is assumed that effective soil volume and therefore the AWC within the RSD are reduced by 35 percent for stony, rudic, concretionary and gravelly soil phases and reduced by 25 percent for petric and skeletic soil phases. When gravel content- and soil volume-reducing soil phases both indicate AWC reductions, then only the most limiting reduction factor is applied.

Step 4: Reduce available water capacity (AWC*)* for soil salinity (ECe): AWC$^{(3)}$ + ECe reduction => AWC$^{(4)}$

Salinity reduces the soil water-holding capacity as a function of soil ECe. The reduction is estimated from the soil salinity attribute information available separately for individual soil layers (D1–D7) in HWSD v2.2 (Table A5.3). Available water capacity adjustments are also made for soil units where a saline or salic phase is indicated. According to the soil phase definition, an ECe ≥4 dS/m is considered for soil layers to 100 cm.

Table A5.3. Available water capacity (AWC) adjustments for soil salinity (ECe)

USDA texture class	Soil salinity dS/m							
	0	2	4	6	8	10	12	14
Clay	1.000	0.933	0.867	0.800	0.733	0.667	0.5	0.3
Silty clay	1.000	0.938	0.875	0.813	0.719	0.625	0.469	0.344
Sandy clay	1.000	0.938	0.875	0.813	0.719	0.625	0.469	0.344
Silty clay loam	1.000	0.95	0.875	0.8	0.725	0. 625	0.475	0.325
Clay loam	1.000	0.95	0.875	0.8	0.725	0. 625	0.475	0.325
Sandy clay loam	1.000	0.933	0.867	0.767	0.667	0. 567	0.433	0.233
Silt loam	1.000	0.95	0.875	0.8	0.725	0. 625	0.475	0.325
Loam	1.000	0.941	0.882	0.824	0.735	0. 618	0.500	0.324
Sandy loam	1.000	0.917	0.875	0.833	0.708	0. 625	0.458	0.292
Loamy sand	1.000	0.929	0.857	0.786	0.714	0. 643	0.500	0.357
Sand	1.000	0.917	0.833	0.792	0.750	0. 583	0.417	0.333

Sources: **Fischer, G., Nachtergaele, F., Van Velthuizen, H., Chiozza, F., Franceschini, G., Henry, M., Muchoney, D. & Tramberend, S.** 2021. *Global Agro-Ecological Zones v4 – Model documentation*. Rome, FAO. https://doi.org/10.4060/cb4744en

USDA (United States Department of Agriculture). 1997. *Irrigation Guide*. Washington, DC, Natural Resources Conservation Service (NRCS). https://www.nrcs.usda.gov/sites/default/files/2023-01/7385.pdf

Step 5: Reduction of rootable soil depth (RSD) due to depth-reducing soil phases

Decreased RSD limits available water capacity. Rootable soil depth is defined as the depth to which plants can exploit the soil for nutrients and moisture. When processing a soil unit record, a RSD class is derived from the respective soil unit and soil phase information, as follows:

- **Deep (>100 cm):** all soils, excluding:
  - Leptosols;
  - soils with depth limiting soil phases;
  - soils with obstacles to roots between 0 and 80 cm depth (soil attribute OTR class values 2–6); and
  - soils with an impermeable soil layer between 0 and 80 cm (soil attribute ISL class values 3 and 4).
- **Moderately deep (50–100 cm):** includes 50 percent of soils with petroferric, petrocalcic, petrogypsic, placic or duripan soil phases,[32] soils with other obstacles to roots between 60 and 80 cm (soil attribute OTR class value 2) and soils with an impermeable soil layer between 40 and 80 cm (soil attribute ISL class value 3).

[32] To deal with RSD-reducing soil phases occurring between 0 and 100 cm from the soil surface, it is assumed that these soil phases for 50 percent occur between 50 and 100 cm and for 50 percent between 0 and 50 cm. This applies for instance for soils with petroferric, petrocalcic, petrogypsic, placic or duripan soil phases. Soils with such soil phases are therefore split (in a statistical sense) and have been assigned so that 50 percent occur in the RSD class of 50–100 cm (moderately deep soils) and 50 percent occur in the RSD class of 10–50 cm (shallow soils).

- **Shallow (10–50 cm):** includes 50 percent of soils with petroferric, petrocalcic, petrogypsic, placic or duripan soil phases, soils with a lithic soil phase, Leptosols (except Lithic Leptosols), soils with other obstacles to roots (soil attribute OTR class values 3–5), and soils with an impermeable soil layer within the top 40 cm (soil attribute ISL class value 4).
- **Very shallow (<10 cm):** includes Lithic Leptosols, soils with an obstacle to roots within the top 20 cm (soil attribute OTR class value 6), and bare rock.

Step 6: Estimation of available water capacity (AWC) to rootable soil depth (RSD): AWC$^{(4)}$ per soil layer + aggregation to rootable depth => AWC$^{(5)}$

This step in the calculation of AWC to the rootable depth pertains to adding up layer-specific AWC values for all layers within the effective rootable depth and in accordance with crop RD class. The AWC value shown in HWSD v2.2 pertains to crop RD class 5 (to 150 cm depth) (Table A5.4).

Table A5.4. Estimation of available water capacity (AWC) to rootable soil depth (RSD) by crop rooting depth (RD) class

Rootable soil depth		Crop rooting depth class (RD)	AWC to RSD
Range (cm)	**Class**		**Calculation**
<10	4	all	0.5 × AWC$^{(4)}$ (D1)
10–50	3	all	AWC$^{(4)}$ (D1 + D2)
50–100	2	1	AWC$^{(4)}$ (D1 + D2 + D3)
	2	2–6	AWC$^{(4)}$ (D1 + D2 + D3 + D4)
>100	1	1	AWC$^{(4)}$ (D1 + D2 + D3)
	1	2	AWC$^{(4)}$ (D1 + D2 + D3 + D4)
	1	3	AWC$^{(4)}$ (D1 + D2 + D3 + D4 + D5)
	1	4	AWC$^{(4)}$ (D1 + D2 + D3 + D4 + D5) + 0.5 × AWC$^{(4)}$ (D6)
	1	5	AWC$^{(4)}$ (D1 + D2 + D3 + D4 + D5 + D6)
	1	6	AWC$^{(4)}$ (D1 + D2 + D3 + D4 + D5 + D6 + D7)

Note: AWC = available water capacity and RSD = rootable soil depth.

