Food and Agriculture Organization
of the United Nations

Global Agro Ecological Zones v4

MODEL DOCUMENTATION

International Institute for
Applied Systems Analysis
IIASA www.iiasa.ac.at

Global Agro-Ecological Zones (GAEZ v4)

Model documentation

Günther Fischer[+], Freddy Nachtergaele[++], Harrij van Velthuizen[+], Federica Chiozza[++], Gianluca Franceschini[++], Matieu Henry[++], Douglas Muchoney[++] and Sylvia Tramberend[+]

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

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

ISBN 978-92-5-134426-2 [FAO]

Contents

Figures

Tables

Foreword

The 2030 Agenda for Sustainable Development puts a strong emphasis on an integrated approach to achieving Sustainable Development Goals (SDGs) that can harness synergies and minimize potential trade-offs. Agriculture systems worldwide must become more productive and less wasteful. Sustainable agricultural practices and food systems, including both production and consumption, must be pursued from a holistic and integrated perspective. The sustainable use of land resources, notably in agriculture, can play an important role in accelerating the achievement of many SDGs.

More innovations and coordinated efforts are needed to sustainably improve the global supply chain, decrease food losses and waste, and ensure that all who are suffering from hunger and malnutrition have access to safe and nutritious food. The current trajectory of growth in agricultural production is unsustainable because of its negative impacts on natural resources and the environment. One-third of farmland is degraded, up to 75 percent of crop genetic diversity has been lost and 22 percent of animal breeds are at risk. Land, water, healthy soils and plant genetic resources are key inputs into food production, and their growing scarcity in many parts of the world with increased environmental challenges, such as climate change, make it imperative to use and manage them sustainably.

An integrated decision-making process at national and regional levels is needed to achieve synergies and adequately address trade-offs in land use, water allocation and climate mitigation measures to avert conflicts among agriculture, energy production and climate change mitigation. Even though traditional knowledge can address some of the challenges at community scale, the full spectrum of available farming possibilities at national, regional and global levels is not known. Little technological means and few comprehensive information systems are available to support well-informed plans or implementation of strategies.

The Agro-Ecological Zones (AEZ) methodology is a successful approach used in land evaluation to support sustainable agricultural development. AEZ relies on well-established land evaluation principles to assess natural resources for identifying suitable agricultural land utilization options. It identifies resource limitations and opportunities based on plant eco-physiological characteristics, climatic and edaphic requirements of crops and it uses these for evaluating suitability and production potentials for individual crop types under specific input and management conditions. Managing the constraints imposed by agro-ecological conditions and knowing what the most viable crop options are, can facilitate planning decisions and induce choices that, while more productive, are sustainable and resilient to climatic variability.

The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have cooperated over several decades to develop and implement the AEZ modelling framework and databases. Both FAO and IIASA have been employing AEZ for evaluating land utilization potentials of natural resources in numerous assessments at global, regional and national scales.

The AEZ methodology was initially implemented in the 1980s to assess the capacity of the world's natural resources to meet the needs of a fast-growing global population, particularly in developing countries. Rapid developments in computing and geo-information technology have produced increasingly detailed global databases and IT resources, which made possible the first global AEZ assessment in 2000 (GAEZ v1). Since then, global AEZ assessments have released in 2002 (GAEZ v2) and 2012 (GAEZ v3).

The current version of GAEZ estimates sustainable crop production potentials for historical, current and future climatic conditions, comprising of several terabytes of spatial data at 5 arc-minutes (about 9 x 9 km at the equator). Production potentials are assessed for various (sustainable) levels of inputs and field management under rain-fed and irrigation water supply systems for several thousand combinations of crop-type, management level, water supply source and time period. Additionally, GAEZ v4 has produced a spatial representation of current agricultural production statistics (FAOSTAT) for year 2010. This database provides a complete spatial representation of current crop areas, yield and production for 26 major crop groups. By linking the actual crop production with corresponding spatial crop potentials, FAO and IIASA achieved unique global estimates of current (year 2010) yield and production gaps.

This model system documentation provides updated information on the GAEZ v4 methodological structure and describes the conceptual framework of individual assessment modules in ten chapters. Model input parameters and additional technical information are provided in appendices. The document will support users of the GAEZ v4 data portal and is specifically recommended for AEZ modelers and users such as researchers and planners at national and international research institutes and multilateral organizations dealing with sustainable utilization of land resources, agricultural development and food security.

Maria Helena Semedo

Deputy Director-General

Food and Agriculture Organization of the United Nations (FAO)

Albert Van Jaarsveld

Director General and Chief Executive Officer

International Institute for Applied Systems Analysis (IIASA)

Acknowledgements

The Global Agro-Ecological Zoning (GAEZ) draws on a wealth of land evaluation and agricultural technical assessment activities resulting of decades of collaboration between FAO and IIASA that have contributed to the process of developing the GAEZ conceptual framework and its databases. The authors thank all those who provided inputs and comments through the years to improve land evaluation and the GAEZ methodological approach. We also acknowledge for their support and comments Sasha KooOshima, Vera Boerger, Jippe Hoogeveen, Feras Ziadat, Beau Damen, Elbehri Aziz, Zhongxin Chen, Karl Morteo, Eduardo Machado, Brendan O'Neill, Sam Libby, Michele Piraux and James Morgan.

Funding from FAO, IIASA and support of its National Member Organizations is gratefully acknowledged.

Abbreviations and acronyms

AEZ	Agro-Ecological Zones
AWC	Available soil Water Capacity
BADC	British Atmospheric Data Centre
CMIP5	Coupled Model Inter-comparison Project Phase 5
CRU	Climate Research Unit
DEM	Digital Elevation Model
ESM	Earth System Model
ETa	Actual evapotranspiration
ETm	Maximum evapotranspiration
ETo	Reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
Fm	Modified Fournier Index
GAEZ	Global Agro-ecological Zones
GLC-Share	Global Land Cover Share
GLWD	Global Lakes and Wetlands Database
GPCC	Global Precipitation Climatology Centre
HI	Harvest index
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied System Analysis
IPCC	Intergovernmental Panel on Climate Change
ISI-MIP	Inter-Sectoral Impact Model Inter-comparison Project
KBA	Key Biodiversity Areas
LAI	Leaf Area Index
LCCS	Land Cover Classification System
LGP	Length of Growing Period
LGP_{t5}	Temperature Growing Period
LGP_{t10}	Frost Free Period
LUTs	Land Utilization Types
NPP	Net Primary Production
P/ETo	Moisture Availability Index
RCPs	Representative Concentration Pathways
SOLAW	Status of Land and Water Resources for Food and Agriculture
SQ	Soil Quality
SRTM	Shuttle Radar Topography Mission
SSPs	Shared Socio-economic Development Pathways
WDPA	World Database of Protected Areas
WDe	Water Deficit

1. Introduction

The Agro-Ecological Zones methodology

The quality and availability of land and water resources, together with socio-economic conditions and institutional factors, are essential to assure sustainable food security. In order to optimize the wise use of the land and water resources it is important to determine their agronomic potential. The crop cultivation potential describes the agronomically possible upper limit to produce different crops under given agro-climatic, soil and terrain conditions for specific levels of agricultural inputs and management conditions.

The Agro-Ecological Zones (AEZ) approach determines for each location of the globe the cultivation potentials for about 50 crops, modelled by more than 300 generic production systems, and is based on the fundamental principles of land evaluation (FAO, 1976, 1978, 1984, 1993, 2007a). The AEZ concept was originally developed by the Food and Agriculture organization of the United Nations (FAO) and over time, the International Institute for Applied System Analysis (IIASA) and FAO have together further developed and applied the AEZ methodology and the supporting databases and computer programs.

The current Global AEZ (GAEZ v4) provides a further update of data and extension of the methodology compared to the release of GAEZ v3 (Fischer *et al.*, 2012). The GAEZ v4 update includes 2010 baseline data (compared to a baseline of 2000 in v3) comprising land cover, protected areas and areas of high biodiversity value, renewable water resources and climatic conditions for a time series of historical data and a selection of future climate simulations using recent IPCC AR5 Earth System Model (ESM) outputs for four Representative Concentration Pathways (RCPs).

Climatic data comprises precipitation, temperature, wind speed, sunshine duration and relative humidity. These parameters are used to compile agronomically meaningful climate resources inventories including quantified thermal and moisture regimes in space and time. Geo-referenced global climate, soil, terrain and land cover data are combined into a land resources database, which is assembled on the basis of global grids, with a resolution of 30 arc-seconds (about 0.9 km by 0.9 km at the equator) and 5 arc-minutes (about 9 km by 9 km).

Matching procedures to identify crop-specific limitations of prevailing climate, soil and terrain resources and evaluation with simple and robust crop models, under assumed levels of inputs and management conditions, provide maximum potential and agronomically attainable crop yields for basic land resources units. The assessed agricultural production systems are defined by water supply systems and levels of inputs and management circumstances. These generic production systems used in the analysis are referred to as Land Utilization Types (LUT).

Attributes specific to each LUT include crop information such as crop parameters (crop growth cycle duration, harvest index, maximum leaf area index, maximum rate of photosynthesis, etc.), cultivation practices and input requirements, and utilization of main produce, crop residues and by-products. For each LUT, the GAEZ procedures are applied for rain-fed and irrigated conditions.

Recent national, regional and global land cover data and land use statistics have been used to produce a global land cover database that quantifies by 30 arc-second grid cell the fractions of land occupied by 12 major land cover categories. These land cover data layers were derived from FAO's GLC-Share (Latham *et al.*, 2014) and GMIA v5 (Siebert *et al.*, 2013) databases. Spatial layers of rain-fed and irrigated cropland were calibrated with national and sub-national agricultural statistics of 2009–2011, mainly from FAOSTAT (arable land and land under permanent crops; land equipped with full control irrigation).

Spatial representation of actual yields and production has been derived through downscaling the annual national average of 2009–2011 agricultural statistics (FAOSTAT), including all food and fiber crops, onto all rain-fed and irrigated cropland areas. Spatially explicit downscaled results are presented as (i) overall crop production value, and (ii) for 26 major commodities in terms of crop area, yield and production. Comparison of simulated potential yields and production with statistically recorded yield and production of crops currently grown provides yield and production gap information for main commodities.

In summary, GAEZ v4 has generated large spatial databases of (i) natural resources endowments relevant for agricultural uses and (ii) assessments of suitability and attainable yields of individual LUT, (iii) harvested area, yields and production of main food and fiber commodities for rain-fed and irrigated cultivated land areas in 2000 and 2010, and (iv) yield and production gaps. These databases can provide the agronomic backbone for various applications including the quantification of potential land productivity. Geographical layers at 30 arc-seconds used for data aggregation include: (i) gridded maps of the global administrative unit layers updated in 2015 (FAO, 2007b, 2015) and (ii) hydrological basin boundaries, based on the spatial units delineated in World Map of Major Hydrological Basins (FAO, 2011). Further, results were aggregated in numerous tables for 2010 major land cover patterns, land protection/exclusion status and by about 30 classes of broad agro-ecological zones.

GAEZ v4 data are available from Data Portals at IIASA and FAO. The GAEZ v4 Data Portals are interactive data access facilities, which provide visualization and access to data and information, and offer users various analysis outputs and download options. The Data Portal covers six thematic areas as follows:

- **Land and Water Resources**, including agro-ecological zonation, land cover patterns, soil resources, terrain resources, examples of soil and terrain suitability, protected areas and land with high biodiversity value, and selected socio economic data;
- **Agro-climatic Resources**, including a variety of climatic indicators regarding climate classification, thermal and moisture regimes, and growing period length and conditions;
- **Agro-climatic Potential Yield** for more than 300 crop/land utilization types assessed under different input and management assumptions for historical, current and future climate;

- **Agro-ecological Suitability and Attainable Yield**, providing for more than 50 crops estimates of suitable extents, attainable yields and related attributes of the crop water balance assessed under rain-fed and irrigated conditions for historical, current and future climate;
- **Actual Yields and Production**, giving downscaled historical harvested area, production and yield of 26 main crops/crop groups, and
- **Yield and Production Gaps**, calculated in terms of ratios and differences between actual yield and production and attainable potentials for main crops.

Structure and overview of GAEZ procedures

The suitability of land for the cultivation of a given crop/LUT depends on specific crop requirements as compared to the prevailing agro-climatic and agro-edaphic conditions at a location. GAEZ combines these two components systematically by successively modifying grid-cell specific agro-climatic potential yields according to assessed soil limitations and terrain constraints. This structure allows stepwise review of results. An overview of the overall GAEZ v4 model structure and data integration is shown in Figure 1-1. The GAEZ v 4 user guide explains where the model outputs are located on the GAEZ v 4 data portal.

Calculation procedures for establishing crop suitability estimates include five main steps of data processing, namely:

i. Module I: Climate data analysis and compilation of general agro-climatic indicators for historical, baseline and future climates.

ii. Module II: Crop-specific agro-climatic assessment and water-limited biomass/yield calculation.

iii. Module III: Yield-reductions due to the impacts of agro-climatic risks and constraints of workability, pests and diseases.

iv. Module IV: Crop specific edaphic assessment and yield reductions due to soil and terrain limitations.

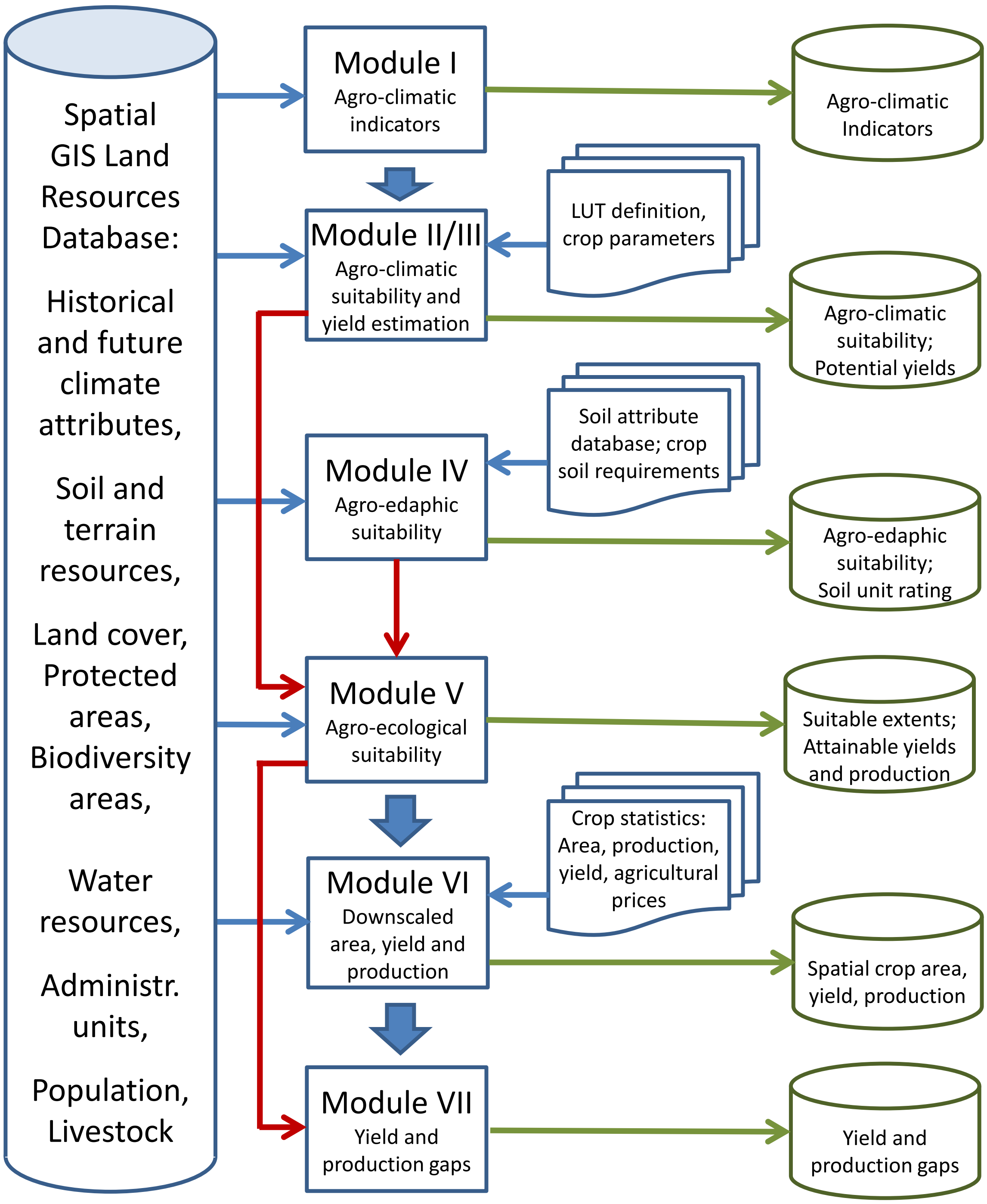
v. Module V: Integration of results from Modules I-IV into crop-specific grid-cell databases. These are used to map by crop, input level and time period the agro-ecological suitability and attainable yields and production.

In addition to estimating crop potentials, two main activities were involved in obtaining grid-cell level harvested area, yield and production of main crops for the period 2009–2011, namely:

vi. Module VI: Joint attribution of area, yield and production of all statistically recorded crops to the rain-fed and irrigated cropland shares of the amended GLC share land cover database.

vii. Module VII: Quantification of yield gaps between potential attainable crop yields and downscaled current crop yield statistics for the period 2009–2011, by comparing potential rain-fed and irrigated yields with yields of downscaled statistical production

Figure 1-1 Overall structure and data integration of GAEZ v4 (Module I-VII)



Module I: agro-climatic data analysis

The main purpose of Module I is the compilation of a geo-referenced climatic resources inventory offering a variety of relevant agro-climatic indicators. These agro-climatic indicators provide a general characterization of land resources and suitability for agricultural uses. Several agro-climatic layers are used as input during the estimation of crop yields and production in Module II, quantification of agro-climatic constraints in Module III, and for estimating agro-ecological suitability and attainable yields in Module V.

Unlike in previous GAEZ versions, GAEZ v4 makes use in the water balance calculations of daily input data for temperature and precipitation (distributions of historical period 1961 to 2010 derived from WATCH Forcing Data (Weedon *et al.*, 2011); see Chapter 2 on GAEZ input data). In previous GAEZ versions a daily water balance was calculated using pseudo-daily data generated from monthly observation data. The use of observed daily data improves the capability of GAEZ to consider extreme events such as occurrence of frost days, heat waves and periods of excessive or no rainfall.

For future years, daily precipitation and temperature in GAEZ v4 is derived from daily outputs of five major ESMs and for four different RCPs (alternative representative greenhouse gas concentration pathways).

Another extension in GAEZ v4 as compared to previous versions of GAEZ is the compilation of three 30-year historical reference periods, namely the period 1961–1990 (the only one used in GAEZ v3), but also the periods 1971–2000 and 1981–2010. In addition to simulations for these three reference periods, annual time series results were computed for fifty years, from 1961 to 2010.

For projections of future climate, the GAEZ v4 analysis considers three future reference periods: years 2011–2040, 2041–2070 and 2070–2099, referred to respectively as the '2020s', the '2050s' and '2080s'. Year-by-year simulations and time series analysis with GAEZ Module I are performed for 140 years, from 1960 to 2099, providing in addition to period averages also information on the distribution and variability of agro-climatic indicators within each 30-year period.

Module II: biomass and yield calculation

The main purpose of Module II is the calculation of agro-climatic potential biomass and yield for a wide range of LUTs under various input/management levels and for rain-fed and irrigated conditions. Biomass and yield calculations and the procedures used for the computation of daily crop water balances are based on the eco-physiological model developed by various FAO technical reports (Allen *et al.*, 1998; Doorenbos and Kassam, 1979; Doorenbos and Pruitt, 1977; Kassam, 1977; Smith, 1992).

Module II consists of two main steps:

i. Calculation of maximum crop biomass and yield potentials considering only prevailing radiation and temperature conditions, and

ii. Computation of yield losses due to water stress during the crop growth cycle. The estimation is based on rain-fed crop water balances for a range of 8 different levels of soil water holding capacity. Yield estimation for irrigation conditions assumes that irrigation will be scheduled such that no yield-reducing crop water deficits occur during the crop growth cycle.

Revisions of Module II relate to the refined representation of phenological stages, local adjustments of crop water coefficients to reflect local wind and relative humidity conditions, and update of water-deficit yield response coefficients. In addition, due to data and validation experiences available in various national AEZ studies, adjustments have been made to biomass and yield parameters for several crops and crop/LUTs. The range and methods of assigning soil water holding capacity classes used in Module II have been revised and extended to account for the presence of coarse material and soil salinity.

Results of Module II include LUT-specific temperature/radiation defined maximum yields, yield reduction factors accounting for sub-optimum thermal conditions, for yield impacts due to crop water deficits, estimated amounts of net irrigation requirements, potential and actual LUT evapotranspiration, the accumulated temperature sums during each LUT crop cycle, and the simulated optimum crop calendars.

Module III: agro-climatic constraints

Agro-climatic constraints cause direct or indirect losses in the yield and quality of produce. The relationships between these constraints with general agro-climatic conditions such as moisture stress and excess air humidity, and risk of early or late frost are varying by location, between agricultural activities as well as using control measures as assumed for different input levels.

Module III computes for each grid cell LUT-specific multipliers corresponding to different types of agro-climatic risks and constraints which are applied to further reduce previously calculated agro-climatic potential yields (i.e., the results of Module II).

This step is carried out in a separate module, termed Module III, to make explicit the climatic effect of limitations due to pests and diseases, and workability constraints and to permit time-effective reprocessing in case new or additional information becomes available. Four groups of agro-climatic constraints are applied, including:

- Yield losses because of pests, diseases and weed constraints on crop growth;
- Yield losses due to water stress, pest and diseases constraints on yield components and yield formation of produce (e.g., affecting quality of produce);
- Yield losses due to workability constraints (e.g., excessive wetness causing difficulties for harvesting and handling of produce), and
- Yield losses due to occurrence of early or late frosts.

These agro-climatic constraints are expressed as yield reduction factors according to the different constraints and their severity for each crop/LUT and by level of inputs. Due to paucity of available empirical data, the estimates of constraint ratings have been mostly obtained through expert opinion.

For application in GAEZ v4, the approximation of the impact of these yield constraints based on prevailing climatic conditions has been reviewed and adjusted in some cases (e.g. for silage maize). Agro-climatic constraints for new LUTs (e.g., grain-, sugar- and biomass-producing sorghum species; napier grass; para rubber) have been added.

Module IV: agro-edaphic constraints

Module IV estimates yield reductions due to the constraints induced by soil limitations and prevailing terrain-slope conditions. Crop yield impacts resulting from sub-optimum soil and terrain conditions are quantified separately for soils and terrain-slopes. The soil suitability is assessed through crop specific evaluations of seven major agronomic soil qualities estimated from soil attributes available in the Harmonized World Soil Database, HWSD v1.2 (Nachtergaele *et al.*, 2012). Soil qualities include soil nutrient availability, soil nutrient retention capacity, soil rooting conditions, soil oxygen availability, presence of lime and gypsum, presence of soil salinity and sodicity (sodium) conditions, and soil management/workability constraints. These limitations are estimated on a crop-by-crop basis and are combined into a crop and input specific edaphic suitability rating. Available soil Water Capacity (AWC), an important parameter in the crop water balance, is estimated from physical and chemical soil characteristics, effective soil depth and rooting depth of individual crops.