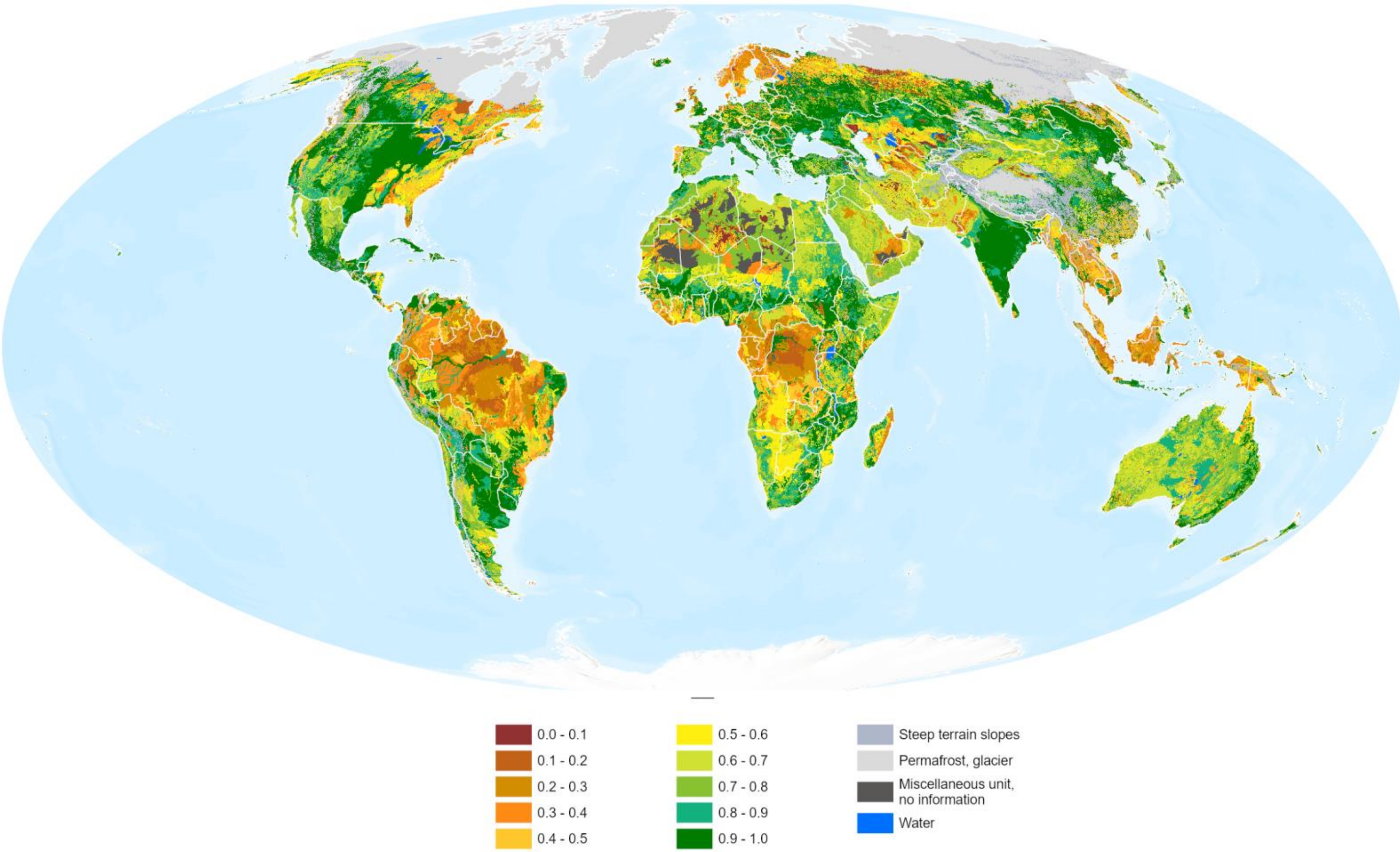
The RSD class is as defined in Step 5. Crops are put in six RD classes (0–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, 100–150 cm and >150 cm) (see Appendix 3).

For very shallow soils in RD class 1, a soil depth of 10 cm is assumed in the AWC calculation. In case of shallow soils (10–50 cm) – RD depth class 2 – only the depth layers D1 and D2 are available in the database and are used for AWC calculation regardless of crop RD class. Moderately deep soils (50–100 cm) are assumed to allow full development of crops in RD class 1 and RD class 2. For all other crops, this RD class is assumed to limit crop development to depth layers D1 to D4. Available water capacity calculations for deep soils (RD class 1 [>100 cm]), include an increasing number of soil depth layers according to crop rooting depth. We note that the depth range indicated for RD classes creates some uncertainty for AWC calculations and procedures can be adjusted when more detailed soil depth information becomes available.

Appendix 6. Global maps of soil qualities for rainfed grain maize with conventional management

Figure A6.1, Figure A6.2, Figure A6.3, Figure A6.4, Figure A6.5, Figure A6.6, and Figure A6.7 show the results of soil quality assessments for rainfed grain maize under conventional farming. Nutrient availability (SQ1) is of foremost importance for low-input cultivators, while SQ2 (nutrient retention) is key for cultivation with high inputs. The remaining soil qualities (SQ3 to SQ7) are important for all systems and are shown here for assumed high-input grain maize LUTs. Soil quality estimates fall in the range of 0 (very severe limitation) to 1 (no limitation) and are shown in ten classes. Separately shown are areas with very steep terrain slopes, with glaciers or permanent snow, or other (non-soil) miscellaneous units such as salt flats, sand dunes, bare rock or inland water.

Figure A6.1. Nutrient availability (SQ1) for maize (conventional farming with low level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Source: **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis)**. 2025b. *Global Agro-Ecological Zoning version 5*. (Accessed on 12 July 2025). https://data.apps.fao.org/gaez/. Licence: CC-BY-4.0.

Figure A6.2. Nutrient retention (SQ2) for maize (conventional farming with high level inputs)

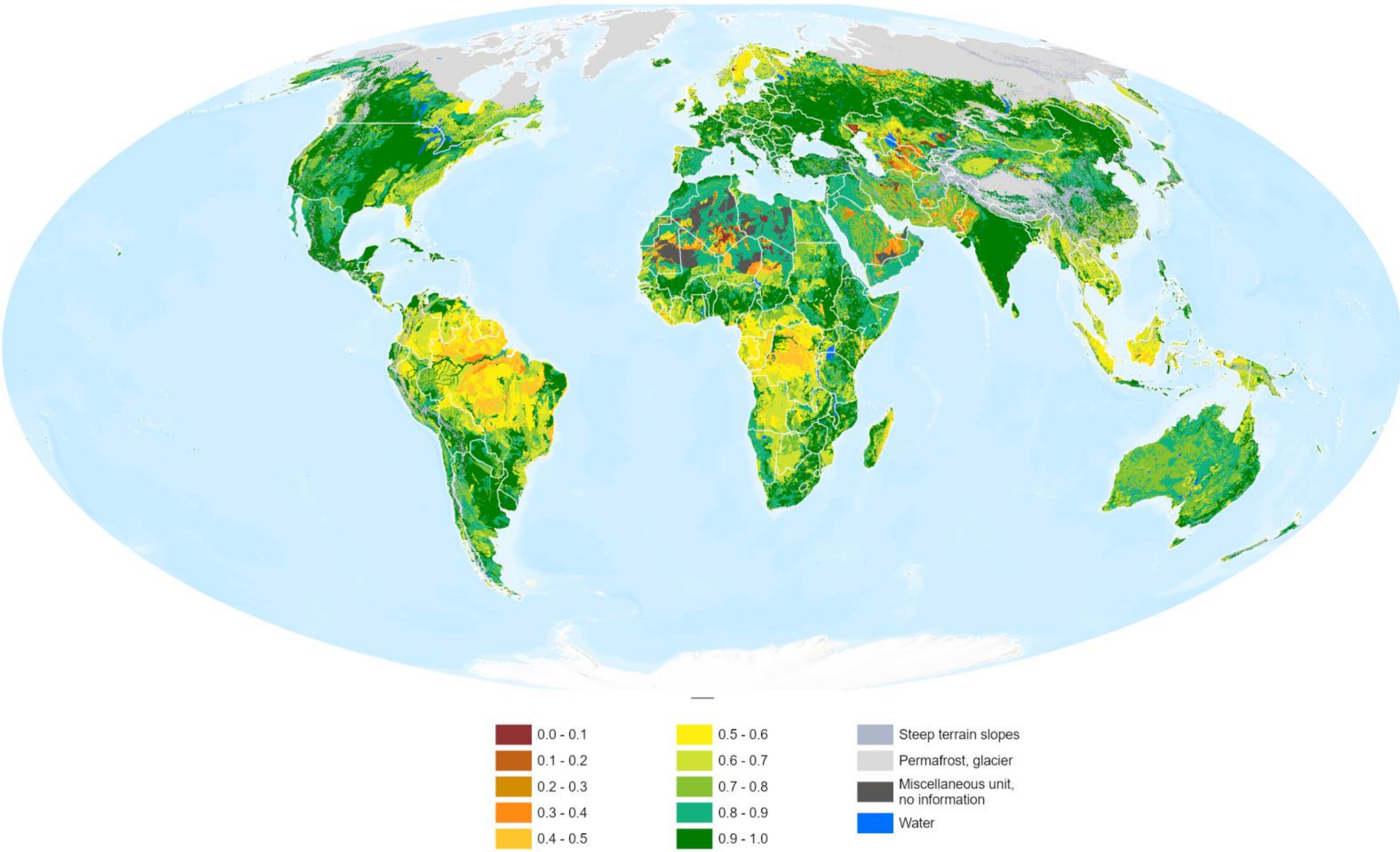


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Figure A6.3. Rooting conditions (SQ3) for maize (conventional farming with high level inputs)

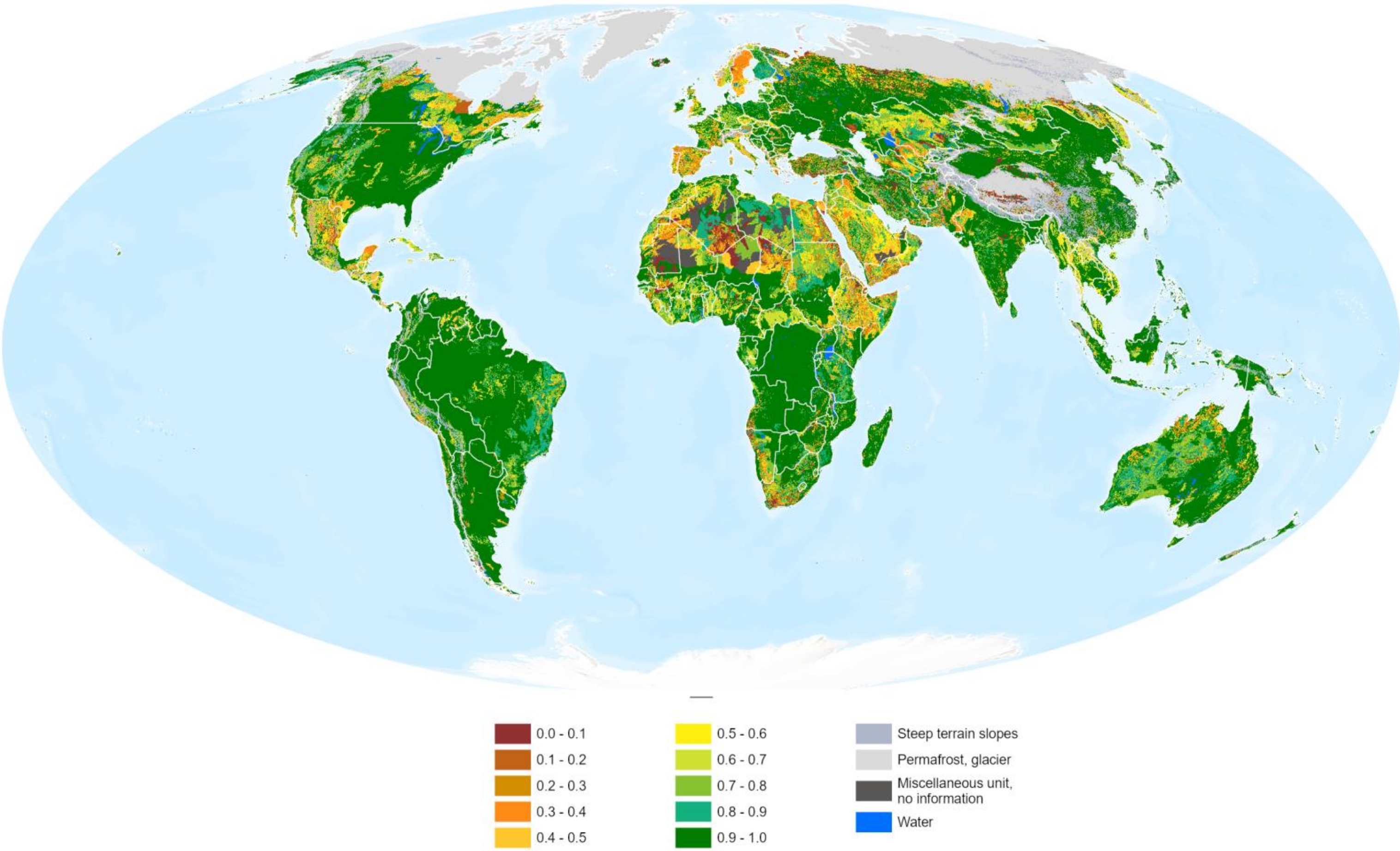

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Figure A6.4. Oxygen availability (SQ4) for maize (conventional farming with high level inputs)