The output of Module IV comprises of result tables by crop and water source (rain-fed, gravity irrigation, sprinkler irrigation, drip irrigation), which list for each component soil of the soil map units recorded in HWSD v1.21 the calculated soil quality indicators and soil unit ratings.

Module V: integration of climatic and edaphic evaluation

Module V executes the final step in the GAEZ crop suitability and land productivity assessment. It incorporates the LUT specific results of the agro-climatic evaluation for biomass and yield calculated in Module II/III for different soil AWC classes and it uses the edaphic ratings produced for each crop/soil/slope combination assessed in Module IV.

The inventories of soil resources and terrain-slope conditions are integrated by ranking all soil types in each soil map unit regarding the occurrence in different slope classes. Considering simultaneously the slope class distribution of all the grid cells belonging to a particular soil map unit and the characteristics of soil types and the shares of the soil map unit assigned to different soil types, a data pre-processing step of Module V results in an overall consistent distribution of soil-terrain slope combinations by individual soil association map units and 30 arc-sec grid cells (i.e., approximately 0.9 km by 0.9 km at the equator).

The algorithm in Module V steps through the grid cells of the spatial soil association layer of the Harmonized World Soil Database and determines for each grid cell the respective make-up of land units in terms of soil types and slope classes. Each of these component land units is separately assigned the appropriate suitability and yield values and results are accumulated for all elements. Processing of soil and slope distribution information takes place at 30 arc-second grid cells, separately for rain-fed and irrigated conditions. One hundred of these 30 arc-second grid cells produce the aggregate agro-ecological characterization at 5 arc-minutes, the resolution used for storing and providing GAEZ results.

Cropping activities are among the most critical in causing topsoil erosion, because of their management and the particular cover dynamics of annual crops. For this reason, GAEZ applies in Module V a terrain-slope suitability rating procedure to account for important factors that influence production sustainability. This is achieved through: (i) defining permissible slope ranges for cultivation of various crop/LUTs and setting maximum slope limits; (ii) for slopes within the permissible limits, accounting for likely yield reduction due to loss of fertilizer and topsoil, and (iii) distinguishing among a range of farming practices, from manual cultivation to fully mechanized cultivation. In addition, the terrain-slope suitability rating is varied according to amount and distribution of rainfall, which is quantified in GAEZ by means of the modified Fournier index. Terrain suitability is estimated according to terrain-slope class and location specific rainfall amounts and concentration characteristics. Soil and terrain characteristics are read by 30 arc-second grid-cells for which sub-grid soil and terrain combinations have been quantified in the database. These calculations are crop/LUT specific and are separately performed for three basic input levels for rain-fed and irrigated water supply systems.

The processing in Module V also accounts for fallow period requirements, which have been established for main crop groups, by level of inputs, and for different climatic conditions. The fallow factors included in GAEZ are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow, foremost to maintain its soil fertility status. In crop summary tabulations produced in Module V, the fallow requirement factors are applied for the estimation of attainable average annual production that can be achieved on a sustainable basis under the assumed level of inputs and management.

Application of the procedures in modules I to V, described above, result in an expected yield and suitability distribution under rain-fed and irrigation conditions by 5 arc-minute grid-cell and for each crop/LUT and input level. Land suitability results for each crop are stored as six classes: very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS), very marginally suitable (vmS), and not suitable (NS). The processing results in large databases, which are used to derive additional characterizations and aggregations of the land. Examples include the calculation of land extents with cultivation potential by land cover type and protection/exclusion status, quantification of climatic production risks by using historical time series of suitability results, impacts of climate change on crop production potentials, and irrigation water requirements under current and future climates.

Beyond using administrative units, additional aggregations of results by hydrological basins (and the intersection of countries and major hydrological basins) were implemented in GAEZ v4, thereby increasing the available options of crop summary and statistical tables.

Module VI: actual yield and production

Agricultural production and land statistics are available at national scale from FAO, but these statistical data do not reflect the spatial heterogeneity of agricultural production systems at finer resolutions within country boundaries. A "downscaling" method is needed for attribution of aggregate national production statistics to individual spatial units (grid cells) by applying formal methods that account for land characteristics, assess possible production options and can use available evidence from observed or inferred geo-spatial information, e.g. remotely sensed land cover, soil, climate and vegetation distribution, population density, etc.

Two main steps were involved in Module VI for obtaining downscaled grid-cell level area, yield and production of main crops:

i. Compilation of calibrated shares of rain-fed and irrigated cropland by 30 arc-seconds (and aggregation to 5 arc-minute) grid cell, and

ii. Attribution of crop specific harvested area, yield and production to the rain-fed and irrigated cropland of each grid cell.

Based on recent national, regional and global land cover products and land use statistics, FAO has produced a global land cover database GLC-Share (Latham *et al.*, 2014) consisting of a quantification by 30 arc-second grid cell of the fraction of land occupied by 11 main land cover classes. In step 1 of Module VI the spatial cropland shares available from GLC-Share were calibrated with national and sub-national agricultural land statistics of 2009–2011 (i.e., the share of land occupied by arable land and land under permanent crops).

In step 2 the spatial representation of actual yields and production consistent with national and sub-national statistical data around year 2010 (mainly FAOSTAT average of period 2009–2011) has been derived through jointly downscaling[1] the agricultural statistics of all cultivated (food, fodder and fiber) crops onto the spatial rain-fed and irrigated cropland areas identified in the updated land cover dataset. Spatial results are presented as: (i) overall crop production values, and (ii) crop area, yield and production for 26 major commodities.

To achieve consistency of land balances, all recorded food, feed and fiber crops (statistical data derived from FAOSTAT, AQUASTAT and selected national sources) were attributed to the total delineated spatial physical cropland.

Module VII: yield and production gaps

Module VII carries out the final modelling step in GAEZ v4 processing. The quantitative yield gap analysis relies on both the results of crop suitability and potential yield analysis produced in Module V and the downscaling of base year agricultural area and production statistics undertaken in Module VI.

Apparent yield and production gaps have been estimated by comparing at a spatially detailed level of 5 arc-minutes the potential attainable yields and production (as estimated in GAEZ v4)

[1] Global change processes raise estimation problems challenging the conventional statistical methods. These methods are based on the ability to obtain observations from unknown true probability distributions, whereas the new problems require recovering information from only partially observable or even unobservable variables. For instance, aggregate data exist at global and national level regarding agricultural production. Sequential rebalancing procedures that were developed at IIASA, rely on appropriate optimization principles (Fischer *et al.*, 2006b, 2006a, 2012) such as cross-entropy maximization, and combine the available real observations and spatial data with other “prior” hard (statistics, accounting identities) and soft (expert opinion, scenarios) information.

and the harvested areas, estimated actual yields and production obtained by downscaling statistical data for respectively the years 1999–2001 and for 2009–2011.

Comparisons are presented as achievement ratios (actual/potential) for yields and as absolute differences of potential and actual production. The results of yield gap analysis are stored as GIS raster data at 5 arc-minutes resolution, separately for total cropland, irrigated and rain-fed cropland.

Limitations

Many spatial datasets used in GAEZ v4 have been improved in resolution and accuracy compared with previous GAEZ v3. One exception is the soil information (HWSD v1.21), which includes only a minor update from HWSD v1.2 used previously. Accurate and detailed soil information is crucial for reliable GAEZ estimates and a major update of soil information is desirable and seems possible if international partners would be willing to cooperate and provide best available soil data of their regions.

The land cover dataset used in GAEZ v4 (GLC-Share v1.1) was a significant step forward but new regional and global land cover products, at even higher resolution and with improved accuracy became available after GAEZ v4 datasets were frozen.

The agronomic data, such as the data on environmental requirements for some crops, contain generalizations necessary for global applications. In particular, assumptions on occurrence and severity of some agro-climate related constraints to crop production (used in Module III) would certainly benefit from additional systematic data collection and verification.

Land degradation in its multiple aspects, including crucial elements such as soil degradation (soil erosion, contamination, ealing, compaction, nutrient depletion, and biodiversity loss), vegetation degradation, and water resources decline in quality and quantity, are not or only partially taken into account. They obviously influence sustainable yield and production capacities and a more thorough treatment of these factors would be desirable.

Socioeconomic needs of rapidly increasing and wealthier populations are the main driving force in the allocation of land resources to various kinds of uses, with food production as the primary land use. For rational planning of sustainable agricultural development, a systematic and spatially detailed understanding of farmers' land-use and socioeconomic considerations and constraints will be crucial. So far, the use of socioeconomic information in global AEZ is limited to the specification of modes and purpose of agricultural production, the quantification of levels of inputs and management, the inclusion of agricultural prices and the consideration of population numbers and distribution.

Agriculture covers, by definition, apart from cropping a wide range of other activities and land uses include agro-forestry, livestock rearing and inland fisheries. The GAEZ v4 assessment does not encompass all these sectors and focuses mostly on the potential for growing crops (for food, fodder, fiber or biofuel feedstock). Nonetheless, the outputs of the model can and have been used as spatial agronomic backbone to support various other applications in agricultural development planning, scenario studies of climate change impacts and adaptation, or for assessing renewable bio-energy production options and deployment.

Land has many important functions. GAEZ outputs emphasize the suitability of land for crop production. The need to plan for more and better food supplies, from less resources and with less environmental impacts, will have to continue with high priority in the next decades. Current GAEZ respects land marked by protection/exclusion status or with recognized biodiversity value by using in Module V an ‘exclusion’ layer compiled from up-to-date and reliable international datasets (see Chapter 2 on GAEZ spatial input data). However, GAEZ currently cannot by itself compare the value of a potential production service in a location with the value of potential other ecosystem services of the land. Integration of supplementary modules to quantify additional ecosystem services within the GAEZ framework seems possible and desirable. Appendix 1-1 provides additional recommendations on possible further development of AEZ applications for sustainable land utilization.

2. GAEZ input datasets

Climate data

Observed climate

Time series data were used for the Global Agro-Ecological Zones historical assessment, which were obtained from the Climate Research Unit (CRU) at the University of East Anglia, the Global Precipitation Climatology Centre (GPCC), and the EU WATCH Integrated Project.

Climatic Research Unit TS v3.21 (time-series) datasets (Harris *et al.*, 2014) were obtained from British Atmospheric Data Centre (BADC) in 2014. These are month-by-month variations in climate over the last century covering the period January 1901 to December 2012. CRU TS v3.21 data are produced on 0.5° x 0.5° latitude by longitude grids (i.e., about 55 km at the equator), which are based on an archive of monthly average daily data provided by more than 4000 weather stations distributed around the world. CRU TS v3.21 variables used in GAEZ v4 are daily mean temperature, diurnal temperature range, cloud cover, vapor pressure, wind speed and wet day frequency.

For monthly precipitation the GPCC Full Data Reanalysis Product Version 6 is used (Schneider *et al.*, 2011). This is the centennial GPCC Full Data Reanalysis of monthly global land-surface precipitation based on the 67,200 stations world-wide that feature record durations of 10 years or longer. This product contains the monthly totals on a regular grid with a spatial resolution of 0.5° x 0.5° latitude by longitude. The temporal coverage of the dataset ranges from January 1901 until December 2010. The GPCC v6 data reanalysis product replaced in GAEZ v4 the GPCC VASClimO 50-Year Data Set (period 1950 to 2000) which was used for historical monthly precipitation in GAEZ v3.

New global sub-daily (3 hours) meteorological forcing data were provided in WATCH[2] for use with land surface- and hydrological-models (Weedon *et al.*, 2011). The data are derived from the ERA-40 and ERA-Interim reanalysis products via sequential interpolation to half-degree resolution, elevation correction and monthly-scale adjustments based on CRU (corrected-temperature, diurnal temperature range, cloud-cover) and GPCC (precipitation) monthly observations combined with new corrections for varying atmospheric aerosol-loading and separate precipitation gauge corrections for rainfall and snowfall. The ERA-40 and ERA-Interim products include all the key near-surface meteorological variables required in AEZ. However, in order to remove model biases, the ERA data were subjected to adjustment (usually called "bias-correction") based on monthly observational data using recent versions of respectively CRU-TS and GPCC v5/v6 time series data.

With these updated climate databases, historical year-by-year climatic data analysis was extended from year 2000 (as used in GAEZ v3) to 2010 for GAEZ v4. Time series data were

[2] WATCH was a large Integrated Project funded by the European Commission under the Sixth Framework Programme, Global Change and Ecosystems Thematic Priority Area (contract number: 036946). The WATCH project started early 2007 and continued to 2011.

combined to compile three average 30-year historical data sets for respectively the periods 1961–1990, 1971–2000 and 1981–2010 and to compute raster data with related statistics of medians, standard deviations and coefficients of variation.

Six variables monthly data and three variables with daily climatic data are employed in GAEZ climate analysis and crop biomass/yield estimation, as shown in Table 2-1. Original monthly CRU and GPCC 30 arc-minute latitude/longitude climatic surfaces were interpolated at IIASA to a 5 arc-minute grid (about 9 x 9 km at the equator) for all years between 1960 and 2010. Monthly climatic variables used include precipitation, number of rain-days, mean minimum and mean maximum temperature, cloudiness/sunshine duration, wind speed, and vapor pressure. For all variables except temperature, a bilinear interpolation method was applied. It uses the values of the nearest input grid cells to determine the value of the 5 arc-minutes output raster. The value of a 5 arc-minute output grid cell is the weighted average of the input values, obtained by inverse distance weighting.

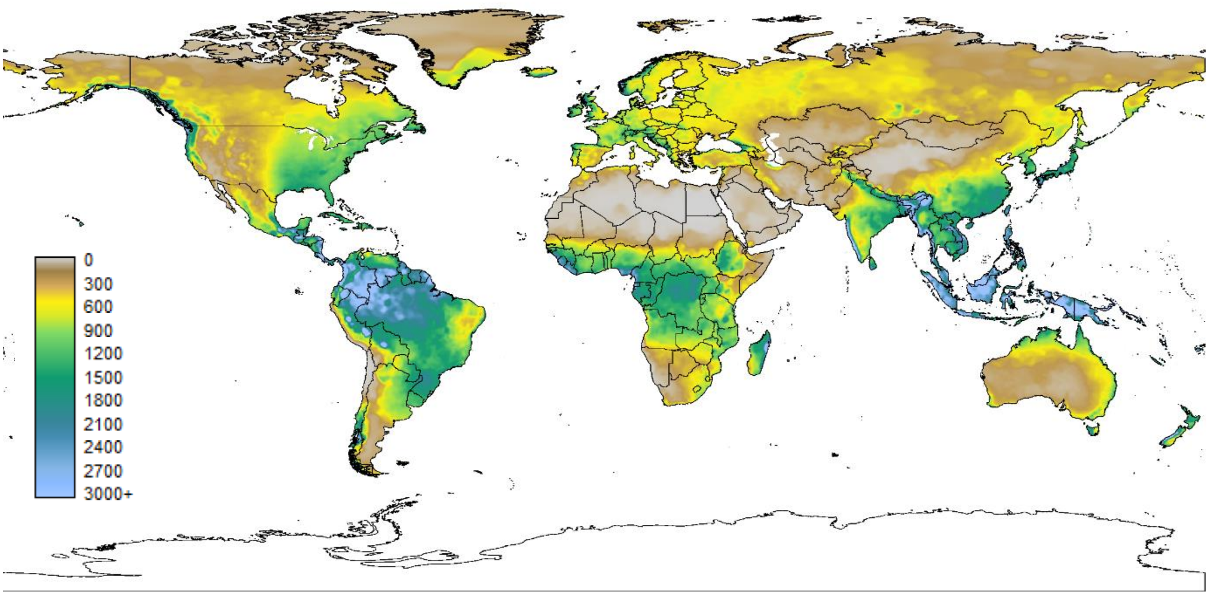
For temperature, a correction for altitude was included in the interpolation. A lapse rate of 0.55^0C per 100-meter elevation was applied together with the respective digital elevation data at 30 arc-minutes (for input data) and 5 arc-minutes (for output data). First, 30 arc-minute elevation data (provided by CRU) were used to calculate temperature values adjusted to sea level. Second, bilinear interpolation was performed for temperatures at sea level. Third, 5 arc-minute elevation data, derived from Shuttle Radar Topography Mission (SRTM) data, was used to calculate temperatures at the median altitude of each 5 arc-minute grid cell, compiled from detailed 3 arc-second (about 90 m at the equator) elevations.

Table 2-1 Base period climatic input variables used in the GAEZ v4 assessment

Variable	Units	Source
Mean monthly minimum temperature	ºC	Interpolated from CRU TS 3.21
Mean monthly maximum temperature	ºC	Interpolated from CRU TS 3.21
Sunshine fraction	%	Interpolated from CRU TS 3.21
Wind speed	m/s	Interpolated from CRU TS 3.21
Relative humidity	%	Interpolated from CRU TS 3.21
Precipitation	mm	Interpolated from GPCC v6
Daily deviation of Tmax from monthly mean	ºC	Compiled from WATCH
Daily deviation of Tmin from monthly mean	ºC	Compiled from WATCH
Share of daily in total monthly precipitation	%	Compiled from WATCH

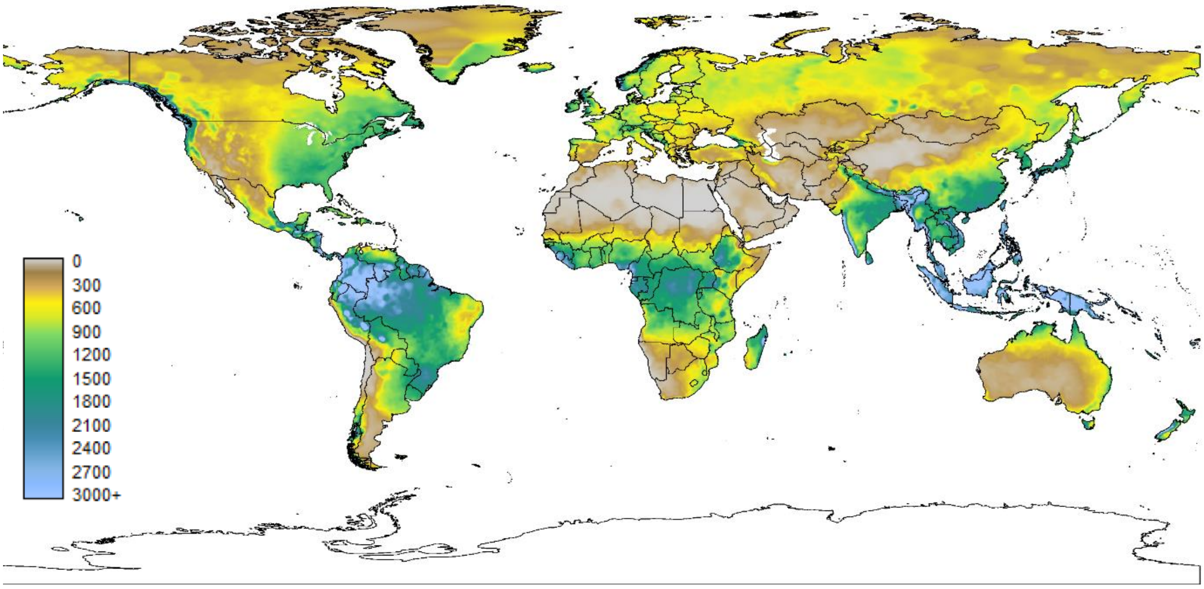
As an example of the gridded climate data, Figure 2-1 shows the average annual precipitation for the reference period (1981–2010). For comparison, Figure 2-2 shows the projected average annual precipitation in 2041–2070 for the ensemble mean of five earth system models under representative concentration pathway RCP8.5 (for an explanation of RCPs see also section 2.1.2 below).

Figure 2-1 Average annual precipitation (mm) in 1981–2010



Source: FAO and IIASA, 2021

Figure 2-2 Ensemble mean of average annual precipitation (mm) in 2070–2099, RCP8.5



Source: FAO and IIASA, 2021

The figures indicate that the global-scale pattern of annual precipitation will broadly persist into the future. There are, however, decreases of annual rainfall visible in the Mediterranean region and some increases occur at higher latitudes in Eurasia and North America. Note that global warming will substantially increase evaporative demand of vegetation, changes which are often larger than increases of rainfall, and will in some areas, notably in subtropical regions, result in a drying effect.

Climate scenarios

IPCC AR5 climate model outputs for four Representative Concentration Pathways (RCPs) are used to characterize a range of possible future climate distortions included in the agro-climatic resources inventory and crop potential assessments for the 2020's (period 2011–2040), the 2050's (period 2041–2070) and the 2080's (period 2070–2099). These climate model projections replace the SRES-based climate scenarios assessed in GAEZ v3.

Acknowledging the importance of the fundamental linkages between climate and socio-economic development, the climate change research community has been pursuing development of a new framework for the creation and use of scenarios to improve interdisciplinary analysis and assessments of climate change, its impacts, and response options. To define a range of future scenarios, this process includes a set of forcing pathways, known as the Representative Concentration Pathways (RCPs), which are combined with different possible Shared Socio-economic Development Pathways (SSPs) (Moss *et al.*, 2010; O'Neill *et al.*, 2017).

RCPs define dynamic greenhouse gas concentrations (not emissions) trajectories developed for the climate modelling community as a basis for long-term and near-term modelling experiments adopted by the IPCC for its fifth Assessment Report (AR5). The four RCPs used in GAEZ v4 together span the range of year 2100 radiative forcing values found in the open literature, i.e., from 2.6 W/m^2, achievable under stringent emission mitigation measures, to 8.5 W/m^2 associated by-and-large with fossil fuel intensive development assumptions. The four RCPs – RCP2.6, RCP4.5, RCP6, and RCP8.5 – are named after a possible level of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m^2, respectively). Development of RCPs has been completed and these pathways are documented in a special issue of Climatic Change (van Vuuren *et al.*, 2011), and climate model simulations based on them were undertaken as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor, Stouffer and Meehl, undated).

Multi-model ensembles for each of the climate forcing levels of the RCPs were analyzed based on spatial data from the IPCC's AR5 CMIP5 process. GAEZ v4 applies data which were bias-corrected and downscaled to 0.5 degree in the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel *et al.*, 2013). ISI-MIP data at half-degree resolution of five climate models (GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M) and for four RCPs (RCP 2.6, 4.5, 6.0 and 8.5) - totaling 20 combinations of respectively RCPs and climate models - were used to generate time series of climate input data in GAEZ v4 covering the period 2011 to 2099 and for compiling 30-year average climate attributes for the 2020s, 2050s and the 2080s. These new climate scenarios update/extend the 11 GCM/IPCC SRES emission scenario combinations that were applied in GAEZ v3.

Use of climate data in GAEZ

The 30-year average climate and year-by-year time series databases for the period 1960–2099 were used to quantify:

i. Agro-climatic indicators, such as the number of growing period days, thermal climate classification, moisture availability indices, net primary production, etc.;

ii. By crop/LUT agro-climatic potential crop yields, variability and related (yield optimizing) crop calendars and crop water requirements/deficits, and

iii. Ensemble mean data sets of agro-climatic indicators and potential crop yields by RCPs and three future 30–year periods.