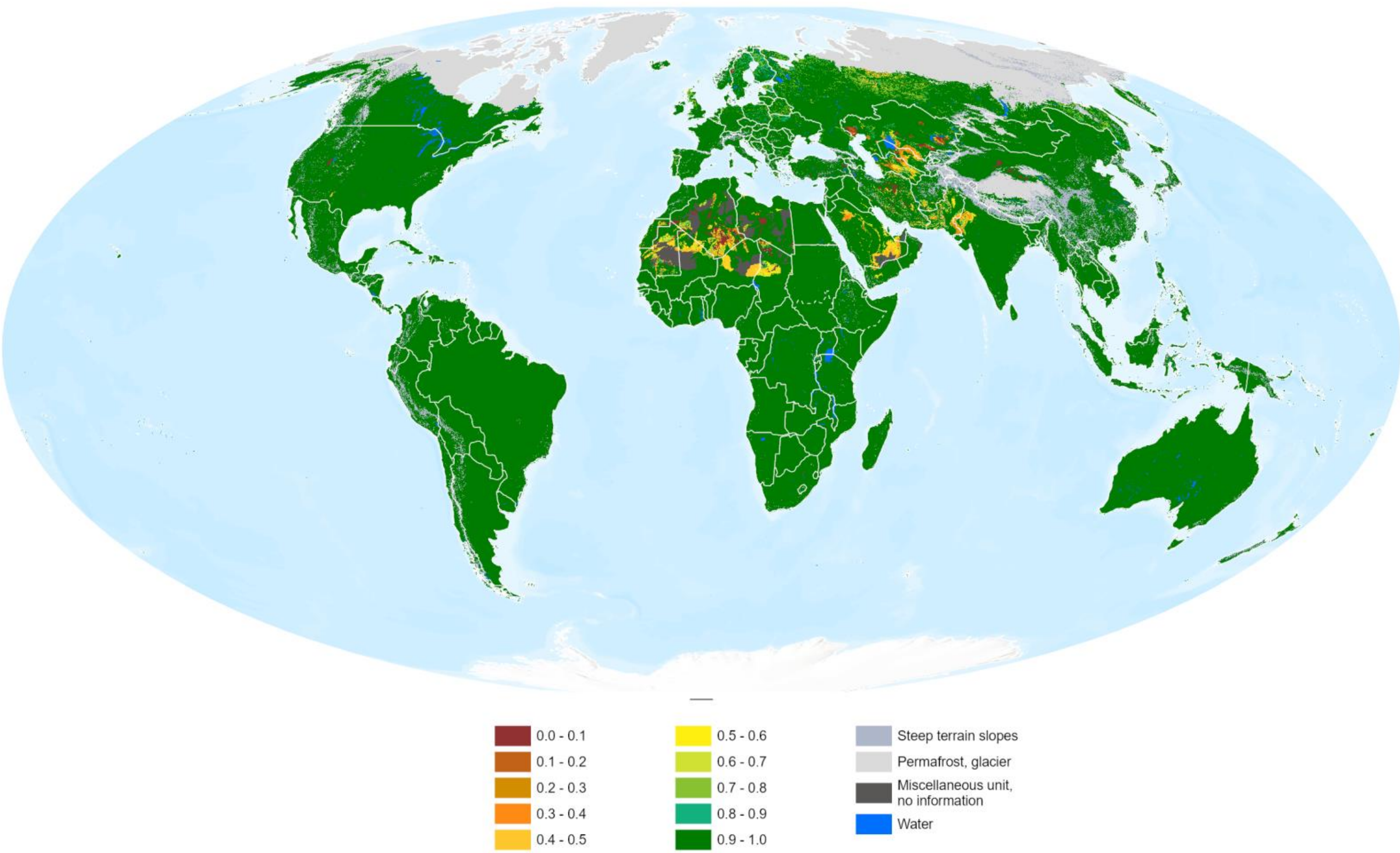

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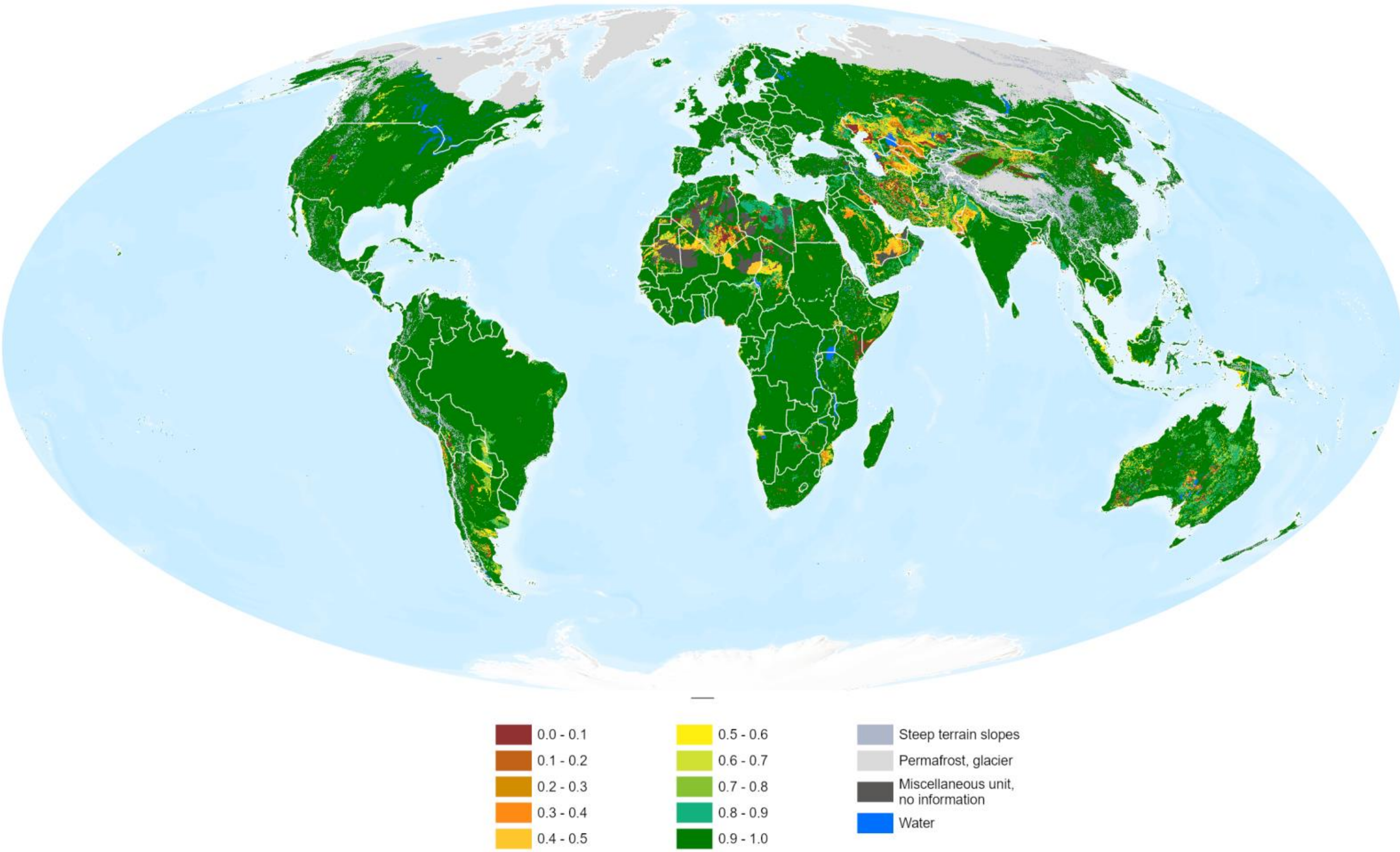
Figure A6.5. Salinity and sodicity (SQ5) for maize (conventional farming with high level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

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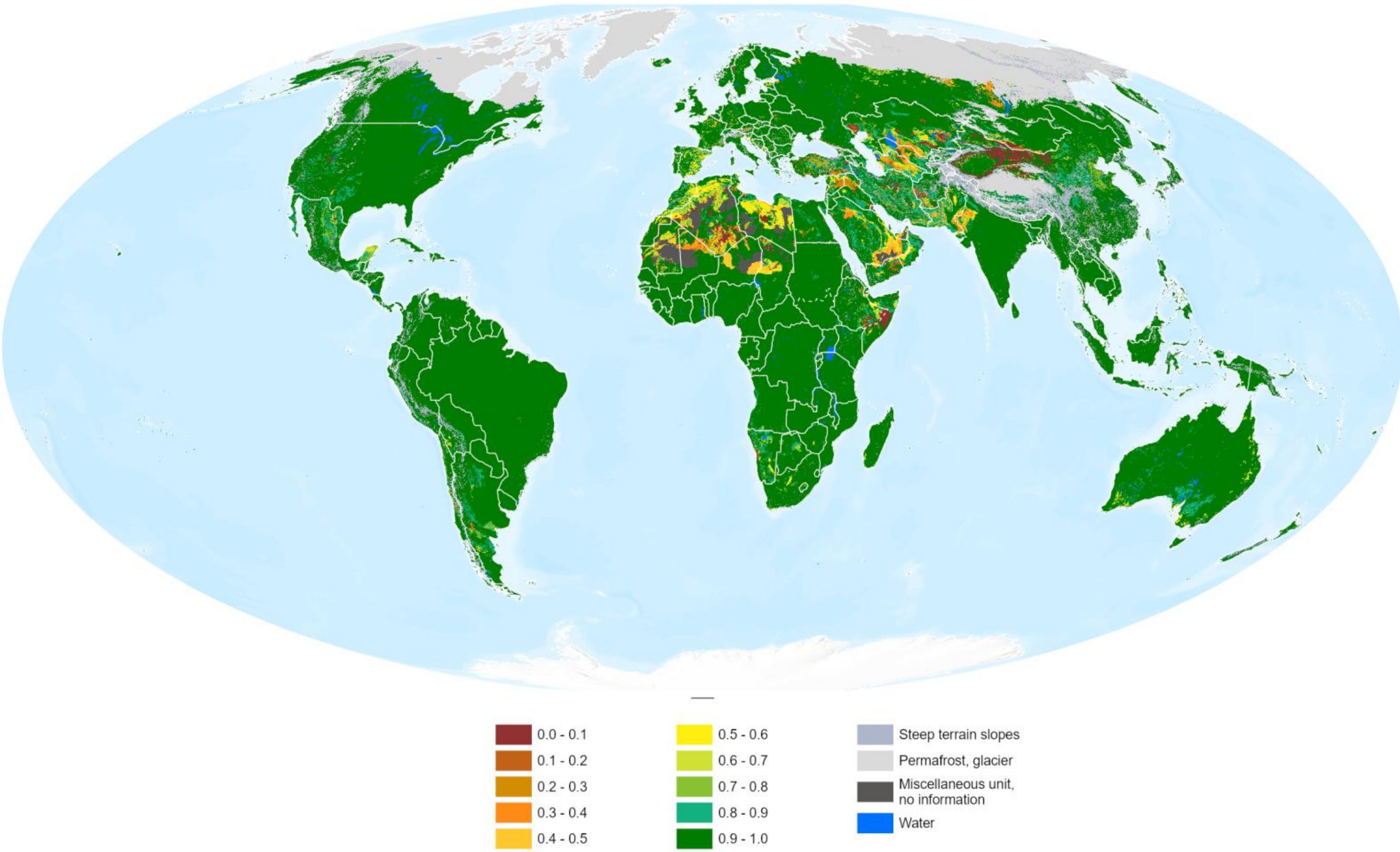
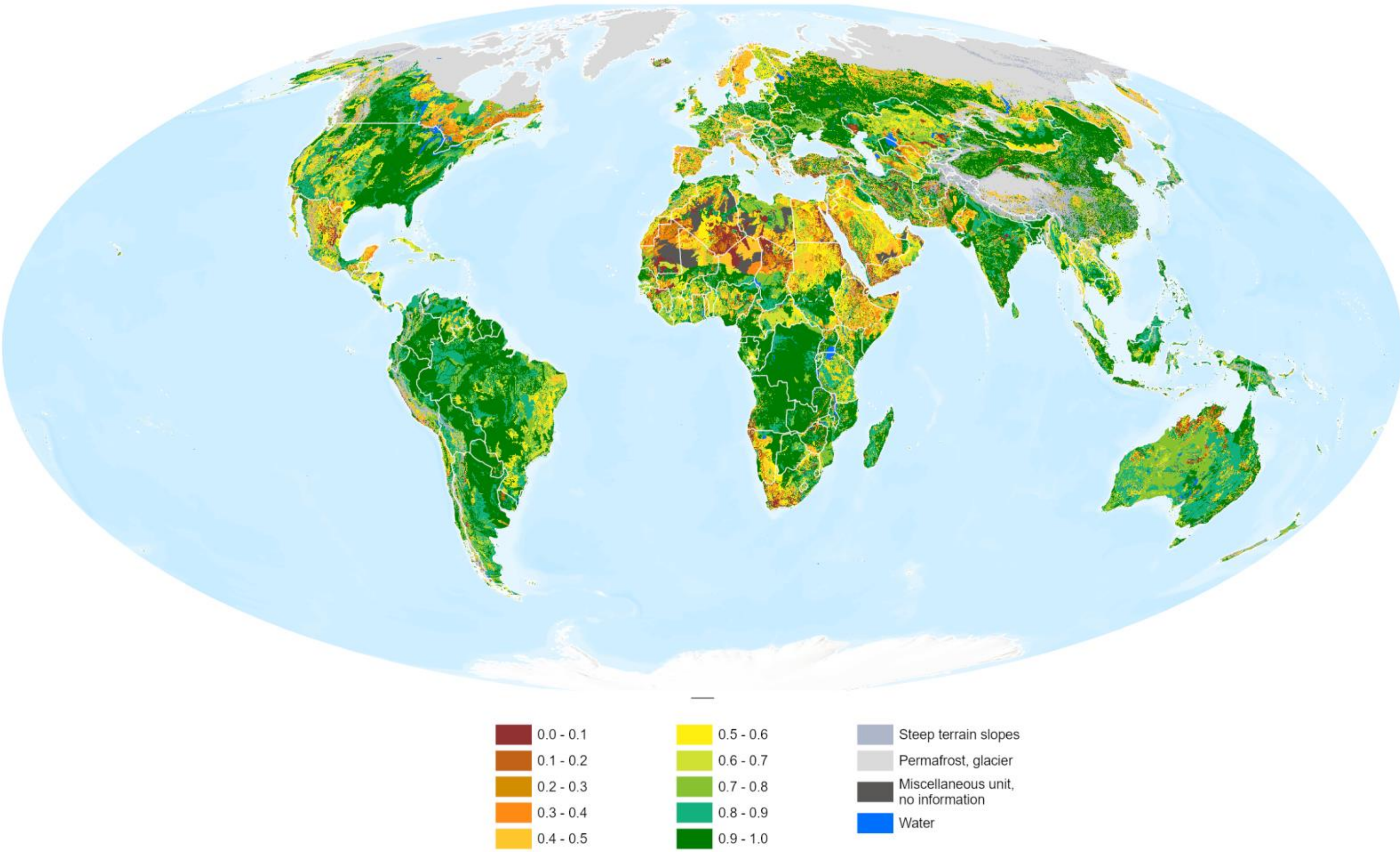
Figure A6.6. Calcium carbonate and gypsum (SQ6) for maize (conventional farming with high level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Source: **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis)**. 2025b. *Global Agro-Ecological Zoning version 5*. (Accessed on 12 July 2025). https://data.apps.fao.org/gaez/. Licence: CC-BY-4.0.