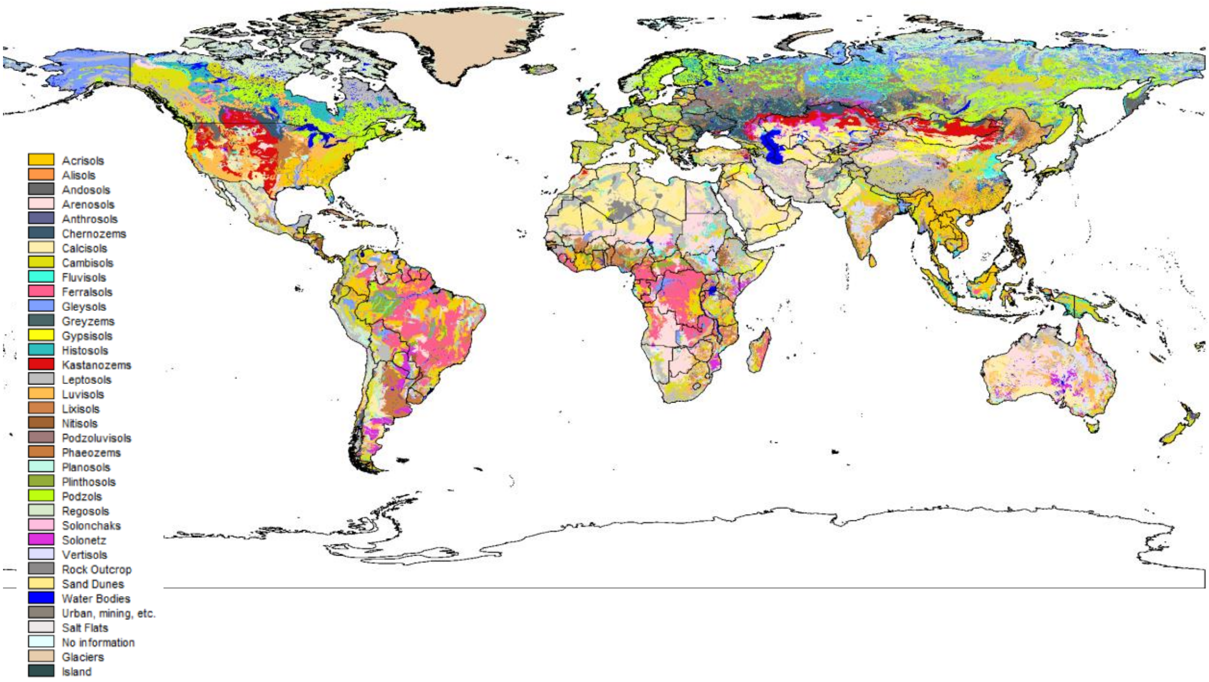
Soil and terrain data

GAEZ v4 includes an inventory of soil and terrain resources. Data are stored at a resolution of 30 arc-seconds, which represents the finest unit of analysis used in the global assessment.

Soil resources data

GAEZ v4 uses the Harmonized World Soil Database (HWSD v1.2.1) (Nachtergaele *et al.*, 2012) as source of soil resources data for spatially detailed evaluation of soil qualities and edaphic crop suitability. The HWSD is composed of a global level geographical layer containing reference to more than 16,000 map units linked to some 48,000 soil component records (Figure 2-3).

Figure 2-3 Harmonized World Soil Database (HWSD)



Source: Nachtergaele et al., 2012

This information is stored as a 30 arc-second soil map unit raster in GIS, linked to an attribute database stored in MS-Access format. Each HWSD record indicates soil type and soil phase information and includes 17 soil characteristics, each for two soil layers of respectively 0–30 cm and 30–100 cm soil depth.

For the purpose of use in GAEZ v4, the procedures for calculating water holding capacity of soils have been enhanced (see Chapter 6, section 6.5). Procedures for dealing with soil phases in cropland have been revisited and revised.

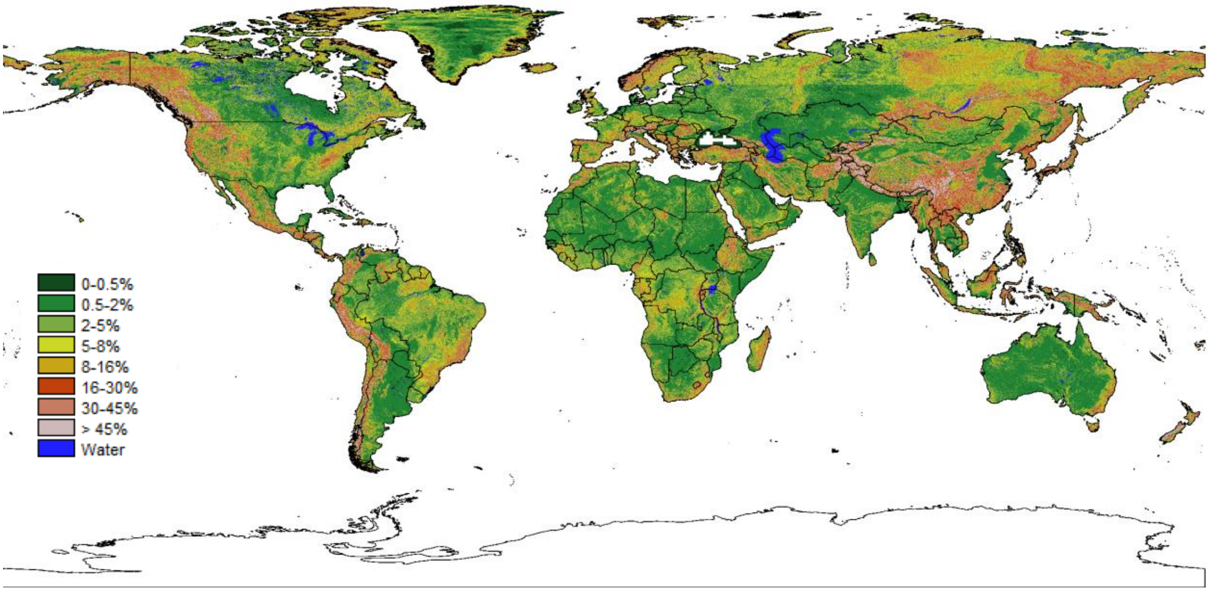
Elevation and terrain-slope data

The altitude and terrain slope database have been compiled using elevation data from the Shuttle Radar Topography Mission (SRTM). The SRTM data is available as 3 arc-second (about 90 x 90 meters at the equator) DEMs (e.g., CGIAR-CSI, 2006).

The elevation and terrain slope database comprise of the following elements:

- Elevation (m) by 3 arc-second grid-cells and related median altitude calculated for each 30 arc-second grid cell and 5 arc-minute grid cell of the GAEZ v4 inventory, and
- Terrain slopes (%) calculated at 3 arc-seconds and grouped into eight slope gradient classes of respectively 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.

Figure 2-4 Median slope class compiled from 3 arc-second SRTM data



Source: CGIAR-CSI, 2006

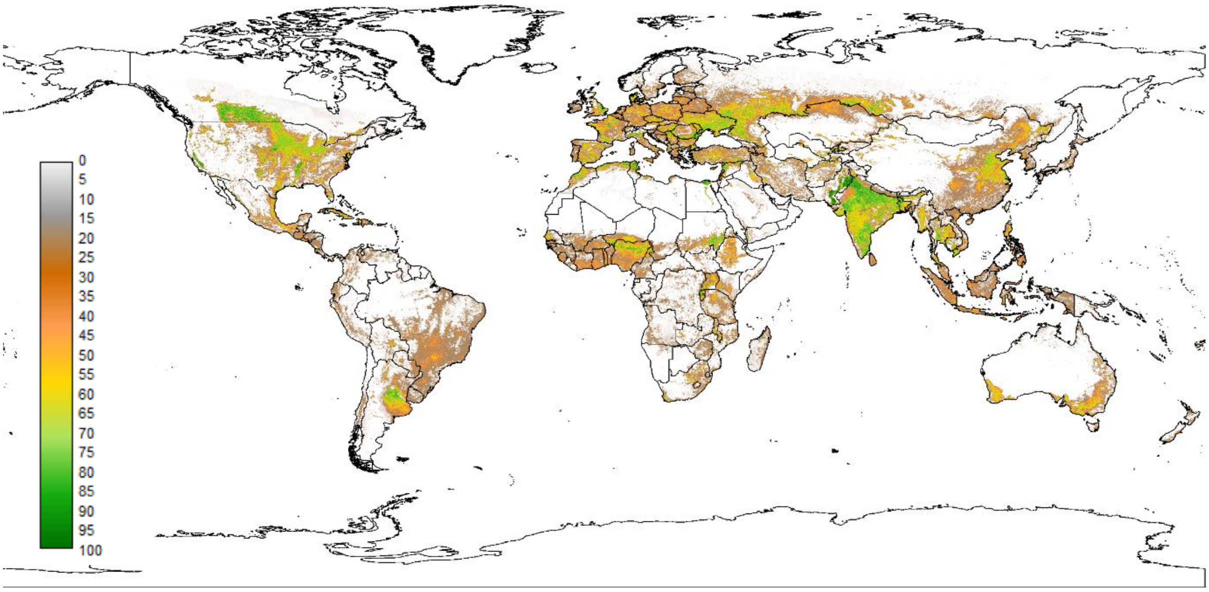
Note, the compilation of terrain slopes from 3 arc-second SRTM data results for each 30 arc-second grid cells in a distribution of the area in terms of the eight slope gradient classes (Figure 2-4). This feature is exploited in Module V (see Chapter 7) to partition each 30 arc-second grid cells into relevant soil/slope class components, which are each assessed separately for edaphic limitations.

Land cover data

GAEZ v4 makes use of the Global Land Cover-SHARE (GLC-Share), a global land cover database with spatial resolution of 30 arc-seconds (Latham *et al.*, 2014). GLC-Share was created by the Land and Water Division of FAO in partnership with and based on contributions from various institutions by a combination of "best available" high resolution national, regional and/or sub-national land cover databases. GLC-Share provides a set of eleven major thematic land cover layers with each layer presenting the proportion of the 30 arc-second pixels in the land cover class. The 11 aggregated land cover classes are: artificial surfaces (01), cropland (02), grassland (03), tree covered areas (04), shrubs covered areas (05), herbaceous vegetation, aquatic or regularly flooded (06), mangroves (07), sparse vegetation (08), bare soil (09), snow and glaciers (10), and water bodies (11).

The major benefit of the GLC-Share product is that it combines its global extent with a capacity to preserve the available land cover information at the country level obtained by spatial and multi-temporal source data. Thus, the high accuracy obtained at national level by local mapping agencies and/or national projects at a more detailed scale is integrated with the best synthesis of global satellite-based, but less validated, datasets in areas where no better national data are available. Harmonization of the various available land cover databases is based on the Land Cover Classification System (LCCS) (FAO, 2005).

Figure 2-5 Distribution and intensity of cropland in GLC-Share (% of 30 arc-second grid cell)



Source: Latham et al., 2014

In GAEZ v4 cropland shares were calibrated with national and sub-national agricultural statistics of 2009–2011 (mainly FAOSTAT arable land and land under permanent crops). The GAEZ v4 land cover layers include also information of the Global Map of Irrigated Areas (GMIA version 5), i.e., land equipped for irrigation (Siebert *et al.*, 2013). In addition, the 5 arc-minute GMIA, version 5 (released in October 2013) has been used for its provision of data layers indicating water source of irrigation (surface water, groundwater, other) and spatial estimates of actually irrigated areas. In 2015 the GLC-Share database used in GAEZ has been updated with latest data on built-up areas and inland water and the remaining land cover shares were adjusted proportionally in each grid cell in order to maintain consistency. Figure 2-5 shows an example of land cover data in GLC-Share.

The GLC-Share and GMIA v5 databases provide key inputs for the downscaling procedures used in Module VI (see Chapter 8) to spatially allocate actual statistical production of the period 2009–11.

Observed phenology and crop calendars

As part of the GAEZ v4 update, additional data was collected to compare AEZ generated beginning and ending dates of growing seasons with available remote sensing phenology data and with published actual crop calendar data available from FAO.

Actual crop calendars often reflect traditional crop management practices, consider agronomic requirements of multi-cropping conditions in regions with two or more growing seasons (e.g. South and East Asia), and possibly of local marketing and socio-economic constraints. It is therefore useful and important that the AEZ modeling framework can be set up to simulate crop potentials for time windows defined according to actual crop calendars and to compare 'optimal' crop calendars as generated in GAEZ Module II (see Chapter 4) with actual crop calendars observed in the field.

Population distribution

Gridded population distribution (Oak Ridge National Laboratory, 2013) is used to relate spatial population numbers with availability of agro-resources and to estimate rural housing and infrastructure land requirements (in addition to artificial surfaces mapped in GLC-Share). The 30 arc-second population raster used in GAEZ v4 was compiled at FAO, based on LandScan (Oak Ridge National Laboratory, 2013) spatial data and with calibration to match UN population statistics of 2009–2011 available by country.

Livestock distribution

Livestock distribution data in GAEZ v4 is represented by the 30 arc-second resolution raster maps of the Gridded Livestock of the World database (GLW 2.01; released in May 2014) available from FAO GeoNetwork. The compilation methodology and data sources are described in the report Mapping the Global Distribution of Livestock (Robinson *et al.*, 2014).

The GLW reports heads of cattle, sheep, goats and other animals per grid-cell. A practical example, where the results of grassland productivity simulated in GAEZ v4 have been combined with spatially detailed ruminant livestock numbers and with crop residues available from cropland production downscaled in GAEZ v4, can be found in Fischer *et al.* (2019), to determine land requirements for grazing livestock and to estimate the extent and intensity of grass/shrub land that may be available for other uses such as commercial biofuel feedstock production.

GAEZ v4 'exclusion' layer

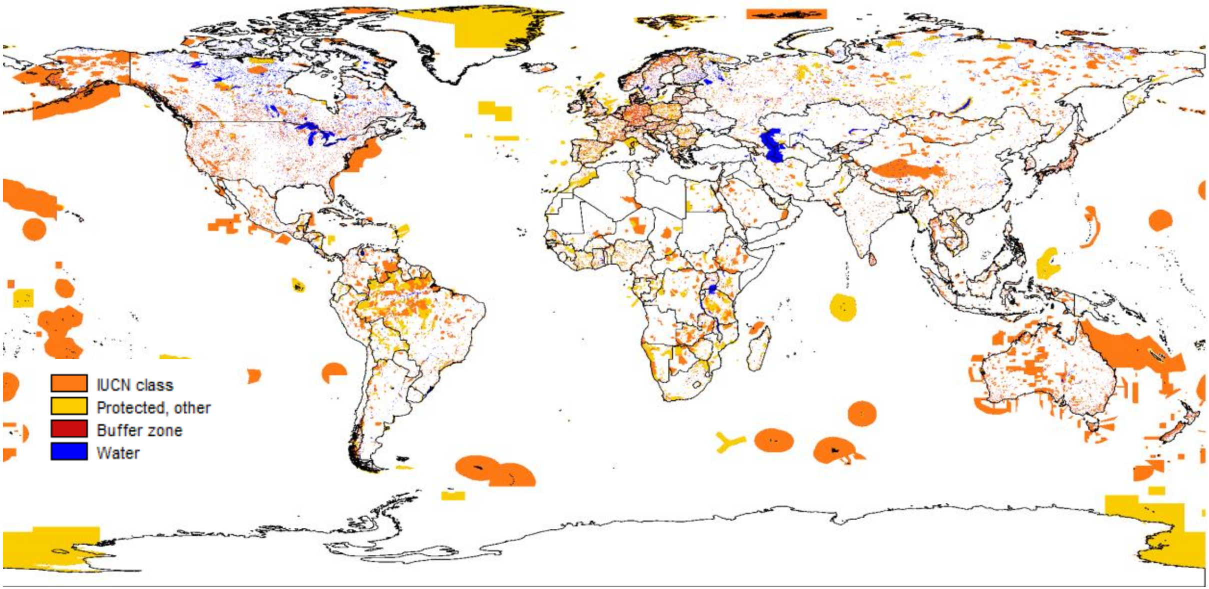
Land has many important functions. GAEZ outputs emphasize the suitability of land for crop production. Planning for more and better food supplies, produced with fewer resources, causing less environmental impacts and safeguarding biodiversity, will have to continue with high priority in the next decades. Current GAEZ v4 respects land marked by a protection/exclusion status or with recognized biodiversity value. It applies in Module V (see Chapter 7) an 'exclusion' layer, which has been compiled from three up-to-date and authoritative international datasets, the World Database of Protected Areas (UNEP-WCMC and IUCN, 2017), the World Database of Key Biodiversity Areas (BirdLife International, 2017) and the Global Lakes and Wetlands Database (Lehner and Döll, 2004a).

World Database of Protected Areas (WDPA)

The World Database on Protected Areas (WDPA) is the most comprehensive global database of marine and terrestrial protected areas. It is a joint project between UN Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN), and is managed by UN Environment Programme World Conservation Monitoring Centre (UNEP-WCMC), in collaboration with governments, non-governmental organisations, academia and industry. The WDPA is updated on a monthly basis. In October 2010, UNEP-WCMC launched the social media-based website *Protected Planet*, which allows users to interact with and improve the data that is currently recorded on the World Database on Protected Areas.

The resource database of GAEZ v4 includes data of the October 2017 update of WDPA. This release had in total 234,468 protected area records comprising of 216,026 polygons and 18,442 point, covering 245 countries and territories. For use in GAEZ v4, all polygons were summarized into two classes depending on whether the category field in the database indicated one of the established IUCN categories (class 1) or not (class 2). The polygon data were rasterized at 30 arc-seconds and a narrow buffer of 30 arc-seconds was drawn around each protected area (class 3). Figure 2-6 shows the protected area raster map utilized in the GAEZ v4 land resources inventory.

Figure 2-6 Protected area raster data extracted from WDPA 2017



Source: WDPA

The World Database of Key Biodiversity Areas (KBA)

Key Biodiversity Areas (KBAs) are sites that contribute significantly to the global persistence of biodiversity. Quoting KBA Standards and Appeals Committee (IUCN, 2019): "The criteria used to identify KBAs incorporate elements of biodiversity across genetic, species and ecosystem levels, and are applicable to terrestrial, freshwater, marine and subterranean systems. KBAs have delineated boundaries and are actually or potentially manageable as a unit. KBAs provide an effective bridge between assessment processes and conservation planning and an important step towards conservation action. However, the process of KBA identification and delineation does not include steps to advance management activity and does not imply that any specific conservation action, such as protected area designation, is required." The 2017 update of the World Database of Key Biodiversity Areas includes more than 15,000 polygons of delineated KBAs. The GAEZ v4 'exclusion' layer includes an inventory of KBA locations outside WDPA protected areas in order to draw attention to recognized high biodiversity values when assessing land for potential agricultural production.

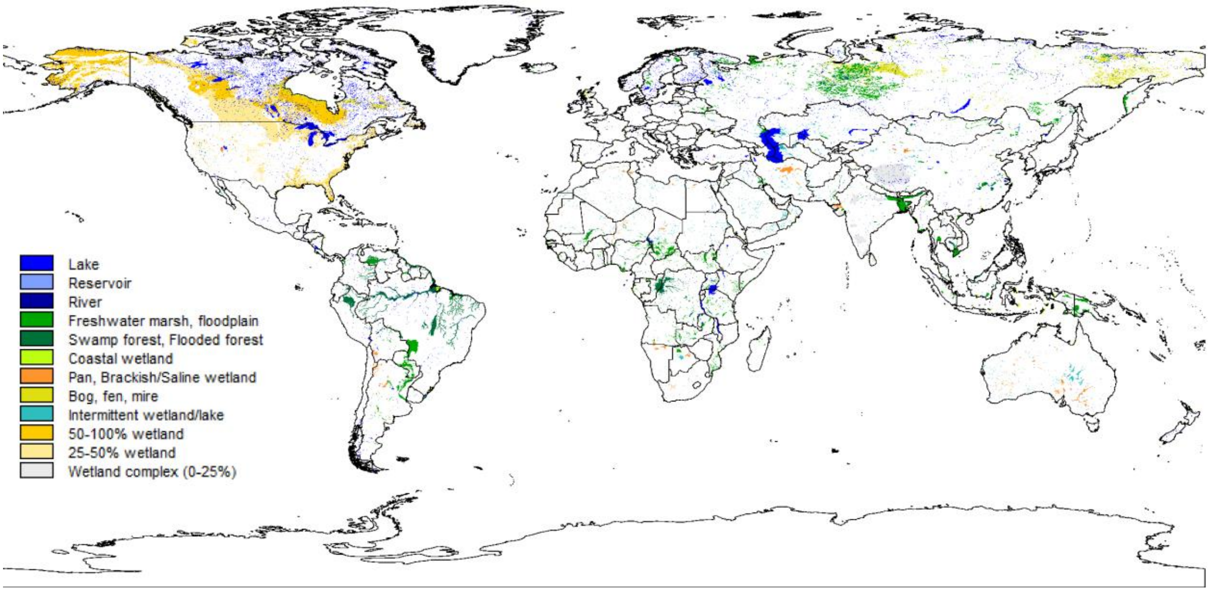
Global Lakes and Wetlands Database (GLWD)

Drawing upon a variety of existing maps, data and information, WWF and the Center for Environmental Systems Research, University of Kassel, Germany created the Global Lakes and Wetlands Database (GLWD). The database focuses in three coordinated levels on (L1) large lakes and reservoirs, (L2) smaller water bodies, and (L3) wetlands (Lehner and Döll, 2004b).

GAEZ v4 incorporates GLWD Level 3 data (GLWD-3) which comprises lakes, reservoirs, rivers and different wetland types in the form of a global raster map at 30 arc-second resolution. The GLWD-3 dataset has 12 classes as follows: (1) Lake; (2) Reservoir; (3) River; (4) Freshwater Marsh, Floodplain; (5) Swamp Forest, Flooded Forest; (6) Coastal Wetland (incl. Mangrove, Estuary, Delta, Lagoon); (7) Pan, Brackish/Saline Wetland; (8) Bog, Fen, Mire (Peatland); (9)

Intermittent Wetland/Lake; (10) 50–100% Wetland; (11) 25–50% Wetland; (12) 0–25% Wetland. Figure 2-7 shows the classes if the GLWD raster map utilized in the GAEZ v4 land resources inventory.

Figure 2-7 Global Lakes and Wetland Database, Level 3 (GLWD-3)



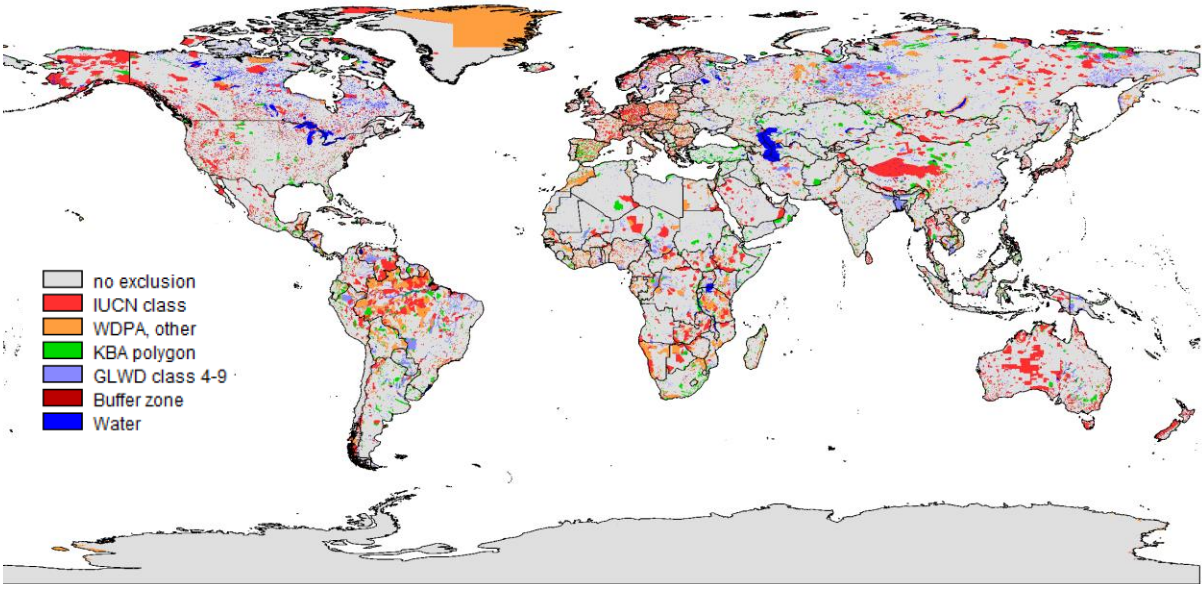
Source: GLWD

Compilation of the GAEZ v4 'exclusion' layer

An 'exclusion' layer, to mark land with a protection status or with high biodiversity value, has been compiled from the three data sources introduced in the previous sections, namely the World Database of Protected Areas, the World Database of Key Biodiversity Areas and the Global Lakes and Wetlands Database. Both the WDPA and KBA databases were obtained in October 2017.

The 'exclusion' layer distinguishes six classes at 30 arc-seconds resolution, which were defined in a hierarchical step by step procedure. In a first step all grid cells with protection status were extracted from WDPA and recorded in two classes (depending on whether an IUCN category was indicated or not). Second, additional grid cells were extracted for locations marked as falling into a KBA polygon. The third step marked grid cells outside protected areas and KBA polygons which were part of GLWD-3 classes 4 to 9. In a last step grid cells recorded as (30 arc-second wide) buffer zones around protected areas (see description in section 2.7.1 above) were included in the 'exclusion' layer if not already assigned a class value by the previous steps. All remaining land is indicated in the exclusion layer as 'no exclusion' class. The six classes are as follows: (1) No exclusion; (2) IUCN category in WDPA; (3) WDPA, not an IUCN category; (4) KBA, outside WDPA protected area; (5) GLWD-3 class 4–9, outside protected area and KBA polygon; and (6) Buffer zone around protected area. The classes of the GAEZ v4 'exclusion' layer are shown in Figure 2-8.

Figure 2-8 GAEZ v4 'exclusion' layer of protected areas and land with high biodiversity values



Source: FAO and IIASA, 2021

Administrative and hydro-basin layers

Two types of geographical layers at 30 arc-seconds are used for data aggregation and for preparing crop summary and statistical tables of results. Gridded maps of the Global Administrative Unit Layers (GAUL) updated in 2015 (FAO 2007b, 2015) are used for reporting at country and sub-national levels and hydrological basin boundaries are used to report with regard to water resources and (potential) irrigation water demand.

The GAUL is the best available information on administrative units for all the countries in the world, providing a contribution to the standardization of the spatial dataset representing administrative units. The GAUL always maintains global layers with a unified coding system at country, first (e.g. provinces, departments) and second administrative levels (e.g. districts).

Hydrological basin boundaries used in GAEZ v4 are based on the spatial units delineated in World Map of Major Hydrological Basins (FAO, 2011). This dataset was obtained at FAO by delineating drainage basin boundaries from hydrologically corrected elevation data. Input data resolution was 15 arc-seconds between 60 N and 60 S latitude (based on SRTM), and 30 arc-seconds for higher latitudes (based on GTOPO30). The dataset was developed as part of an assessment of water resources and is also part of the SOLAW (Status of Land and Water Resources for Food and Agriculture) Report.

Agricultural area and production statistics

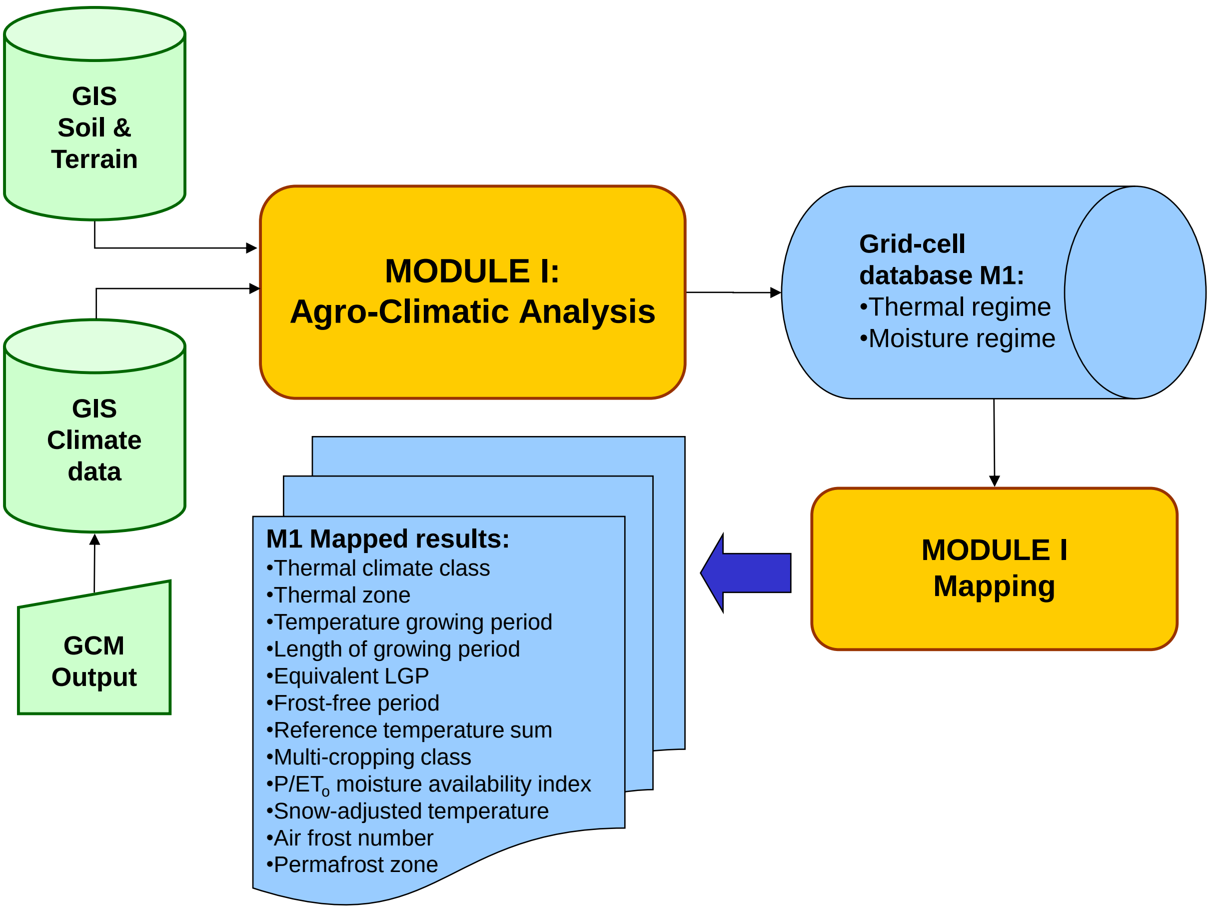
In this GAEZ v4 national and sub-national statistical data of crop area and production around year 2010 (e.g., FAOSTAT average of period 2009–2011) and attributed to spatial resource data and land cover layers. Country-level statistics are provided in FAOSTAT and AQUASTAT and in sub-national distributions of crop harvested areas and relative yields available from AGROMAPS and various national statistical sources for many countries and selected years (period 2009–2011).

3. Module I (Agro-climatic analysis)

Overview Module I

The main purpose of Module I is the compilation of a geo-referenced climatic resources inventory providing a variety of relevant agro-climatic indicators. They give a general characterization of climatic resources and of their suitability for agricultural use. Once generated in Module I, several agro-climatic layers are then used as input for estimation of crop yields and production in Module II (Biomass and yield), quantification of agro-climatic constraints in Module III and for estimating agro-ecological suitability and attainable yields in Module V (integration of climatic and edaphic evaluation). Figure 3-1 provides a brief overview of the information flow in Module I.

Figure 3-1 Information flow in Module I



Preparation of climatic variables

Monthly and daily climatic variables are used in GAEZ for the calculation of soil water balances and agro-climatic indicators relevant to plant production. Below we summarize some key variables simulated in Module I.

Day-time and night-time temperatures

The temperatures during day-time (*Tday*, °C) and night-time (*Tnight*, °C) are calculated as follows:

$$Tday = Ta + \left(\frac{Tx - Tn}{4\pi}\right) \times \left(\frac{11 + T_0}{12 - T_0}\right) \times \sin\left(\pi \times \left(\frac{11 - T_0}{11 + T_0}\right)\right)$$

Night-time temperature is calculated as:

$$Tnight = Ta - \left(\frac{Tx - Tn}{4\pi}\right) \times \left(\frac{11 + T_0}{T_0}\right) \times \sin\left(\pi \times \left(\frac{11 - T_0}{11 + T_0}\right)\right)$$

where *Ta* is average 24-hour temperature, *Tx* and *Tn* are maximum and minimum daily temperature, and T_0 is calculated as a function of day-length (DL, hours).

$$T_0 = 12 - 0.5 \times DL$$

Day-length is calculated in the model and is a function of the latitude of a grid-cell and depends on the day of the year.

Reference evapotranspiration (ETo)

The reference evapotranspiration (*ETo*) represents evapotranspiration from a defined reference surface, which closely resembles an extensive surface of green, well-watered grass of uniform height (12 cm), actively growing and completely shading the ground. GAEZ calculates *ETo* from the attributes in the climate database for each grid-cell according to the Penman-Monteith equation (Allen *et al.*, 1998; Doorenbos and Pruitt, 1977; Monteith, 1965, 1981). A description of the implementation of the Penmann-Monteith equations in GAEZ is provided in Appendix 3-1.

Maximum evapotranspiration (ETm)

In Module I, the calculation of maximum evapotranspiration (*ETm*) for a 'reference crop' assumes that sufficient water is available for uptake in the rooting zone. The value of *ETm* is related to *ETo* through applying crop coefficients for water requirement (Kc), reflecting phenological development and leaf area. The Kc values are crop and climate specific. They vary generally between 0.3–0.5 at initial crop stages (emergence) to 1.0–1.2 at reproductive stages.

$$ETm = Kc \times ETo$$

For the reference crop as modeled in GAEZ, values of *Kc* depend on the thermal characteristics of a grid cell. For locations with a year-round temperature growing period, i.e., when average daily temperature stays above 5^{0}C for the entire year, the *Kc* value applied for the reference crop is always 1.0. When the temperature growing period is < 365 days, the *Kc* value increases linearly from 0.4 at the start of the temperature growing period until reaching the reference value 1.0 after 30 days to account for increasing water demand as the crop canopy develops after the cold period. When assessing specific crops, as is done in Module II, empirically determined *Kc* values for the calculation of crop specific *ETm* are available from various sources (Allen *et al.*, 1998) and differ by the development stage of the crop (see section 4.5.1).

Actual evapotranspiration (ETa)

The actual uptake of water by the 'reference' crop is characterized by the actual evapotranspiration (*ETa*, mm/day) resulting in the daily calculations of the reference crop water balance. The calculation of *ETa* differentiates two possible cases depending on the availability of water for plant extraction:

i. Adequate soil water availability (*ETa*=*ETm*), and
ii. Limiting soil water availability (*ETa*<*ETm*).

When water is not limiting, the *ETa* value is equal to the maximum evapotranspiration (*ETm*) of the 'reference' crop. At limiting water conditions, *ETa* is a fraction of *ETm*, depending on soil water availability as explained in following sections.

<u>ETa for adequate soil water availability</u>

The value of *ETa* is set to be equal to *ETm* as long as the water balance (*Wb*) is above or equal the threshold of "readily" available soil water (*Wr*). This characterizes a situation when crops are able to "easily" extract sufficient water and therefore no water stress occurs. The potentially total available soil moisture *Wx* is the product of total available soil water holding capacity (*Sa*) and rooting depth (*D*). In the operation of Module I the rooting depth *D* in the reference water balance is assumed to be 1 m. The share of *Wx* below which soil moisture starts to become difficult to extract is referred to as 'p', the soil moisture depletion fraction. The fraction *p* varies with the evaporative demand of the atmosphere, crop type, and soil characteristics. Estimates are available from various sources (FAO 1998). The value of *p* normally varies from 0.3 for shallow rooted plants at high rates of *ETm* (>8 mm/day) to 0.7 for deep-rooted plants at low rates of *ETm* (<3 mm/day). In general, the value of *p* declines with increasing evaporative demand. The threshold of readily available soil moisture is in turn calculated from *Wx* and the soil moisture depletion fraction (*p*).

$$Wx = Sa \times D$$

$$Wr = Wx \times (1 - p)$$

A condition of 'adequate soil moisture availability' is defined when (i) daily precipitation (*P*) is greater or equal to *ETm* and/or (ii) precipitation *P* plus the difference between water balance (*Wb*) and threshold of readily available water (*Wr*) is greater than *ETm*. These conditions imply that there is sufficient "easily" extractable water to meet the crop water demand (*ETm*):

$$ETa = ETm$$

when

$$P \geq ETm$$

or when

$$P < ETm \text{ but } P + Wb - Wr > ETm.$$

ETa calculation for limited soil water availability

When soil water is limiting, i.e., when above conditions are not met and $P + Wb - Wr < ETm$, then *ETa* falls short of *ETm*. In this case, *ETa* is calculated as a fraction ρ of *ETm*. The variable ρ is the ratio of current water balance (*Wb*) and the threshold of readily available soil water (*Wr*).

$$\rho = \frac{Wb}{Wr}$$

ETa is then calculated as daily precipitation *P* plus the ρ fraction of *ETm*.

$$ETa = P + \rho \times ETm$$

This procedure assumes rainfall is immediately available to plants on the day of precipitation, prior to replenishing soil moisture.

Snow balance calculation

In seasonally cold climates the calculation of a snow balance (*Sb*, mm) affects the water balance procedure outlined above. The snow balance increases when precipitation falls as snow and decreases with snowmelt and snow sublimation. Precipitation (*P*) is assumed to fall as snow (P^{snow}) when maximum temperature (*Tx*) is below a certain temperature threshold (*Ts*).

Snowmelt (*Sm*) is calculated as a function of daily maximum temperature, the snow melt parameter (δ) and depends on the previously accumulated snow balance. The snow melt factor δ is set to 5.5 mm/°C.

$$Sm = \min(\delta \times (Tx - Ts), Sb)$$

The sublimation factor (*ks*) is used to discount a fraction of maximum evapotranspiration as sublimated snow. This fraction (*ks*ETm*) is subtracted from the snow balance:

$$Sb_j = Sb_{j-1} - Sm - (ks \times ETm) + P^{snow}$$

The sublimation factor (*ks*) is assumed to be 0, 0.1 or 0.2 of reference evapotranspiration (*ETm*, mm), depending temperature:

$ks = 0.0$, when $Tx < Ts$; Ts is assumed as 0^0C in GAEZ

$$ks = 0.1, \text{ when } Tx > Ts \text{ and } Ta < 0^0\text{C}$$

$$ks = 0.2, \text{ when } Tx > Ts \text{ and } 0^0\text{C} < Ta < 5^0\text{C}$$

Once the water balance for the 'reference crop' is calculated, five important indicators are generated. These are:

1. Maximum evapotranspiration of 'reference' crop (*ETm*);
2. Actual evapotranspiration of 'reference' crop (*ETa*);
3. Water balance for 'reference' crop (*Wb*);
4. Snow balance (*Sb*), and
5. Excess water of 'reference' crop water balance (*We*).

After simulating the water balance for the 'reference' crop in Module I, various raster maps of related variables are produced and used for further computations in subsequent AEZ modules.

Thermal regimes

Temperature is a major determinant of crop growth and development. In GAEZ, the effect of temperature on crops is characterized in each grid-cell by thermal regimes. Thermal regimes are represented by six types of indicators: (i) thermal climates; (ii) thermal zones; (iii) length of temperature growing periods; (iv) accumulated temperature sums, (v) temperature profiles, and (vi) permafrost zones.

Thermal climates

Latitudinal thermal climates provide a classification that is used in Module II for the assessment of potential crop-LUT presence in each grid cell. The delineation of thermal climates (Table 3-1) is based on (i) the average monthly temperature, (ii) proportions of respectively summer, winter rainfall[3], and (iii) the temperature amplitude as a measure of continentality (i.e., difference between temperatures of warmest and coldest month). Thermal climates are derived from monthly temperatures corrected to "sea level temperature" with a fixed lapse rate of 0.55^0C/100m. There is a further subdivision for rainfall seasonality in the subtropics and for temperature amplitude in temperate and boreal zones (Figure 3-2). In this way, latitudinal climates approximate temperature seasonality and ranges of prevailing day-lengths, which is used as a proxy for matching short-day, day-neutral and long-day crop requirements.

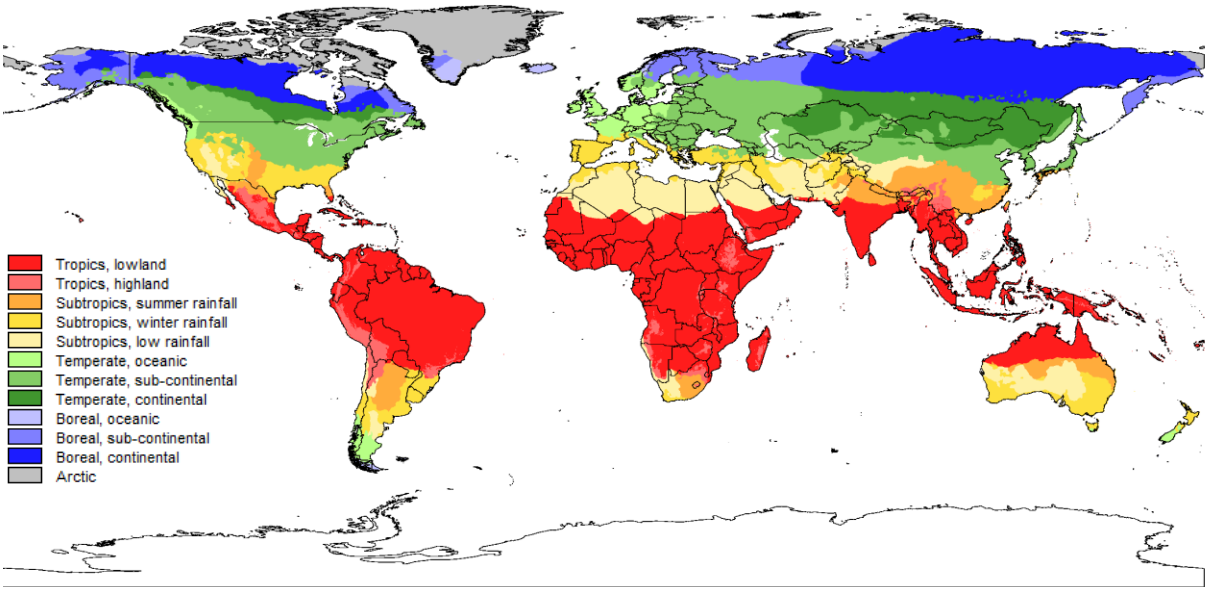
[3] Rainfall has been represented with summer respectively, winter P/ETo ratios.