Figure A6.7. Workability (SQ7) for maize (conventional farming with high level inputs)



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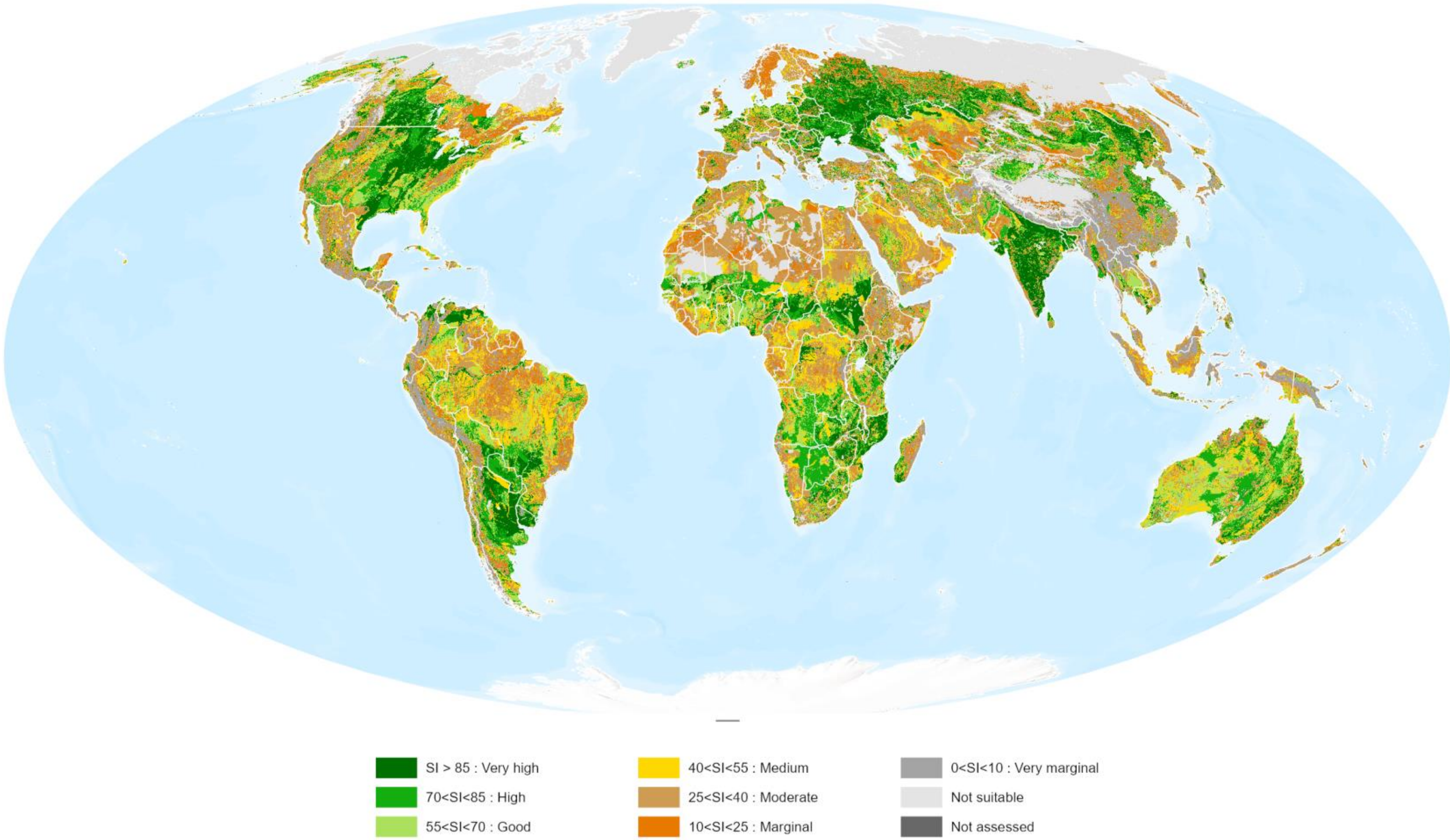
Appendix 7. Global maps of soil suitability for rainfed grain maize under conventional and organic farming systems

Figure A7.1, Figure A7.2, Figure A7.3 and Figure A7.3 present soil and terrain slope suitability for rainfed maize for different farming systems and assumed input levels. The mapped values express a suitability index (range 0 to 100) in terms of eight classes, from very high suitability (with a suitability index >85) to not suitable (where the suitability index is 0). The index values shown for each 30 arc-second pixel are calculated as the weighted average of suitability ratings for the different components, making up a grid cell in terms of occurring soil units and terrain slope classes.