Table 3-1 Classification of thermal climates

Climate	Rainfall and temperature seasonality
Thermal climate classification Thermal climates are derived from monthly temperatures corrected to sea level. The thermal climates have been subdivided for rainfall seasonality in the subtropics and for temperature seasonality in temperate and boreal zones. The tropics have been subdivided in lowland and highland zones.	
Tropics All months with monthly mean temperatures, corrected to sea level, above 18°C	**Tropical lowland:** Tropics with actual mean temperatures above 20°C **Tropical highland:** Tropics with actual mean temperatures below 20°C
Subtropics One or more months with monthly mean temperatures, corrected to sea level, below 18°C, but all above 5°C, and 8–12 months above 10°C	**Subtropics summer rainfall** Northern hemisphere: P/ETo in April-September ≥ P/ETo in October-March. Southern hemisphere: P/ETo in October-March ≥ P/ETo in April-September **Subtropics winter rainfall** Northern hemisphere: P/ETo in October-March ≥P/ETo in April-September. Southern hemisphere: P/ETo in April-September ≥ P/ETo in October-March **Subtropics low rainfall:** Annual rainfall less than 250 mm
Temperate At least one month with monthly mean temperatures, corrected to sea level, below 5°C and four or more months above 10°C	**Oceanic temperate:** Seasonality less than 20°C* **Sub-continental temperate**: Seasonality 20–35°C* **Continental temperate:** Seasonality more than 35°C*
Boreal At least one month with monthly mean temperatures, corrected to sea level, below 5°C and 1–3 months above 10°C	**Oceanic boreal:** Seasonality less than 20°C* **Sub-continental boreal**: Seasonality 20–35°C* **Continental boreal:** Seasonality more than 35°C*
Arctic All months with monthly mean temperatures, corrected to sea level, below 10°C	**Arctic**

**Seasonality refers to the difference in mean temperature of the warmest and coldest month*

Figure 3-2 Thermal climates, climate of 1981–2010

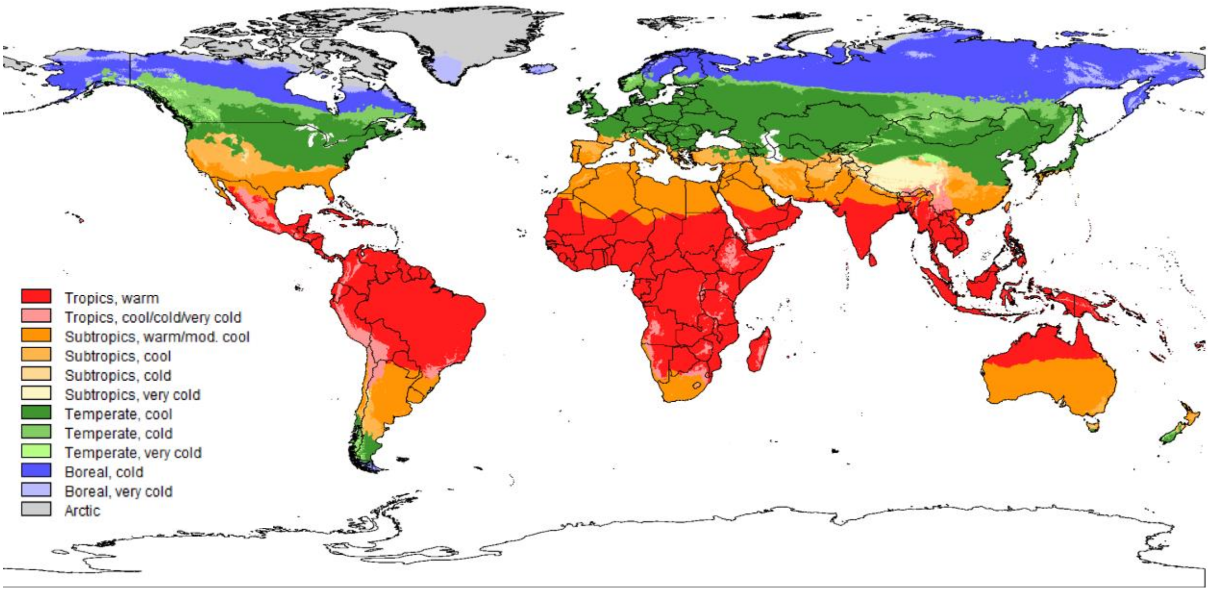


Source: FAO and IIASA, 2021

Thermal zones

Thermal zones, which are based on actual temperatures, reflect the prevailing temperature regimes of major thermal climates. An example for climate of 1981–2010 is presented in Figure 3-3:

Figure 3-3 Thermal zones, climate of 1981–2010



Source: FAO and IIASA, 2021

i. ***Warm*** in tropical zones refers to annual mean temperatures above 20^{0}C, *cool, cold, very cold* tropics refers to annual mean temperature below 20^{0}C;

ii. ***Moderately cool*** refers to actual temperature conditions characterized by one or more months with monthly average temperatures below 18^{0}C but all above 5^{0}C and 8–12 months above 10^{0}C;

iii. ***Cool*** refers to conditions with at least one month with monthly mean temperatures below 5^{0}C and four or more months above 10^{0}C;

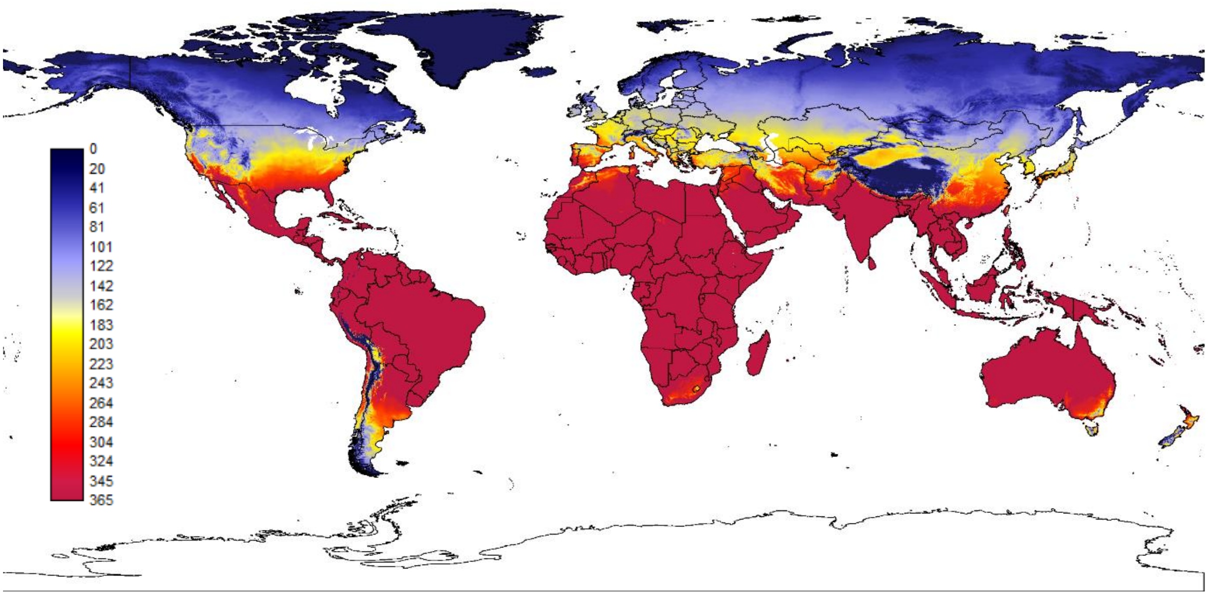
iv. ***Cold*** refers to conditions with at least one month with monthly mean temperatures below 5^{0}C and 1–3 months above 10^{0}C, and

v. **V*ery cold*** refers to polar conditions i.e., all months with monthly mean temperatures below 10^{0}C.

Temperature growing periods (LGP_t)

The time during the year when daily temperatures are conducive to crop growth and development is represented in AEZ by temperature growing periods. The length of the 'temperature growing period' (LGP_t) is calculated as the number of days in the year when average daily temperature (Ta) is above a temperature threshold "t". In AEZ three standard temperature thresholds for temperature growing periods are used: (i) periods with Ta > 0^{0}C (LGP_{t0}), (ii) periods with Ta > 5^{0}C (LGP_{t5}), which is considered as the period conducive to plant growth and development, and (iii) periods with Ta > 10^{0}C (LGP_{t10}), which is used as a proxy for the period of low risks for late and early frost occurrences and termed 'frost-free period' (Figure 3-4).

Figure 3-4 'Frost-free' period (LGP_{t10}, days), climate of 1981–2010



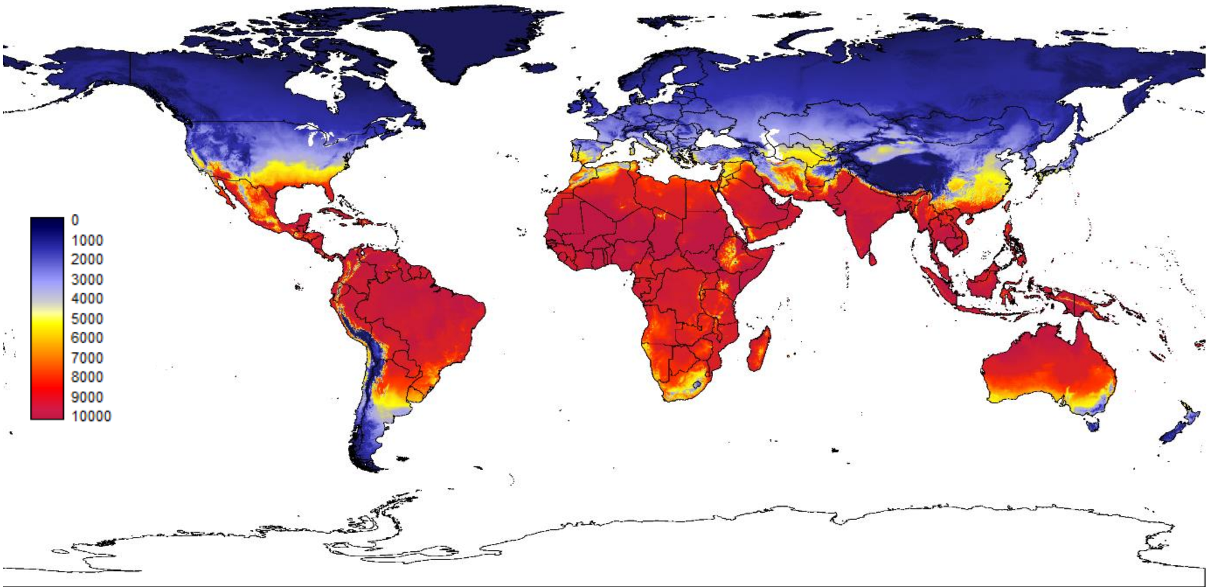
Source: FAO and IIASA, 2021

Accumulated temperature sums (TS)

For crop suitability assessments, individual crop/LUT heat unit requirements are matched with temperature sums during the crop/LUT growth cycle duration, defined as the sum of mean daily temperatures calculated from a base temperature of 0^0C, resulting in optimum, sub-optimum or non-suitable ranges (Figure 3-5).

Heat requirements of crops are expressed in accumulated temperatures. Reference temperature sums (TS) are calculated for each grid-cell by accumulating daily average temperatures (Ta) for days when Ta is above the respective threshold "t" as follows: (i) 0^0C (TS_0), (ii) 5^0C (TS_5), and (iii) 10^0C (TS_{10}).

Figure 3-5 Temperature sums for the period with Ta>10⁰C, climate of 1981–2010



Source: FAO and IIASA, 2021

Temperature profiles

Temperature profiles (Table 3-2) are defined in terms of 9 classes of "temperature ranges" for days with Ta <-5^0C to >30^0C (at 5^0C intervals) in combination with distinguishing increasing and decreasing temperature trends within the year. In Module II of GAEZ, these temperature profiles are matched with crop-specific temperature profile requirements providing either optimum match, sub-optimum match or assessing a crop as not suitable for the respective location.

Table 3-2 Temperature profile classes

Average temperature	Temperature trend	
(Ta, °C)	Increasing	Decreasing
> 30	A1	B1
25–30	A2	B2
20–25	A3	B3
15–20	A4	B4
10–15	A5	B5
5–10	A6	B6
0–5	A7	B7
-5–0	A8	B8
< -5	A9	B9

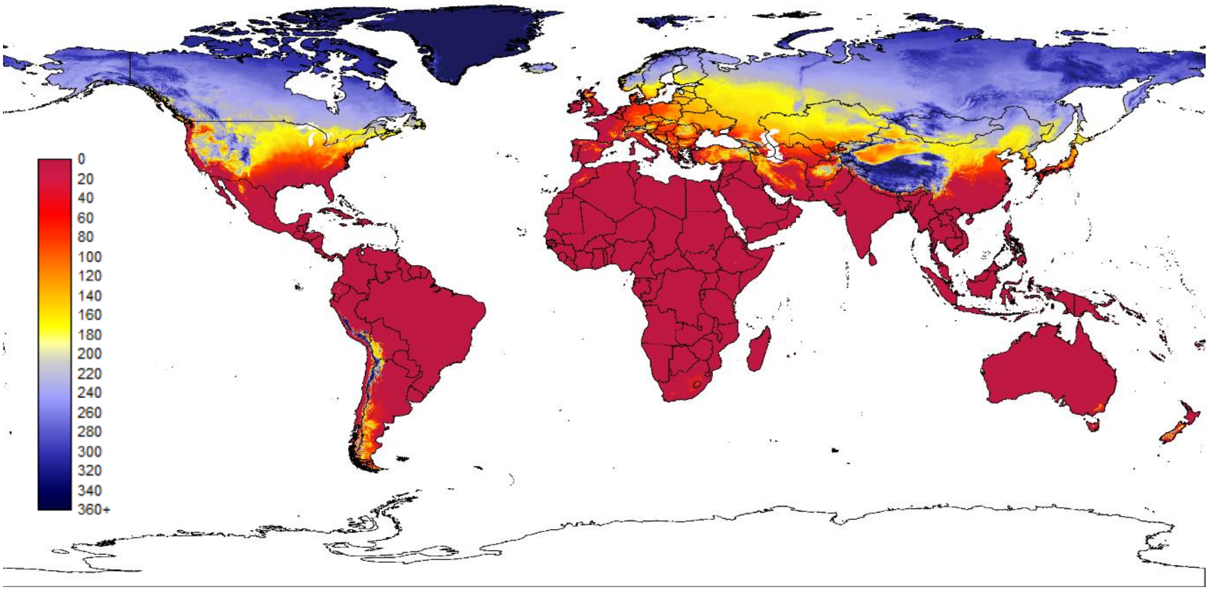
Extreme temperature events

Daily data of minimum and maximum temperatures are used in GAEZ to compute various statistics of extreme temperature events. Several indicators are calculated to capture the risk of occurrence of high temperature events. For instance, the agro-climatic analysis produces a count of the number of 'hot' days, here defined as days when daily maximum temperature exceeds 35^{0}C, which is indicative of periods when temperature may damage development and yields of cool-loving crops such as wheat. Besides 'hot' days (Tmax > 35^{0}C), the module also counts the annual number of days with maximum temperature above 30^{0}C, 40^{0}C and 45^{0}C. Among these, the GAEZ analysis produces a count of 'very hot' days, defined as daily maximum temperature exceeding 40^{0}C. These thresholds were chosen to indicate periods when even thermophilic crops like maize may suffer from high temperatures.

Number of 'frost' days (with Tmin < 0°C)

On the cold side of the temperature range in a grid-cell, one such index of interest to planning in agriculture counts the number of 'frost' days in a year, defined here as days when minimum daily temperature falls below 0°C. A map showing the average number of annual 'frost' days during 1981–2010 is given in Figure 3-6. The module also counts the annual number of days when minimum temperature falls below respectively 5^{0}C, 10^{0}C, 15^{0}C and 20^{0}C.

Figure 3-6 Average annual number of days with frost, average for period 1981–2010



Source: FAO and IIASA, 2021

Permafrost evaluation

Occurrence of continuous or discontinuous permafrost conditions are used in the suitability assessment. Permafrost areas are characterized by sub-soil at or below the freezing point for two or more years. Permafrost or 'gelic' soils are considered unsuitable for crops and therefore their identification is essential for the land resources assessment in GAEZ. Average air temperature and the physical and chemical characteristics of the soils are the main features influencing the presence of permafrost. Consequently, GAEZ considers permafrost in two ways: (i) it determines different reference permafrost zones based on climatic conditions, and (ii) it relies on soil classification; soils with a 'gelic' connotation within or outside permafrost zones are considered to belong to the continuous permafrost zone.

In GAEZ, the procedures proposed by Nelson and Outcalt (1987) are applied to calculate an air Frost Index (FI) which is used to characterize climate-derived permafrost conditions into four classes:

i. Continuous permafrost;

ii. Discontinuous permafrost;

iii. Sporadic permafrost, and

iv. No permafrost.

Reference permafrost zones are determined based on prevailing daily mean air temperature (Ta). The air frost index (FI) is calculated and used to characterize permafrost areas. For this calculation, accumulated degree-days, above and below 0^{0}C, are used to calculate the thawing index (DDT) and the freezing index (DDF).

The thawing index DDT is calculated as:

$$DDT = \sum Ta \text{, for months when Ta > } 0^0\text{C}$$

The freezing index (DDF) is calculated as:

$$DDF = -\sum Ta \text{, when monthly Ta} \leq 0^0\text{C}$$

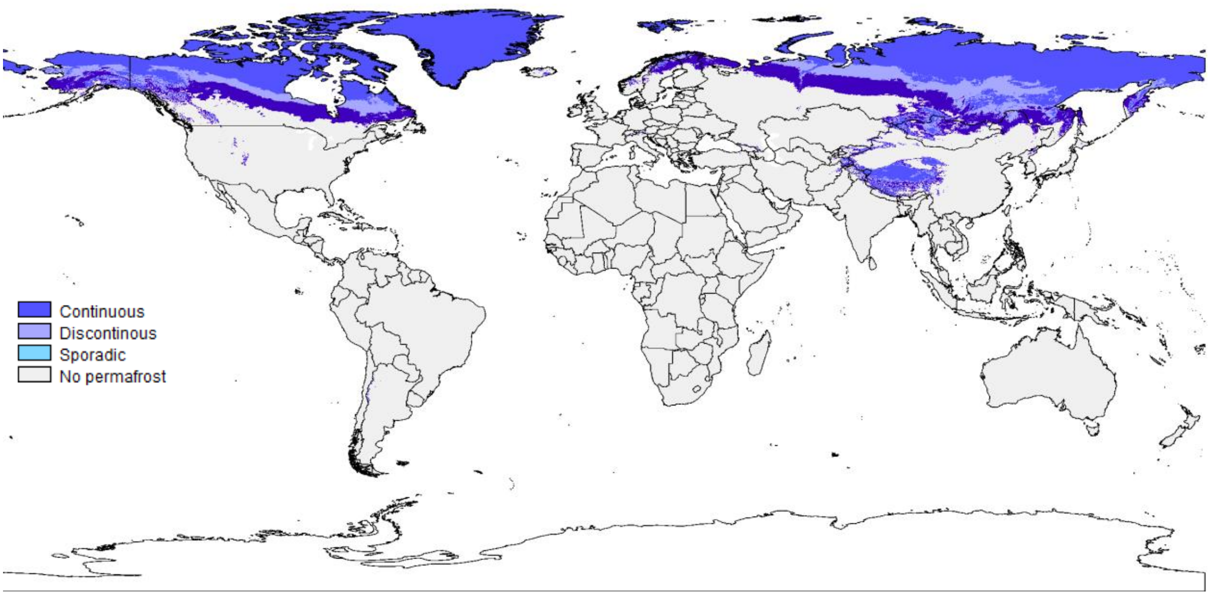
The frost index (*FI*) is then calculated (Nelson and Outcalt, 1987):

$$FI = \frac{DDF^{0.5}}{DDF^{0.5} + DDT^{0.5}}$$

The value of *FI* is regarded a measure of the probability of occurrence of permafrost and used to classify grid-cells in four distinct permafrost classes (Table 3-3).

In the GAEZ assessment, those grid-cells characterized as continuous permafrost (class 1) or discontinuous permafrost (class 2) are considered unsuitable for crop production. Regular yield and suitability calculations are performed in class 3 and 4. Figure 3-7 presents the reference permafrost zones map for climate of 1981–2010.

Figure 3-7 Reference permafrost zones, climate of 1981–2010



Source: FAO and IIASA, 2021

Table 3-3 Classification of permafrost areas used in the GAEZ assessment

Permafrost class	Value of frost Index (FI)	Probability of permafrost* (%)
Continuous permafrost	>0.625	>67
Discontinuous permafrost	0.570 < FI < 0.625	33–67
Sporadic permafrost	0.495 < FI < 0.570	5–33
No permafrost	<0.495	<5

** Probability of permafrost occurrence was calculated based on datasets from Nelson and Outcalt (1987) and analyzed at IIASA*

Soil moisture regime

In Module I, GAEZ calculates a daily reference soil water balance for each grid-cell and estimates actual evapotranspiration (*ETa*) for a reference crop. In the Module II, soil moisture balance calculations are performed considering specific crop/LUTs and their specific water requirements.

Soil moisture balance

Daily soil moisture balance calculation procedures follow the methodologies outlined in "Crop Evapotranspiration" (Allen *et al.*, 1998). The quantification of a crop-specific water balance determines crop "actual" evapotranspiration (*ETa*), a measure used for calculating water-constrained crop yields by comparing *ETa* with a crop's evaporative demand *ETm*.

The volume of water available for plant uptake is calculated by means of a daily soil water balance (Wb). The *Wb* accounts for accumulated daily water inflow from precipitation (*P*) or snowmelt (*Sm*) and outflow from actual evapotranspiration (*ETa*), and excess water lost due to runoff and deep percolation (*We*).

$$Wb_j = \min(Wb_{j-1} + Sm_j + P_j - ETa_j, Wx)$$

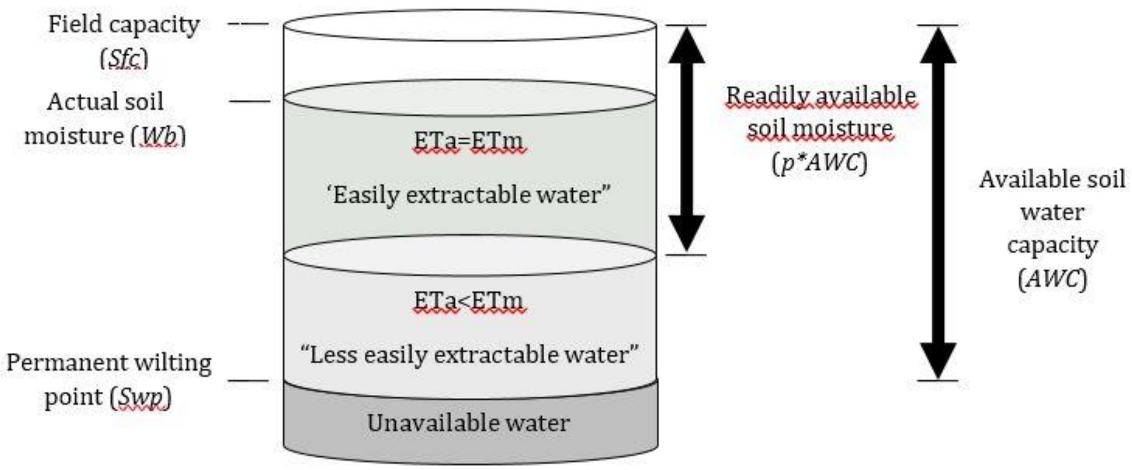
where *j* is the day of the year; *Wx* is the maximum water available to plants. The snowmelt (*Sm*) is accounted within the snow balance calculation procedures and excess water (*We*) is the amount of water that exceeds *Wx*.

The upper limit *Wx* of the water available to plants depends on the soil's physical and chemical characteristics that influence available soil water holding capacity (*AWC*) and volume. *Wx* is the product of available soil water (*Sa*) and rooting depth (*D*).

$$Wx = Sa \times D$$

The maximum *Sa* value is a soil-specific attribute defined as the difference between soil moisture content at field capacity (*Sfc*) and permanent wilting point (*Swp*) over the rooting zone. Therefore, at any given day, an actual soil water content (*Wb*) will be available to plants if *Swp* < *Wb* < *Sfc* (Figure 3-8). However, water extraction becomes more difficult as soil water content (*Wb*) is less than a critical threshold (*Wr*) defined by *p*, the "soil water depletion factor", and the available soil water capacity (*AWC*).

Figure 3-8 Schematic representation of water balance calculations



The values of AWC and rooting depth limitations due to soil are derived from soil information contained in the Harmonized World Soil Database v1.2 (Nachtergaele *et al.*, 2012). Details on the estimation of *AWC* values are provided in section 6-5 in the context of soil evaluation procedures. Any water input into the soil that exceeds *Wx* is "lost" as excess water (*We*) and is considered "not available" in further GAEZ calculations. It accounts for the water lost either by runoff or deep percolation.

Reference length of growing period (LGP)

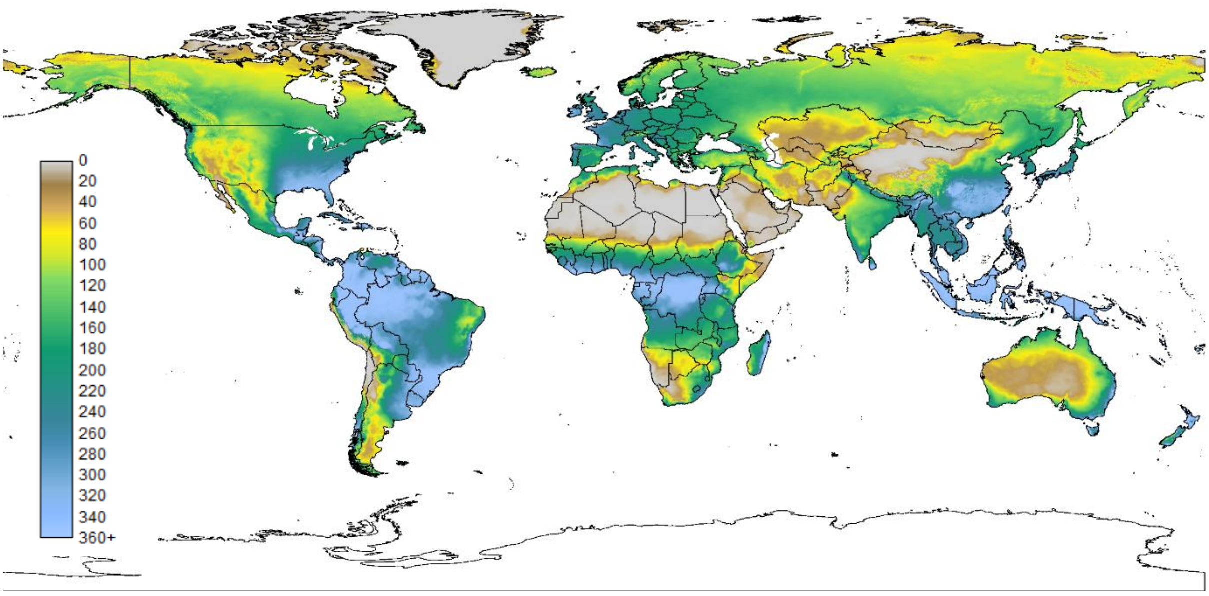
The agro-climatic potential productivity of land depends largely on the number of days during the year when temperature regime and moisture supply are conducive to crop growth and development. This period is termed the length of the growing period (LGP). The LGP is determined based on prevailing temperatures and the above-described water balance calculations for an assumed reference crop. In a formal sense, LGP refers to the number of days when average daily temperature is above 5^0C and *ETa* of this reference crop exceeds a specified fraction of *ETm*. In the current GAEZ parameterization, LGP days are considered when $ETa \geq 0.4 \times ETm$, which aims to capture periods when sufficient soil moisture is available that would allow the establishment of the reference crop. Specifically, the reference water balance underlying LGP calculations assumes an effective soil depth *D* of 1m and a soil water holding capacity *Smax* of 100 mm. The reference water balance is calculated year-round (for 365 days) and the *Kc* values used to relate reference crop potential evapotranspiration (*ETm*) to Penman-Monteith reference evapotranspiration (*ETo*) are listed in Table 3-4.

Table 3-4 Kc values applied in Module I reference water balance

Daily temperature condition	Remarks	Kc
Areas with year-round temperature growing period	$LGP_{t>5}$ = 365 days	
Daily Ta ≥ 5°C; $LGP_{t>5}$ = 365 days	In areas with year-round $LGP_{t>5}$ the Kc value stays at 1	1.0
Areas with dormancy period or cold break	$LGP_{t>5}$ is less than 365 days	
Daily Ta ≤ 0°C; Tmax < 0°C	Precipitation falls as snow and is added to snow bucket	0.0
Daily Ta ≤ 0°C; Tmax ≥ 0°C	Snow-melt takes place; minor evapotranspiration	0.1
0°C < Daily Ta < 5°C; temperature trend upward	Biological activities before start of growing period	0.2
Daily Ta ≥ 5°C; $LGP_{t>5}$ < 365 days; case 1	Kc used for days until start of growing period	0.5
Daily Ta ≥ 5°C; $LGP_{t>5}$ < 365 days; case 2	Kc increases from 0.5 to 1.0 during first month of LGP	0.5–1
Daily Ta ≥ 5°C; $LGP_{t>5}$ < 365 days; case 3	Kc = 1 until daily Ta falls below 5°C	1.0
0°C < Daily Ta < 5°C; temperature trend downward	Reduced biological activities before dormancy	0.2

Figure 3-9 presents a map of reference length of growing period. Note, LGP has been simulated for average 30-year climate, for historical years of 1961 to 2010 and for projected future climates of the period 2011 to 2099.

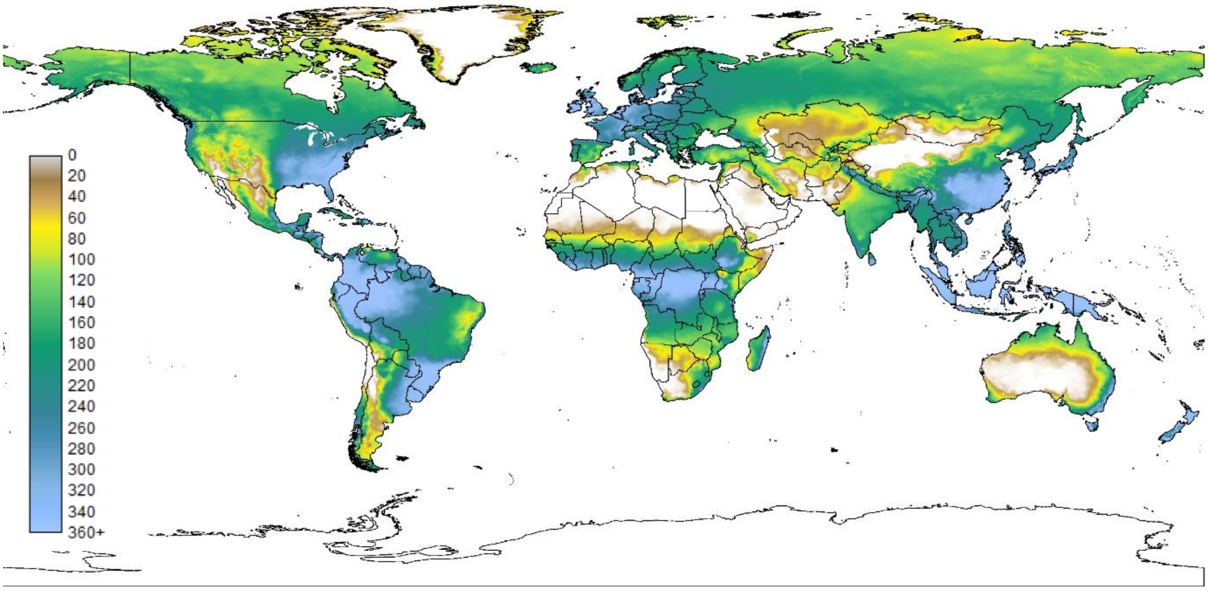
Figure 3-9 Reference length of growing period (days), average for period 1981–2010



Source: FAO and IIASA, 2021

For comparison, Figure 3-10 presents a map showing the ensemble mean of simulated reference length of growing period for climate of 2070–2099 projected by five earth system models under reference concentration pathway RCP 8.5.

Figure 3-10 Reference length of growing period (days), ensemble mean under RCP 8.5 for 2070–2099



Source: FAO and IIASA, 2021

LGP characteristics

Length of growing period data is also used for the classification of land into generalized moisture regimes classes. The GAEZ moisture regimes classes and their definitions are presented in Table 3-5.

Table 3-5 Moisture regimes

Length of growing period (days)	Moisture regime
0	Hyper-arid
<60	Arid
60 to 119	Dry semi-arid
120 to 179	Moist semi-arid
180 to 269	Sub-humid
270 to 364	Humid
≥ 365 (year-round growing period)	Per-humid

The moisture regime within an LGP is characterized by different water supply conditions as follows: *Growing period days without water stress* (days when $ETa=ETm$)*:* When ETa equals ETm, the crop water requirements are fully met (i.e., no water stress for plants occurs). From a soil water balance point of view these LGP days can further be differentiated as follows:

1. Daily rainfall is higher than crop water requirements ($P > ETm$) and available soil moisture Sa is below maximum ($Sa < Smax$). Excess rainfall now adds to replenish the available soil moisture storage.
2. Daily rainfall is higher than crop water requirements, $P > ETm$, and available soil moisture is at its maximum ($Sa = Smax$). In this case excess precipitation is lost to surface runoff and/or deep percolation.
3. Days when rainfall falls short of crop water requirements ($P < ETm$) but easily available soil moisture exceeds crop water requirements. In this case ETa equals ETm and the soil moisture content in the soil profile is decreasing.

Growing period days with water stress (days when $ETa<ETm$)*:* ETa falls short of ETm. The crop experiences water stress as not enough readily available water can be obtained from rainfall or moisture stored in the soil profile. Water stress implies that crop growth and yield formation are reduced.

Discontinuous growing periods

Total annual LGP days may be in one continuous period or may occur as two or more discontinuous growing periods. When available moisture becomes insufficient ($ETa < 0.4 \times ETm$), LGP ends and/or is interrupted by a dry period. In the case of temperature limitations (Ta < 5°C), LGP is interrupted by either a dormancy break or a cold-break. This distinction is determined on the basis of temperature limits for survival of hibernating crops. During a dormancy period hibernating crops can survive as opposed to a cold-break when temperature drops below a crop specific critical temperature limit.

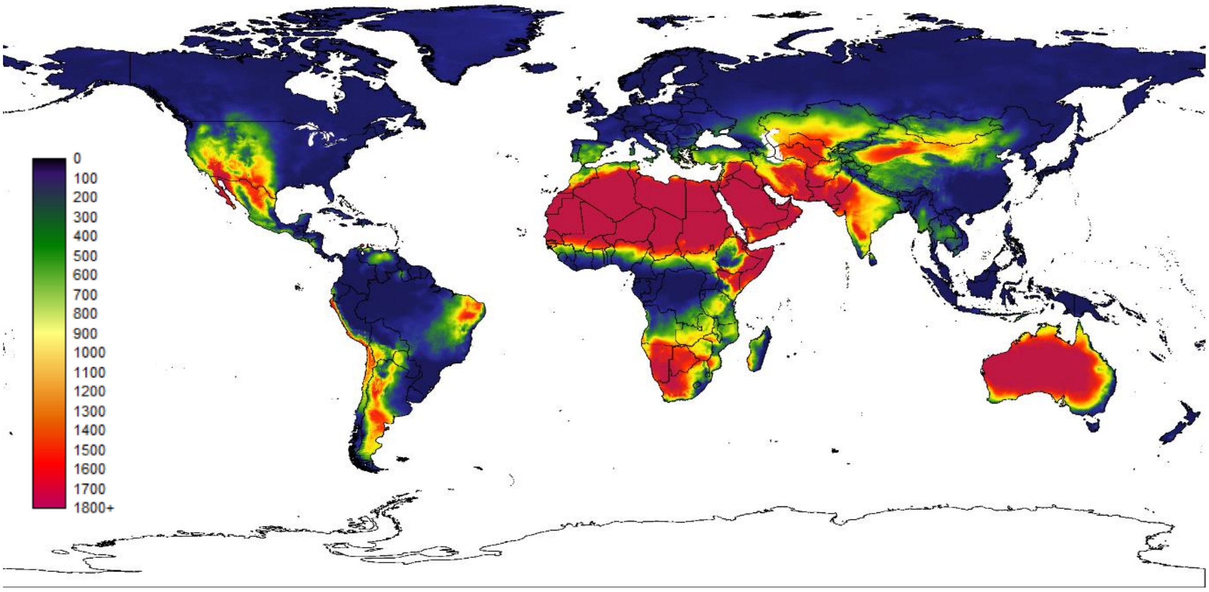
GAEZ can store up to five individual continuous component LGPs. Various soil moisture supply stages during the LGP are recorded and several indicators are calculated, including:

1. Total number of growing period days;
2. Number of growing period days, during which $ETa=ETm$;
3. Number of growing period days when $P>ETm$;
4. Number of individual growing periods;
5. Number of growing period days in individual growing periods;
6. Begin date of individual growing periods, and
7. End date of individual growing periods.

Reference annual water deficit (WDe)

The difference between annual potential and actual evapotranspiration as simulated in the reference water balance (explained in section 3.4.2) and is termed here the reference annual water deficit (*WDe*, mm), *WDe* = *ETm*-*ETa*. It measures the discrepancy between evaporative demand of a well-watered vegetation and the actual moisture supply under rain-fed conditions. A map is shown in Figure 3-11 for the average of historical year-by-year outcomes for the period 1981–2010. Note that *WDe* is computed as an agro-climatic indicator, without consideration of actual soil conditions, and the reference water balance is calculated using a soil water holding capacity *Smax* of 100 mm. In Module V, when the crop specific water deficits are determined, the actual soil and terrain conditions of a grid cell are taken into account in crop water balance calculations.

Figure 3-11 Mean annual reference water deficit WDe (mm), climate of 1981–2010



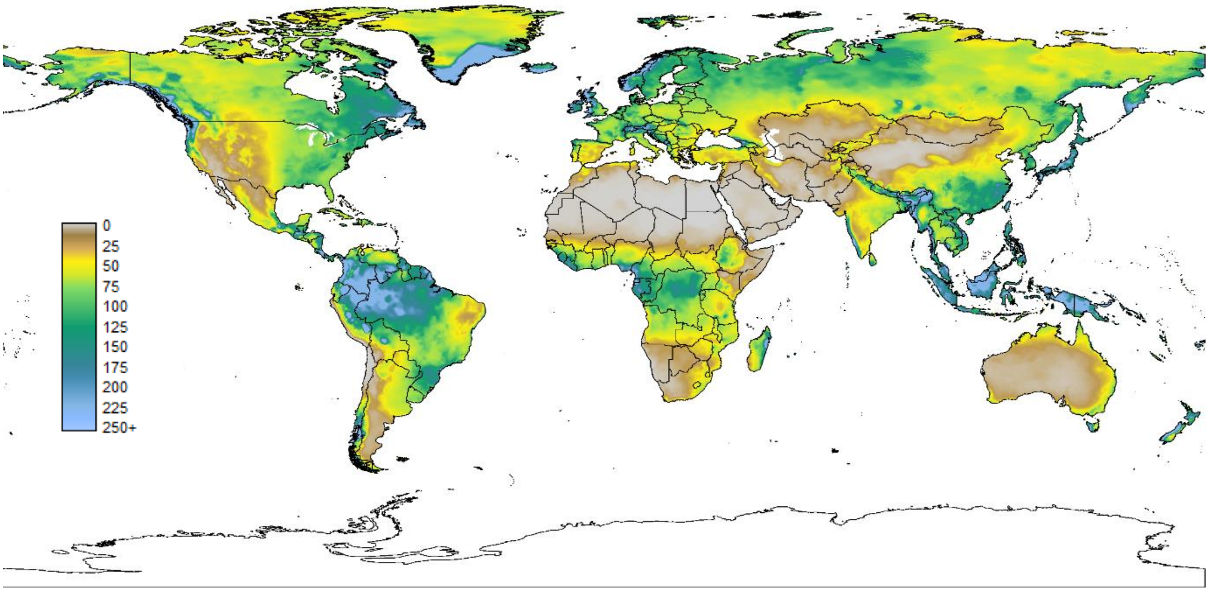
Source: FAO and IIASA, 2021

Annual moisture availability index (P/ETo)

The moisture availability index compares the amount of incoming precipitation to the evaporative demand of the reference crop assumed in the calculation of the Penman-Monteith equation used for reference evapotranspiration *ETo*. An index value of 100 means that precipitation equals reference potential evapotranspiration, i.e., that precipitation on average over the year matches the evaporative demand of the vegetation. Values below 100 indicate the occurrence of some water deficit; values above 100 mean that precipitation exceeds evaporative demand on an annual basis.

In the GAEZ analysis, a moisture availability index is calculated for different periods: for year-round conditions; for 6-month periods (April to September, October to March), and for 3-month periods (January to March, April to June, July to September, and October to December). The indicators provide a general understanding of soil moisture conditions and of the level of water stress occurring overall and within certain periods of a year (Figure 3-12).

Figure 3-12 Mean annual moisture availability index (100xP/ETo), climate of 1981–2010

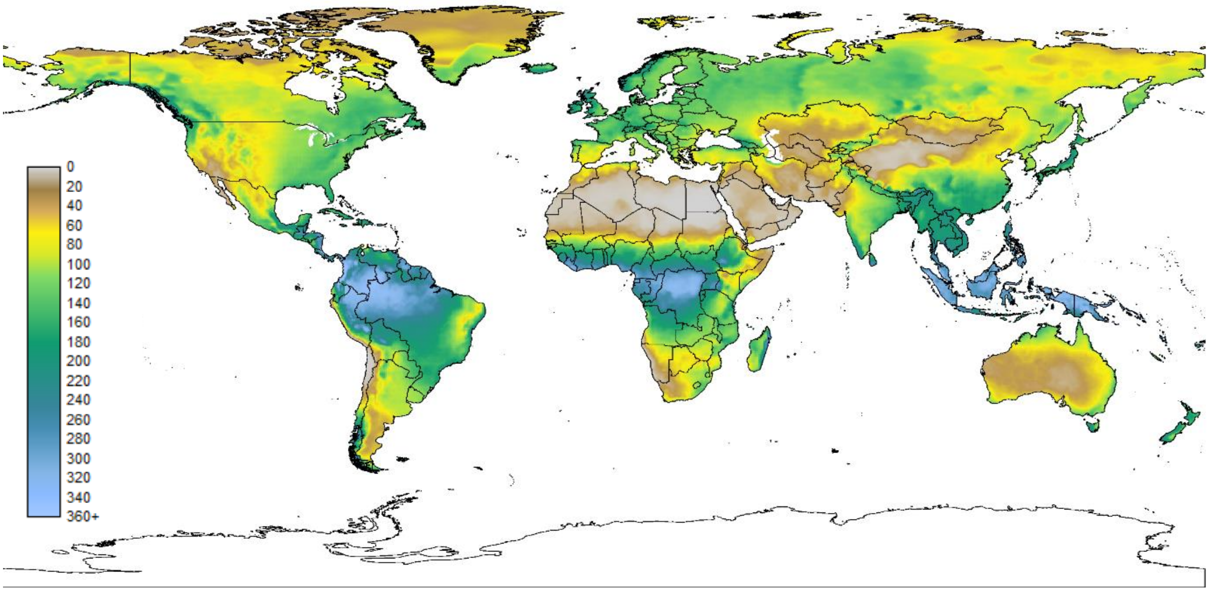


Source: FAO and IIASA, 2021

Annual number of rain-days

The GAEZ analysis uses daily data of precipitation. This allows the computation of various statistics, including the number of rain-days in a year, here defined as days with precipitation P ≥ 1 mm (Figure 3-13).

Figure 3-13 Average number of rain-days (days), climate of 1981–2010



Source: FAO and IIASA, 2021

Additional agro-climatic indicators

The comprehensive climate database in GAEZ is used to generate several additional indicators to portray various aspects that characterize the agro-climatic conditions of a grid cell. For instance, these indicators relate to (i) the possibility of cultivating multiple sequential crops under rain-fed and irrigated conditions, (ii) a general estimate of climate related bio-productivity, and (iii) the quantification of widely used climate classification (Koeppen-Geiger).

Multiple cropping zones classification

In the GAEZ crop suitability analysis, the LUTs considered refer to single cropping of sole crops, i.e., each crop is presumed to occupy the land only once a year and in pure stand. Consequently, in areas where the growing periods are sufficiently long to allow more than one crop to be grown in the same year or season, single crop yields of annual crops do not reflect the full potential of total time available each year for rain-fed or irrigated crop production. To assess the multiple cropping potential, a number of multiple cropping zones have been defined through matching both growth cycle and temperature requirements of individual suitable crops with time available for crop growth. For rain-fed conditions this period is approximated by the LGP, i.e., the number of days during which both temperature and moisture conditions permit crop growth. Under irrigation conditions the length of the temperature growing period and annual accumulated temperature sums are decisive.

According to the above considerations, nine different multiple cropping zones were classified and mapped (see Figure 3-14):

A. *Zone of no cropping* (too cold or too dry for rain-fed crops);

B. *Zone of single cropping*;

C. *Zone of limited double cropping* (relay cropping; single wetland rice may be possible);

D. *Zone of double cropping* (note, in Zone D sequential double cropping including wetland rice is not possible);

E. *Zone of double cropping* with rice (sequential double cropping with one wetland rice crop is possible in Zone E);

F. *Zone of double rice cropping or limited triple cropping* (may partly involve relay cropping; a third crop is not possible in case of two wetland rice crops);

G. *Zone of triple cropping* (sequential cropping of three short-cycle crops; two wetland rice crops are possible in Zone G), and

H. *Zone of triple rice cropping* (sequential cropping of three wetland rice crops is possible).

Delineation of multiple cropping zones for rain-fed conditions is solely based on agro-climatic attributes calculated during AEZ analysis. The following attributes were used in the definition of cropping zones:

- **LGP**: length of growing period, i.e., number of days when temperature and soil moisture permit crop growth;

- **LGP_{t5}**: number of days with mean daily temperatures above 5^0C;
- **LGP_{t10}**: number of days with mean daily temperatures above 10^0C;
- **TS_0**: accumulated temperature (degree-days) on days when mean daily temperature ≥ 0^0C;
- **TS_{10}**: accumulated temperature (degree-days) on days when mean daily temperature ≥ 10^0C;
- **TSG_5**: accumulated temperature on growing period days when mean daily temperature ≥ 5^0C, and
- **TSG_{10}**: accumulated temperature on growing period days when mean daily temperature ≥ 10^0C.

Table 3-6 and Table 3-7 summarize the delineation criteria for multiple cropping zones under rain-fed conditions in respectively the lowland tropics and all other thermal zones. Figure 3-14 presents a multiple cropping zone classification under rain-fed conditions. Figure 3-15 shows the multiple cropping zones classification under irrigation conditions for 5 arc-minute grid cells containing at least 0.5% of cropland equipped for full control irrigation (i.e., at least about 45 ha irrigated cropland in a 5 arc-minute grid cell at the equator). Finally, Figure 3-16 gives multiple cropping zones classes simulated for future climate projected by HadGEM2-ES for 2080s under concentration pathway RCP8.5 and suggests substantial shifts of multiple cropping classes due to climate change.