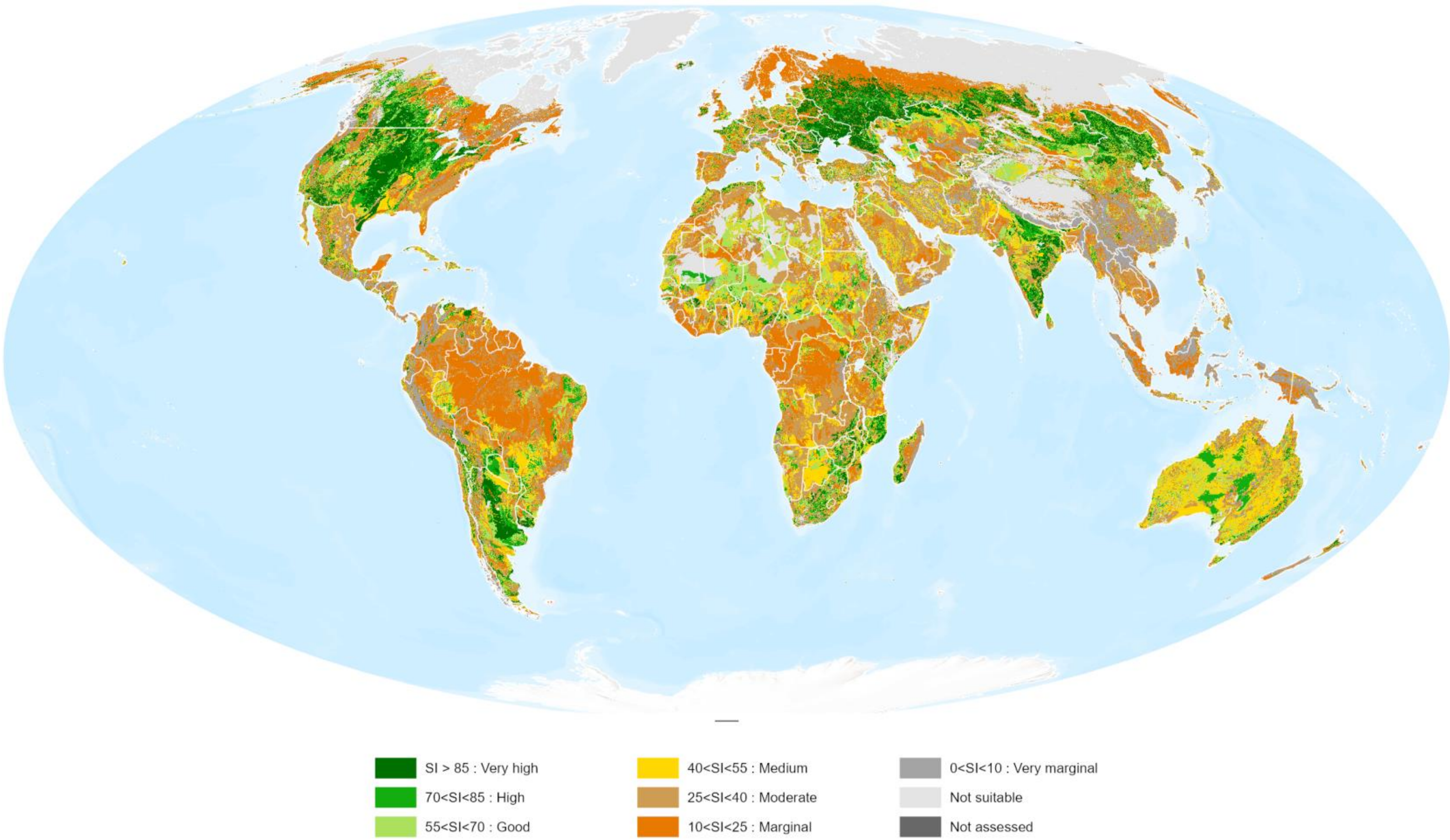
Figure A7.1. Soil/terrain suitability for maize (conventional farming with high level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Source: **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis).** 2025a*. Global Agro-Ecological Zoning version 5 (GAEZ v5) Model Documentation*. In: *GitHub*. San Francisco, USA, GitHub. [Cited 12 July 2025]. https://github.com/un-fao/gaezv5/wiki

Figure A7.2. Soil/terrain suitability for maize (conventional farming with low level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