Table 3-6 Delineation of multiple cropping zones under rain-fed conditions in lowland tropics

Zone	LGP	LGP_{t5}	LGP_{t10}	TS_0	TS_{10}	TSG_5	TSG_{10}
A[19)]	-	-	-	-	-	-	-
B	≥45	≥120	≥90	≥1600	≥1200	-	-
C[20)]	≥220	≥220	≥120	≥5500	-	≥3200	≥2700
C	≥200	≥200	≥120	≥6400	-	≥3200	≥2700
C	≥180	≥200	≥120	≥7200	-	≥3200	≥2700
D[20)]	≥270	≥270	≥165	≥5500	-	≥4000	≥3200
D	≥240	≥240	≥165	≥6400	-	≥4000	≥3200
D	≥210	≥240	≥165	≥7200	-	≥4000	≥3200
E[21)]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
F	≥300	≥300	≥240	≥7200	-	≥5100	≥4800
G[21)]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
H	≥360	≥360	≥360	≥7200	≥7000	-	-

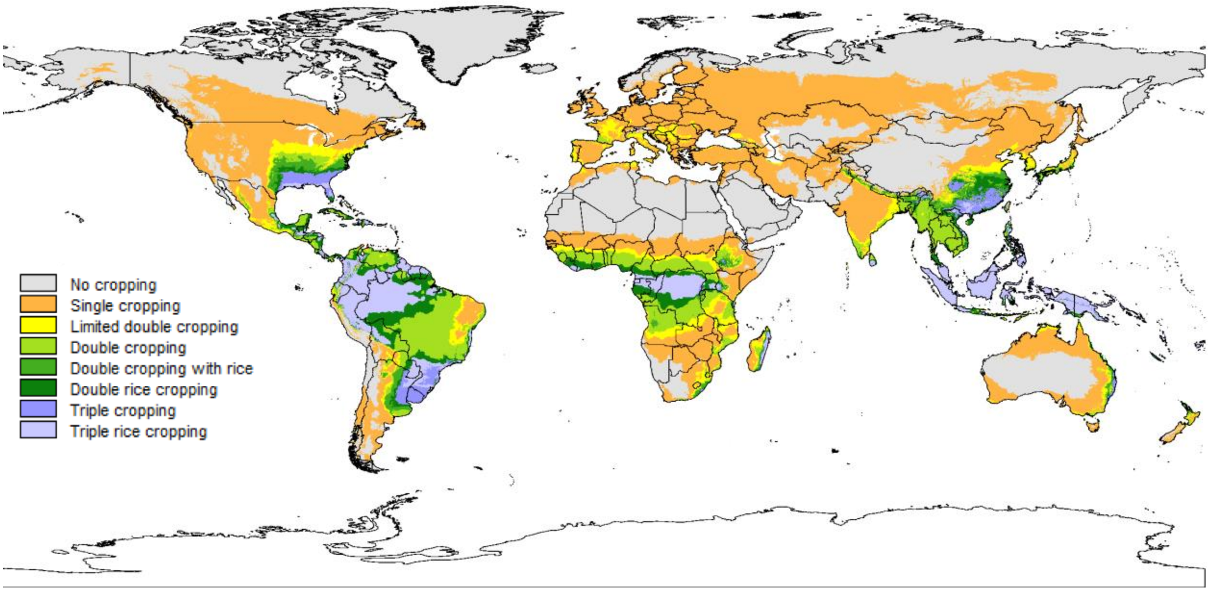
[19)] *Is a residual zone and applies if conditions for zone B ('single cropping') are not met.*
[20)] *Three alternative sets of conditions are tested in lowland tropics and a grid cell is assigned the C or D class when at least one set of conditions is met.*
[21)] *Due to a relatively small temperature amplitude (i.e., calculated temperature difference between warmest month and coldest month in a year) in lowland tropics the multiple cropping zones of type E and G, which combine cool and warm season crops, are not considered in this climate.*

Table 3-7 Delineation of multiple cropping zones under rain-fed conditions in all other thermal zones

Zone	LGP	LGP_{t5}	LGP_{t10}	TS_0	TS_{10}	TSG_5	TSG_{10}
A[19)]	-	-	-	-	-	-	-
B	≥45	≥120	≥90	≥1600	≥1200	-	-
C	≥180	≥200	≥120	≥3600	≥3000	≥3200	≥2700
D	≥210	≥240	≥165	≥4500	≥3600	≥4000	≥3200
E	≥240	≥270	≥180	≥4800	≥4500	≥4300	≥4000
F	≥300	≥300	≥240	≥5400	≥5100	≥5100	≥4800
G	≥330	≥330	≥270	≥5700	≥5500	-	-
H	≥360	≥360	≥330	≥7200	≥7000	-	-

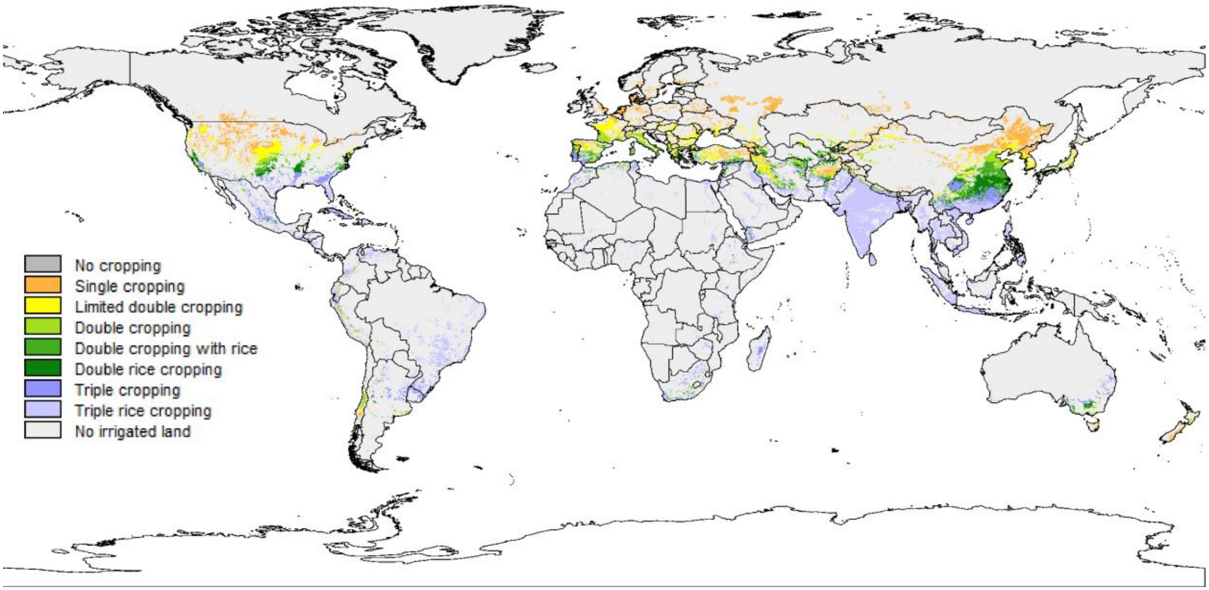
19) Is a residual zone and applies if conditions for zone B ('single cropping') are not met.

Figure 3-14 Multiple cropping zones classes for rain-fed conditions, climate of 1981–2010



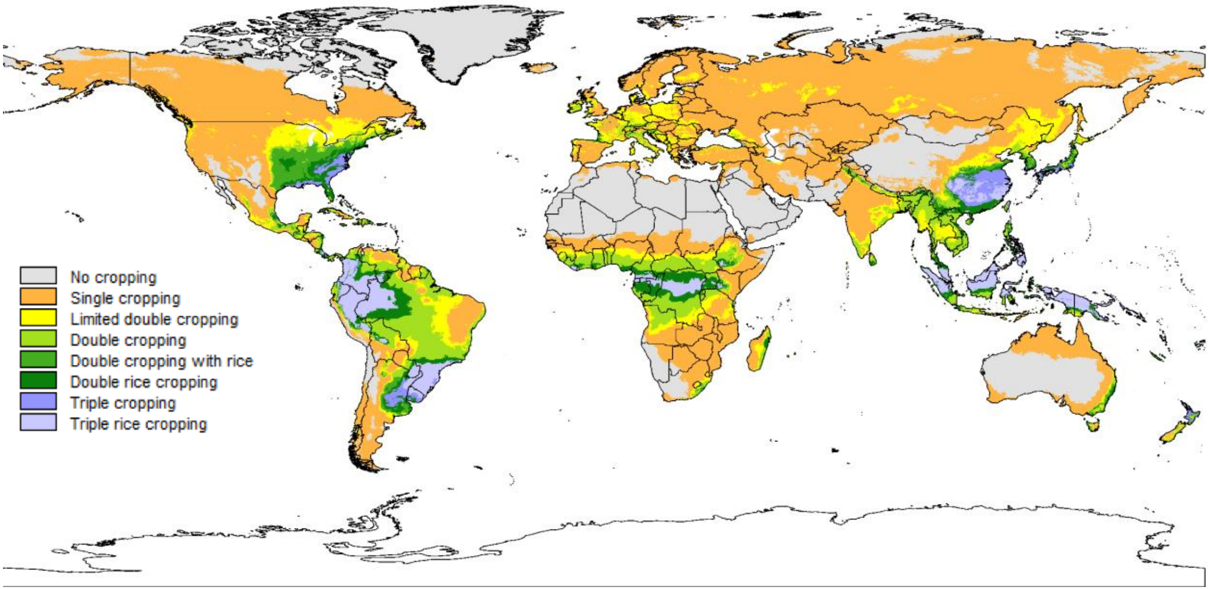
Source: FAO and IIASA, 2021

Figure 3-15 Multiple cropping zones classes for current irrigated land, climate of 1981–2010



Source: FAO and IIASA, 2021

Figure 3-16 Multiple cropping zones classes for rain-fed conditions, HadGEM2-ES, RCP8.5, 2070–2099



Source: FAO and IIASA, 2021

Equivalent length of the growing period (LGPeq)

Reference LGPs account for both temperature and soil moisture conditions and do not necessarily account for significant differences in wetness conditions especially within long LGPs (> 225 days), For the purpose of better reflection of wetness conditions, so-called equivalent LGPs are used. Equivalent LGP is defined on the basis of regression analysis of the reference LGP and the humidity index P/ETo as follows.

A quadratic polynomial is used to express the relationship between the number of growing period days and the annual humidity index. Parameters were estimated using data of all grid-cells with essentially year-round temperature growing periods, i.e., with $LGPt_5 = 365$.

$$LGPeq = \begin{cases} 14.0 + 293.66 \times \left(\frac{P}{ETo}\right) - 61.25 \times \left(\frac{P}{ETo}\right)^2 & ; \quad when \left(\frac{P}{ETo}\right) \leq 2.4; \\ 366 & ; \quad when \left(\frac{P}{ETo}\right) > 2.4; \end{cases}$$

The equivalent LGP is used in the assessment of agro-climatic constraints, which relate environmental wetness with the occurrences of pest and diseases and workability constraints for harvesting conditions and for high moisture content of crop produce at harvest time.

Net Primary Productivity (NPP)

Net primary productivity (*NPP*) is estimated as a function of incoming solar radiation and soil moisture at the rhizosphere. Actual crop evapotranspiration (*ETa*) has a close relationship with NPP of natural vegetation as it is quantitatively related to plant photosynthetic activity which is also driven by radiation and water availability.

NPP is computed based on daily values of actual evapotranspiration (ETa) simulated in the reference water balance and serves as a climate related indicator of rain-fed biological activity.

In GAEZ, *NPP* is estimated according to Zhang and Zhou (1995) as follows:

$$NPP = \sum ETa \times \frac{A_0}{d}$$

The $\sum ETa$ are accumulated estimates of daily *ETa* from the GAEZ water balance calculations for the specific water holding capacity of individual soil types. The variable A_0 is a proportionality constant depending on diffusion conditions of CO_2 and d is an expression of sensible heat. The ratio A_0/d can be approximated by a function of the radiative dryness index (*RDI*) (Uchijima and Seino, 1988).

$$\frac{A_0}{d} \approx f(RDI) = RDI \times \exp\left(-\sqrt{9.87 + 6.25 \times RDI}\right)$$

with:

$$RDI = \frac{\sum_{j=1}^{12} Rn_j}{\sum_{j=1}^{12} P}$$

where, ΣRn is accumulated net radiation for the year and ΣP is precipitation for the year.

In GAEZ, two separate evaluations of the *NPP* function are performed:

a. For *NPP* estimates under natural, i.e., rain-fed conditions, *RDI* is calculated from prevailing net radiation and precipitation of a grid cell and *ETa* is determined by the GAEZ reference water balance:

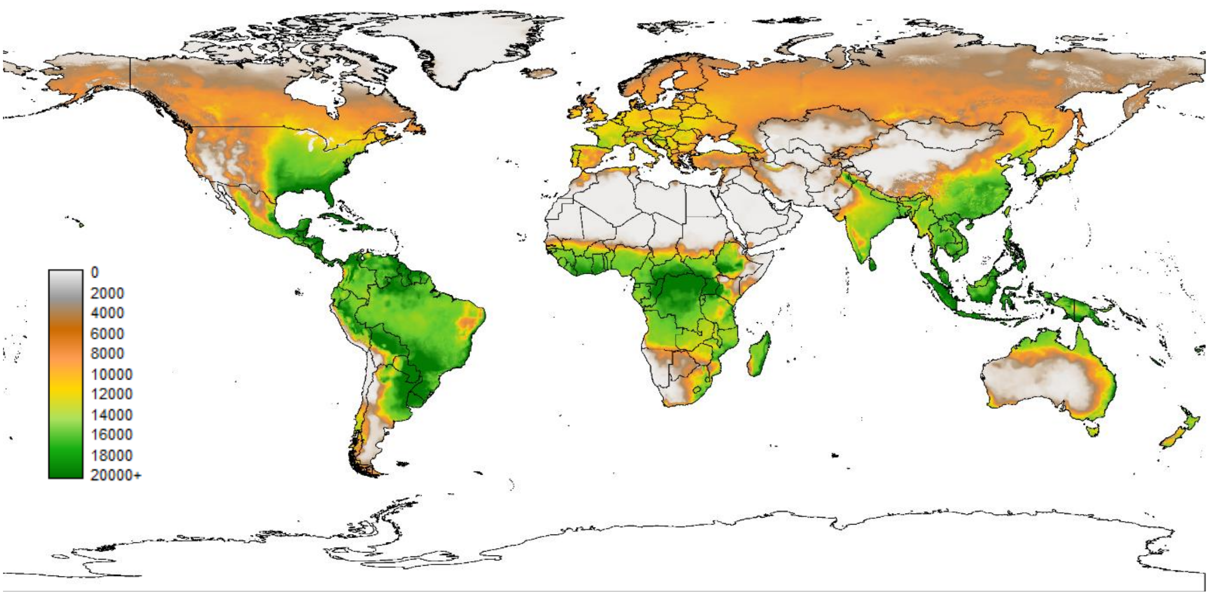
$$NPP_{rf} = \sum ETa \times RDI \times \exp\left(-\sqrt{9.87 + 6.25 \times RDI}\right)$$

b. For an *NPP* estimate applicable under irrigation conditions, *ETa* = *ETm* is assumed and a *RDI* of 1.375 is used, a value which results in a maximum for the function term approximating the A_0/d ratio:

$$NPP_{ir} = \sum ETa \times 1.375 \times \exp\left(-\sqrt{9.87 + 6.25 \times 1.375}\right)$$

NPP is computed using daily values of estimated actual evapotranspiration (*ETa*) of the reference water balance and serves as a climate related indicator of rain-fed biological activity (Figure 3-17). Separate *NPP* potential calculations are performed for moisture supply under natural conditions and for conditions when adequate water is supplied (e.g. by irrigation) to ensure daily *ETa* = *ETo*.

Figure 3-17 Net Primary Production potential under rain-fed conditions (kg C/ha), climate of 1981–2010



Source: FAO and IIASA, 2021

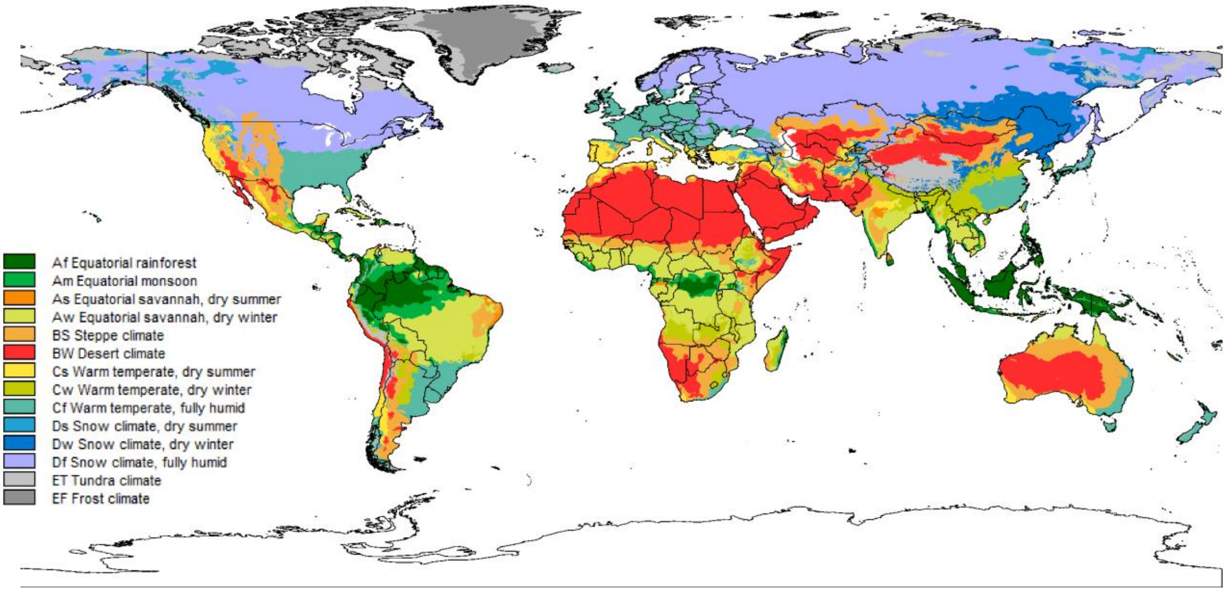
Koeppen-Geiger climate classification (KG2)

The Köppen climate classification is a widely used, vegetation-based, empirical climate classification system developed by Wladimir Köppen in the early 20th century (Köppen, 1900) and later updated by Rudolf Geiger (Geiger, 1954, 1961) with the aim was to devise formulas that would define climatic boundaries in such a way as to correspond to different observed vegetation zones (biomes).

Köppen's classification is based on a subdivision of terrestrial climates into five major types, which are represented by the capital letters A (tropical), B (dry), C (temperate), D (cold), and E (polar). Each of these climate types, except for B, is defined by temperature criteria. Type B designates climates in which the controlling factor on vegetation is dryness (rather than coldness). Dry climates are divided into arid (BW) and semi-arid (BS) subtypes. Other climate types are sub-divided according to seasonal precipitation characteristics. The level-2 classification distinguishes 14 classes. A global map of level-2 Koeppen climate classes, based on the climate attributes of period 1981–2010, is shown in Figure 3-18.

The computations in Module I produce also a level-3 classification with 31 classes where additional temperature criteria are applied for a further subdivision in temperate and cold climates (classes with capital letters B and C).

Figure 3-18 Koeppen-Geiger climate classification (level-2), climate of 1981–2010



Source: FAO and IIASA, 2021

Module I outputs

Module I produces two binary intermediate output files, which respectively contain for each grid cell the calculated indicators of thermal and moisture conditions. These files are then used to generate tabulations by administrative or watershed territorial units and a variety of GIS raster maps of the agro-climatic analysis results (see Table 3-8) for visualization and download. Several indicators are also used as input variables to the computations in Modules II, III, and V.

The indicators are calculated for average climate conditions, for time-series of individual years (TS) and, based on time-series results, for 30-year statistics (TS30) including for each variable the mean, median, 10% and 90% quantiles, standard deviation and coefficient of variation.

Table 3-8 Agro-climatic indicators provided in GAEZ v4

Type	Description	Unit
ET0	Reference evapotranspiration (Penman-Monteith)	mm
ETa	Actual evapotranspiration of FAO reference crop	mm
fss	Snow-adjusted air frost number	Scalar
fst	Air frost number	Scalar
KG2	Koeppen-Geiger climate classification (2-character)	Class
KG3	Koeppen-Geiger climate classification (3-character)	Class
ld1	Longest component growing period	Days
lgb	Starting day of longest component growing period	Day-of-Yr
lgd	Total number of growing period days	Days
lgp	Length of growing period zones	Class
lt2	Temperature growing period LGP_{t5}: Number of days when Ta ≥ 5 °C	Days
lt3	Temperature growing period LGP_{t10}: Number of days when Ta ≥ 10 °C	Days
mc2	Thermal Zones class	Class
mci	Multi-cropping class, irrigation conditions	Class
mcl	Thermal Climate class	Class
mcr	Multi-cropping class, rain-fed conditions	Class
ndd	Maximum number of consecutive dry days (P < 1mm) during LGP_{t5}	Days
ndr	Number of rain days, i.e., days with P ≥ 1mm	Days
nhum	Number of humid months (with P > ETo)	Months
nn00	Number of 'frost' days with minimum temperature T_{min} < 0 °C	Days
nn05	Number of days with minimum temperature T_{min} < 5 °C	Days
nn10	Number of days with minimum temperature T_{min} < 10 °C	Days
nn20	Number of days with minimum temperature T_{min} < 20 °C	Days
np1	Potential net primary productivity, irrigation conditions	kg C/ha
np2	Potential net primary productivity, rain-fed conditions	kg C/ha

nx30	Number of days with maximum temperature T_{max} > 30 °C	Days
nx35	Number of 'hot' days with maximum temperature T_{max} > 35 °C	Days
nx40	Number of 'very hot' days with maximum temperature T_{max} > 40 °C	Days
nx45	Number of 'extremely hot' days with maximum temperature T_{max} > 45 °C	Days
prc	Annual precipitation	mm
prf	Permafrost zone	Class
rfm	Fournier index	mm
ri2	P/ETo ratio (*100) for temperature growing period when Ta ≥ 5 °C	Scalar
rid	Annual Moisture Availability index (100×P/ETo)	Scalar
riS	Seasonal P/ETo ratio (×100) for April-September	Scalar
riW	Seasonal P/ETo ratio (×100) for October-March	Scalar
rQ1	Quarterly P/ETo ratio (×100) for January-March	Scalar
rQ2	Quarterly P/ETo ratio (×100) for April-June	Scalar
rQ3	Quarterly P/ETo ratio (×100) for July-September	Scalar
rQ4	Quarterly P/ETo ratio (×100) for October-December	Scalar
ta0	Mean temperature of coldest month	°C
td2	Annual temperature amplitude (Ta of warmest month – Ta of coldest month)	°C
tmp	Mean annual temperature	°C
ts2	Annual accumulated temperature sum for days with Ta ≥ 5 °C	∑°C
ts3	Annual accumulated temperature sum for days with Ta ≥ 10 °C	∑°C
wde	Annual water deficit of FAO reference crop (= ETo – ETa)	mm

An example of results from the calculation procedures of Module I are presented for a sample grid-cell in Appendix 3-2, providing output data of the agro-climatic data analysis for reference climate (1981–2010) for a grid-cell near Ilonga in Tanzania.

4. Module II (Biomass and yield calculation)

Introduction

The main purpose of Module II is the calculation of agro-climatical potential biomass and yield for a wide range of land utilization types (LUTs) under various input/management levels for rain-fed and irrigated conditions.

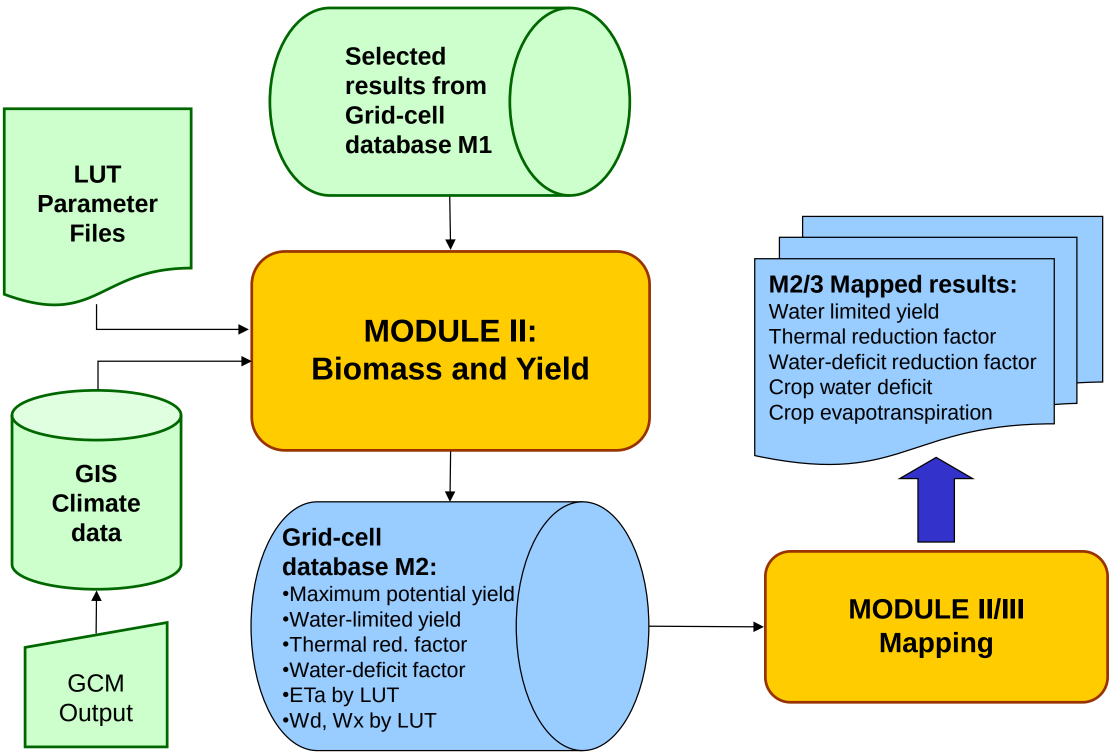
Module II consists of two steps:

i. Calculation of crop biomass and yield potentials considering only prevailing radiation and temperature conditions, and

ii. Computation of yield losses due to water stress during the crop growth cycle. The estimation is based on rain-fed crop water balances for different levels of soil water holding capacity. Yield estimation for irrigation conditions assumes that no crop water deficits will occur during the crop growth cycle.