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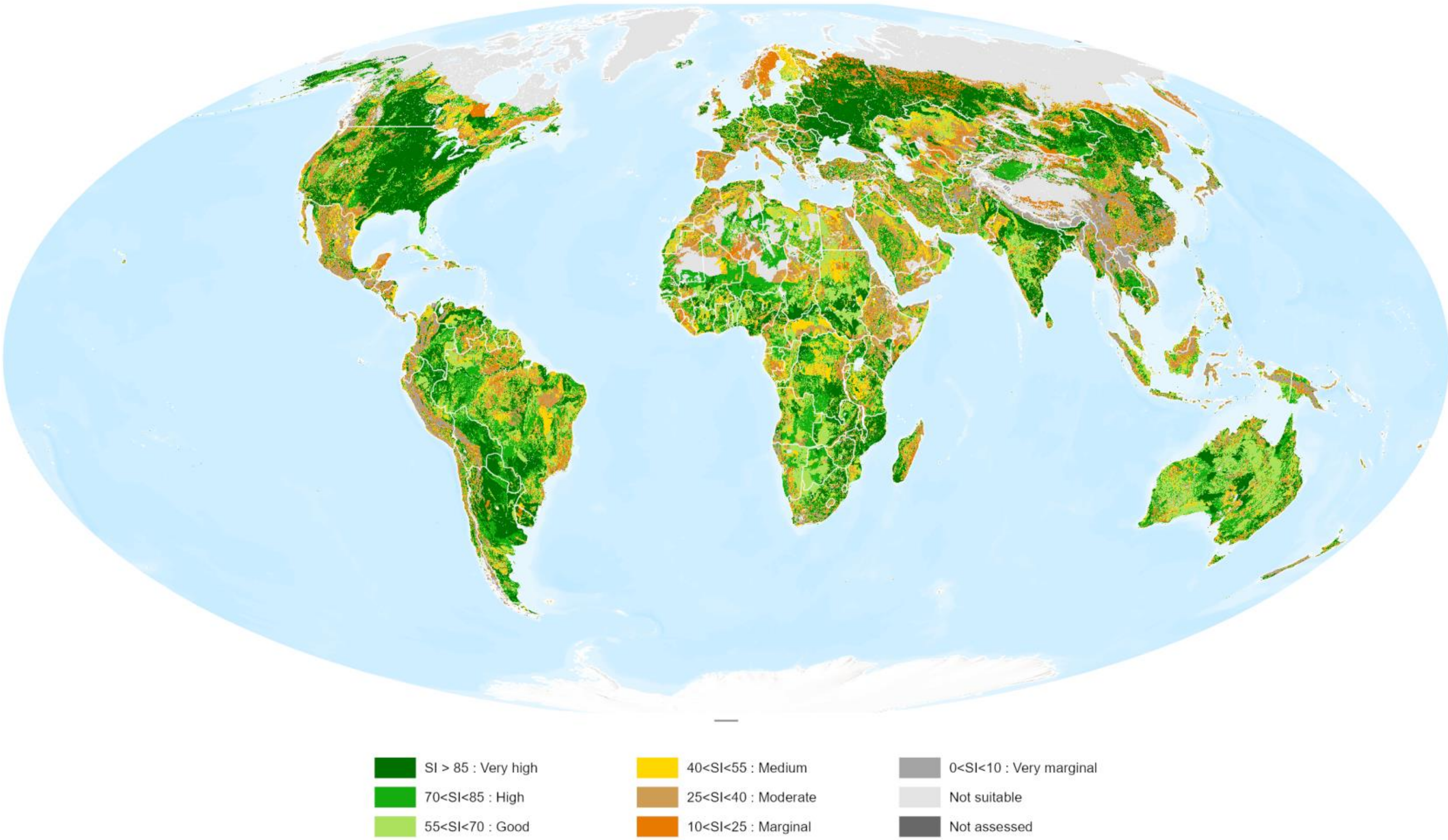
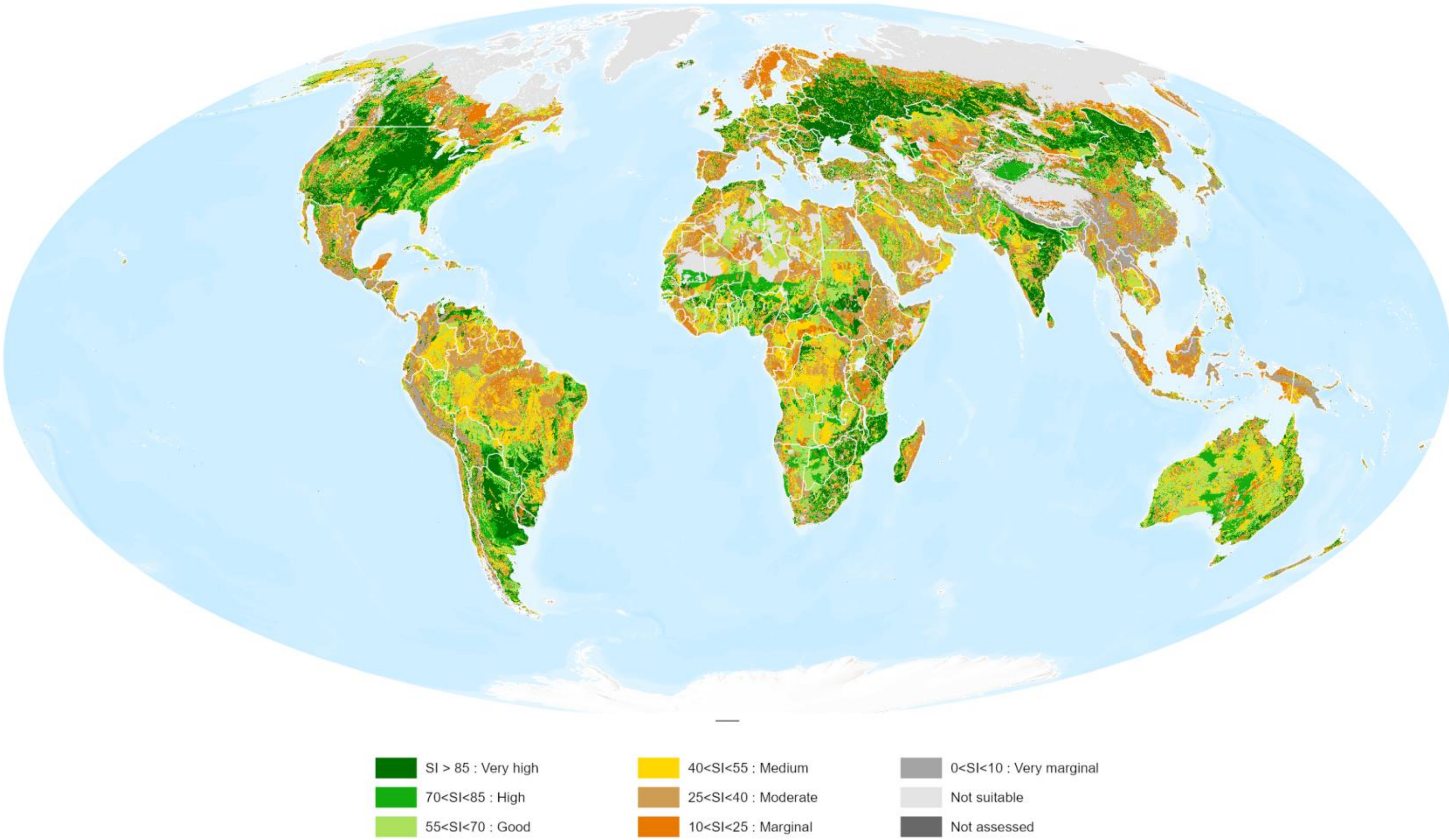
Figure A7.3. Soil/terrain suitability for maize (organic farming with advanced level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Source: **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis).** 2025a*. Global Agro-Ecological Zoning version 5 (GAEZ v5) Model Documentation*. In: *GitHub*. San Francisco, USA, GitHub. [Cited 12 July 2025]. https://github.com/un-fao/gaezv5/wiki

Figure A7.4. Soil/terrain suitability for maize (organic farming with moderate level inputs)



Notes: Refer to the disclaimer on page ii for the names and boundaries used in this map. 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. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.

Source: **FAO (Food and Agriculture Organization of the United Nations) & IIASA (International Institute for Applied Systems Analysis).** 2025a*. Global Agro-Ecological Zoning version 5 (GAEZ v5) Model Documentation*. In: *GitHub*. San Francisco, USA, GitHub. [Cited 12 July 2025]. https://github.com/un-fao/gaezv5/wiki

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used in Global Agro-Ecological Zoning version 5

ISBN 978-92-5-140434-8

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CD8206EN/1/03.26