The activities and information flow of Module II are shown in Figure 4-1.

Figure 4-1 Information flow of Module II



Land Utilization Types (LUTs)

Differences in crop types and production systems are empirically characterized by the concept of Land Utilization Types (LUTs). A LUT comprises technical specifications for crop production within a given socioeconomic setting. Attributes specific to a LUT include agronomic information, type of the main produce, water supply type, typical cultivation practices, utilization of produce, and associated crop residues and by-products. The GAEZ v4 framework distinguishes more than 1000 crop/LUT and management combinations, which are separately assessed for rain-fed and irrigated conditions. These LUTs are grouped into about 50 different food, feed, fiber, and bio-energy crops (Appendix 4-1, Table A4-1.2 and Table A4-1.3).

The calculated yield of each crop/LUT is affected by water source (rain-fed, irrigated) and by the assumed intensity of inputs and management. In GAEZ, three generic levels of input/management are defined: low, intermediate, and high input level.

Low level inputs

Under a low level of inputs (traditional management assumption), the farming system is largely subsistence based. Production relies on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars), labor intensive techniques, and no application of plant nutrients, no use of chemicals for pest and disease control and minimum conservation measures. Fallows are required to maintain soil fertility.

Intermediate level inputs

Under an intermediate level of input (improved management assumption), the farming system is partly market oriented. Production for subsistence plus commercial sale is a management objective. Production is based on improved varieties, on manual labor with hand tools and/or animal traction and some mechanization, is medium labor intensive, applies some nutrients/fertilizer and chemical pest disease and weed control, and uses adequate fallows and some conservation measures.

High level inputs

Under a high level of input (advanced management assumption), the farming system is mainly market oriented. Commercial production is a management objective. Production is based on improved or high yielding varieties, is fully mechanized where possible with low labor intensity and uses optimum applications of nutrients and chemical pest, disease and weed control.

In GAEZ, this variety in management and input levels is translated into yield differences by assigning different parameters for LUTs depending on the input/management level, e.g. such as harvest index and maximum leaf area index.

LUTs are parameterized to reflect environmental and eco-physiological requirements for growth and development of different crop types. Numerical values of crop parameters used in the simulations differ depending on the assumed input/management level to which LUTs are subjected.

Thermal suitability screening of LUTs

As initial criteria to screen the suitability of grid-cells for the possible presence of individual LUTs, GAEZ tests the match of prevailing thermal conditions with the LUT's temperature requirements.

There are several steps applied to evaluate the extent to which thermal and relative humidity conditions during the crop cycle fit the respective LUT requirements: (i) Thermal (latitudinal) climatic conditions; (ii) permafrost conditions; (iii) length of temperature growing period (LGP_{t5}); (iv) length of frost free period (LGP_{t10}); (v) temperature sums ($Tsum_t$); (vi) temperature profiles; (vii) vernalization conditions; (viii) diurnal temperature ranges (for selected tropical perennials), and (ix) relative humidity conditions (especially for selected tropical perennials).

LUT specific requirements are individually matched with temperature regimes (and relative humidity) prevailing in individual grid-cells. Matching is tested for the full range of possible starting dates and resulting in optimum match, sub-optimum match and not suitable conditions. The "optimum and suboptimum match categories" are considered for further biomass and yield calculations.

Thermal climate

In Module II, the GAEZ procedures first check whether a LUT is considered suitable to be cultivated in the thermal regime prevailing in a grid-cell. The procedure assesses the compatibility of the LUT requirements in terms of overall temperature provision, climatic seasonality and seasonal day-length to enable the screening for respectively long-day, day neutral and short days crop LUTs.

The screening of crop/LUTs about prevailing thermal climate results in a "yes/no" filter for further calculations to be performed for an LUT in individual grid-cells.

Permafrost

Areas classified as continuous or discontinuous permafrost (see section 3.3.7 on classification of permafrost zones) are considered not suitable. Gelic soils, indicating permafrost, that occur outside the reference continuous and discontinuous permafrost zones are further appraised in the agro-edaphic suitability assessment.

Temperature growing period

The period during the year when temperatures are conducive to crop growth and development is represented by the temperature growing period, which is defined as the period during the year with mean daily temperature above 5^0C, also referred to as LGP_{t5}. Growth cycle lengths of crop/LUTs are matched with LGP_{t5}. The result of the matching provides optimum match when the growth cycle can generously be accommodated within LGP_{t5}. Otherwise the match is considered sub-optimum or not suitable.

Hibernating crops survive low temperatures, e.g. during a winter season, by entering a dormancy period. GAEZ considers five hibernating crop species: winter wheat, winter barley, winter rye, winter rape, winter onion. These are the only annual crop/LUTs considered for cultivation at daily average temperatures <5⁰C. A dormancy period occurs when Ta ranges between 5⁰C and the crop-specific critical low temperature for cold-break. If the dormancy period is longer than 200 days, or daily average temperatures drop below critical thresholds (see below), the winter LUT is not suitable. For the effect of snow cover on lowering temperature thresholds for cold break, see details in Fischer *et al.*, 2002.

Frost free period

Difference in sensitivity of crop/LUTs for early and late frost is accounted for through the matching of crop/LUT growth cycles with prevailing frost free periods. The frost free period is approximated by the period during the year when mean daily temperatures are above 10⁰C (LGP_{t10}). Depending on the sensitivity of a specific crop/LUT the matching of growth cycle length with the available frost free period provides optimum match, sub-optimum match or not suitable conditions.

Accumulated temperature sum

Individual crop/LUT heat unit requirements are matched with temperature sums accumulated during the crop/LUT growth cycle duration ($Tsum^c$). The $Tsum^c$ is defined as the sum of mean daily temperatures calculated from a base temperature of 0⁰C.

The match of the crop LUT heat unit requirements with the prevailing temperature sum is optimum, when the requirements are falling within the specified optimum $Tsum^c$ range, sub-optimum when falling in $Tsum^c$ range conditions and not suitable when prevailing $Tsum^c$s are too high or too low. Optimum and sub-optimum $Tsum^c$ ranges are presented for all crops/LUTs in the Appendix 4-6.

Temperature profile

The temperature profile requirements are crop/LUT-specific rules that specify conditions for crop cycle duration in terms of classes of mean daily temperatures. These classes in 5⁰C intervals are defined separately for days with increasing or decreasing temperature trends (Fischer, G., H. van Velthuizen, 2002). Updated temperature profile requirements data sets, for respectively optimum conditions and for sub-optimum conditions, have been specified for use in GAEZ v4 (Appendix 4-3).

Potential crop calendars of each LUT are tested for the match of crop/LUT temperature profile requirements and grid-cell temperature profiles, while considering growth cycle starting days within the length of the growing period for rain-fed conditions, and separately within the year for irrigated conditions. For all feasible crop calendars within the LGP (rain-fed) or within the year (irrigated) the temperature profile conditions are tested against optimum and sub-optimum crop temperature profile requirements and in each case an “optimum”, “sub-optimum” or “not suitable” match is established.

Vernalization

Some crops require a vernalization period (i.e., days with cold temperatures) for performing specific phenological development phases such as flowering. The production of flowers and grains, which directly influences crop yield, is dependent on the extent and intensity of exposure to periods with cold temperature. This cold temperature requirement is measured in vernalization days. In GAEZ, there are four hibernating crops that need to fulfill vernalization requirements in order to produce: winter wheat, winter barley, winter rye and winter rape. Details are provided in Appendix 4-4.

Diurnal temperature range and relative humidity conditions

For several tropical perennial crops such as coconut, cacao and oil palm, diurnal temperature ranges and/or relative humidity levels affect crop growth and yield. For these perennials requirements vis-à-vis optimum, sub-optimum and not suitable diurnal temperature ranges as well as permissible ranges of average, maximum or minimum relative humidity have been defined.

Combining temperature related constraints

When optimum conditions for crop cultivation are not met for all requirements, the degree of sub-optimality is derived by quantifying for each tested requirement a constraint factor fc_{1k}, k=1, …, K, based on the distance of the calculated indicator from respectively the thresholds for 'optimum', 'sub-optimum' and 'not suitable' levels. At the threshold defining sub-optimum conditions it is assumed that crop growth and yield are reduced by 25%, whereas no reduction is applied for values exceeding the threshold for optimum conditions. When the calculated constraint value falls in between the optimum and sub-optimum thresholds, a constraint factor is assigned by linear interpolation. When the constraint value lies between sub-optimum and not suitable thresholds, then again a linear function is applied to calculate the constraint factor. Details of tested constraints for each crop are given in Appendix 4-3.

For instance for sugar cane, optimal conditions require a temperature sum of at least 6750°C, for sub-optimal conditions of 6000°C, and sugar cane is regarded as not suitable when the temperature sum is less than 5700°C. For a calculated temperature sum of 6250°C in a specific grid cell, the prevailing conditions fall in between the specified optimal and sub-optimal thresholds. In this case the resulting constraint factor will have a value of 0.833 = 0.75 + 0.25 x ((6250–6000)/(6750–6000)), i.e., a reduction by 16.7%. For an even lower annual temperature sum of only 5800°C, the constraint factor for sugar cane would be 0.250 = 0.75 x (5800–5700)/(6000–5700), i.e., a reduction by 75%.

The "most limiting" evaluated related constraint factor is then used to reduce potential yields calculated in Module II. For this yield adjustment a reduction factor fc_1 is calculated over all constraints:

$$fc_1 = \ min\, k\ \{fc_{1k}, k = 1, \dots, K\},$$

which represents the minimum, i.e., the most severe of the individual temperature (and relative humidity) related reduction factors.

Biomass and yield calculation

In this section the calculation procedures of constraint-free biomass and yield (i.e., carbon accumulation driven mainly by prevailing radiation and temperature regimes in a grid-cell) are explained. The procedures used are based on the ecophysiological model developed at FAO by A.H. Kassam (Kassam, 1977; Kassam *et al.*, 1983, 1991a).

The constraint-free crop yields calculated in the AEZ biomass model reflect yield potentials with regard to temperature and radiation regimes prevailing in the respective grid-cells. The model requires the following crop characteristics: (a) Average length of growth cycle (days from emergence to full maturity); (b) minimum and maximum length of growth cycle; (c) minimum temperature requirements for emergence; (d) maximum rate of photosynthesis, (e) respiration rates for leguminous and non-leguminous crops as a function of temperature during the growth cycle; (f) length of yield formation period; (g) leaf area index (LAI) at maximum growth rate; (h) harvest index; (i) crop adaptability group, and (j) sensitivity of crop growth cycle length to heat provision. Appendix 4-5 presents details of the calculation procedures and Appendix 4-6 provides the model parameters.

The results of the biomass and yield calculation depend on the timing of the crop growth cycle (crop calendar). Maximum biomass and yields are separately calculated for irrigated and rain-fed conditions, as follows:

Irrigation: For each day within the window of time when crop temperature and radiation requirements are met optimally or at least sub-optimally, the period resulting in the highest biomass and yield is selected to set the crop calendar of the respective crop/LUT for a particular grid-cell.

Rain-fed: Within the window of days with optimum or sub-optimum temperature conditions, and starting within the duration of the moisture growing period, the crop calendar resulting in the highest expected (water-limited) yield is selected to represent maximum biomass and yield for rain-fed conditions of the respective crop/LUT in a particular grid-cell.

In other words, for each crop type and grid-cell the starting and ending dates of the crop growth cycle are determined optimally to obtain best crop yields, separately for rain-fed and irrigated conditions. This procedure also entails adaptation of crop calendars ('smart farmer') in simulations with year-by-year historical weather conditions, or under climate distortions applied in accordance with various climate change scenarios.

Net biomass and yields for most LUTs in GAEZ are expressed in kilograms of dry matter (DM) per hectare with the exception of some oil crops (yield expressed as oil), sugar crops (yield expressed as sugar) and cotton (yield expressed as lint). In the case of forage crops and grasses the yields are expressed as 10 kg DM per hectare. This includes Alfalfa, Miscanthus, Switchgrass, Reed canary grass, napier grass, Grass legumes and Grasses.

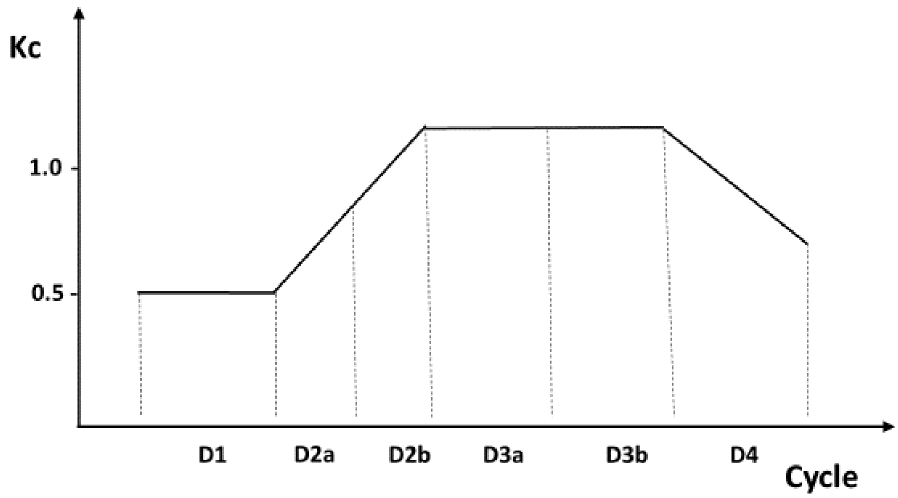
Water limited biomass production and yields

Under rain-fed conditions, water stress may occur during different stages of the crop development reducing biomass production and the yields achieved. In GAEZ v4, water requirements of each LUT are calculated daily and are considered in the calculation of LUT-specific water balance and actual evapotranspiration in a grid-cell. A water-stress yield-reduction factor (fc_2) is calculated and applied to the net biomass (*Bn*) and calculated potential yield (*Yp*).

Crop water requirement

The total water requirement of a crop without any water stress is assumed to be the crop-specific potential evapotranspiration (*ETm*). *ETm* is calculated in proportion to reference potential evapotranspiration (*ETo*), as in Module I, multiplied by crop and crop-stage specific parameters 'Kc'. The values of Kc for different stages of crop development (Figure 4-2) are given as input parameters (Allen *et al.*, 1998).

Figure 4-2 Schematic representation of Kc values for different crop development stages



- **D1:** initial phase: from planting to 10% ground cover (from planting/germination/emergence to establishment);
- **D2a:** early crop development stage;
- **D2b:** late crop development stage;
- **D3a:** early mid-season stage (flowering);
- **D3b**: late mid-season stage (reproductive stage), and
- **D4:** late season stage (start maturation to full maturity).

Input parameters define the relative length of each crop stage as a percentage of total cycle length (GC). Further three input parameters define the crop coefficients for water requirements (*Kc*, fractional) as follows: *Kc1* being the reference crop coefficient for the initial stage, *Kc3* being the reference crop coefficient for the mid development stage, and *Kc5* being the reference *Kc* crop coefficient applying at the end of late season stage. In addition, an average *Kc* parameter representative for the entire growth cycle (*KcT*) can be specified to calculate an overall crop water requirement. Procedures described in Allen *et al.* (1998) are applied in each grid cell to adapt reference *Kc* coefficients to local conditions in terms of rainfall distribution, average relative humidity and wind during each crop development stage.

The value of *Kc* for a particular day *j* of the year is defined by:

$$Kc_j = \left\{ \begin{matrix} Kc1 & j \in D_1 \\ Kc1 + (j - d1) \times \dfrac{Kc2 - Kc1}{d2} & j \in D_{2a} + D_{2b} \\ Kc2 & j \in D_{3a} + D_{3b} \\ Kc2 + \big(j - (d1 + d2 + d3)\big) \times \dfrac{Kc3 - Kc2}{d4} & j \in D_4 \end{matrix} \right\}$$

where *d1*, *d2*, *d3* and *d4* denote the length (number of days) of the respective major crop development stages. Parameters used for simulations in GAEZ v4 are listed in Appendix 4-2.

Yield reduction due to water deficits

Yield reduction in response to water deficits is calculated as a function of the relationship between actual crop evapotranspiration ($\sum ETa$, mm/day) and maximum crop evapotranspiration ($\sum ETm$, mm/day), both accumulated within each crop development stage. Daily *ETa* is calculated from the water balance as described also in Module I, with the difference of being LUT-specific in Module II. Also, in Module II, the value of the soil water depletion fraction (*p*) varies depending on the crop and the level of potential evapotranspiration *ETo*.

The sensitivity of each crop to water stress is expressed by the value of the water stress coefficient (*Ky*, fractional), a LUT-specific parameter which changes with crop development stage (Doorenbos and Kassam, 1979; Doorenbos and Pruitt, 1977) There are *Ky* values specified for each crop development stage as follows:

- **Ky1:** yield response factor initial phase;
- **Ky2a:** yield response factor early crop development stage;
- **Ky2b:** yield response factor late crop development stage;
- **Ky3a**: yield response factor early mid-season stage (flowering);
- **Ky3b:** yield response factor late mid-season stage (reproductive stage);
- **Ky4:** yield response factor late season stage (start maturation to full maturity), and
- **KyT**: yield response factor total growth cycle.

GAEZ uses both the crop stage specific coefficients and estimated water deficits and the overall value of KyT to calculate a water-stress yield reduction factor (fc_2).

$$\boldsymbol{fc_2^T = 1 - KyT \times \left(1 - \frac{\sum_1^{TCL} ETa_j}{\sum_1^{TCL} ETm_j}\right)}$$

$$TETa_j = \sum_{k \in D_j} ETa_k\,, \qquad TETm_j = \sum_{k \in D_j} ETm_k\,, \quad j = 1,\dots,4$$

$$fc_2^{CS} = \min_{j=1,\dots4} \{1 - ky_j \left(1 - \frac{TETa_j}{TETm_j}\right)\}$$

and

$$\boldsymbol{fc_2 = min(\,fc_2^{CS}, fc_2^T)},$$

where $TETa_j$ and $TETm_j$ are respectively total actual evapotranspiration and total potential evapotranspiration for days during crop stage D_j. Factor fc_2 is the minimum of factor fc^T_2, representing the effect of overall water deficit, and the factor fc^{cs}_2 represents the most severe impact of crop-stage specific water stress.

Water limited yield (Y_w) is then calculated as potential yield (Y_p) multiplied by the water-stress reduction factor fc_2:

$$Y_w = Y_p \times fc_2$$

Adjustment of LAI and HI for perennial crops

Perennial crops have limited opportunity to express their genetic potential to expand canopy (i.e., develop leaf area index, *LAI*) and to complete formation of yield components (e.g. fill grains) if the period for growth, here termed effective growth cycle length (CYC_{eff}, days) is too short in a given location. These two aspects of perennial crops are captured in GAEZ by adjustment factors for *LAI* (fp_{LAI}) and for harvest index (fp_{HI}), which are adjusted if the length of the effective growth cycle falls below a crop-specific critical threshold. Under rain-fed conditions the CYC_{eff} is limited by the number of growing period days in a year. Under irrigation conditions temperature growing periods LGP_{t10} or LGP_{t5} are used depending on the crop:

$$CYC_{eff} = (LGP, CYL_{max}) \qquad \text{under rain-fed conditions}$$

and

$$CYC_{eff} = (LGP_{t=t0}, CYL_{max}) \quad \text{for irrigated conditions,}$$

where *t0* is set to 5°C or 10°C depending on the crop.

Then the adjustment factors for *HI* and *LAI* are computed as follows:

$$fP_{HI} = \frac{CYC_{eff} - \alpha_{HI}}{\beta_{HI}}$$

$$fP_{LAI} = \frac{CYC_{eff} - \alpha_{LAI}}{\beta_{LAI}}$$

with CYC_{eff} as defined above.

For example, when simulating rain-fed sugar cane, the maximum annual growth cycle is set in the parameter file to a value of CYC_{max} = 330 days. In a location with only 240 growing period days the effective growth cycle would be set to CYC_{eff} = 240 days and using the parameter values in Table 4-1 would result in fP_{HI} = (240–120)/180 = 0.667 and fP_{LAI} = (240–70)/200 = 0.850.

Table 4-1 Parameterization used to correct harvest index (HI) and leaf area index (LAI) for sub-optimum length of the effective growth cycle (CYCeff)

Crop	fP_{LAI}		fP_{HI}	
	$\alpha_{LAI.}$	$\beta_{LAI.}$	α_{Hi}	β_{Hi}
Cassava	0	240	60	120
Sugar cane	70	200	120	180
Banana	0	300	90	240
Oil palm	0	330	180	180
Yellow yam	0	270	90	180
Cocoyam	0	270	90	180
Citrus	0	180	90	120
Cocoa	0	270	90	180
Tea	0	270	120	150
Coffee (arabica)	0	240	60	180
Coffee (robusta)	0	270	90	180
Coconut	0	240	60	180
Tea	0	300	120	180
Alfalfa	0	180	30	150
Miscanthus	0	210	30	180
Switchgrass	0	180	30	150
Reed canary grass	0	150	30	120
Napier grass	0	180	30	150
Para Rubber	0	330	180	180

The adjustment factors for Olive and Jatropha are using more complex piecewise linear function and are not shown here.

For each of the two variables two separate parameters are used to calculate the adjustment factors for *HI* and *LAI* of perennials. These parameters relate to critical values of the length of the effective growth cycle, below which a yield reducing adjustment is applied or no yield is obtained. Also, note that a perennial crop may be considered not suitable for levels of CYC_{eff} well above α_{Hi} or α_{LAI}. The effective growth cycle accounts for the days in the year when perennial crops are effectively growing. Under rain-fed conditions CYC_{eff} cannot exceed the number of growing period days determined for a grid cell and therefore the period of vigorous growth may be limited by temperature, rainfall and soil moisture availability. It also excludes any period of dormancy or resting of perennial crops. The parameterization for perennial crops used in GAEZ v4 is given in Table 4-1. The adjusted harvest index HI_{adj} and leaf area index LAI_{adj} for perennial crops are then calculated as:

$$HI_{adj} = HI_{max} \times fP_{HI} and$$

$$LAI_{adj} = LAI_{max} \times fP_{LAI}$$

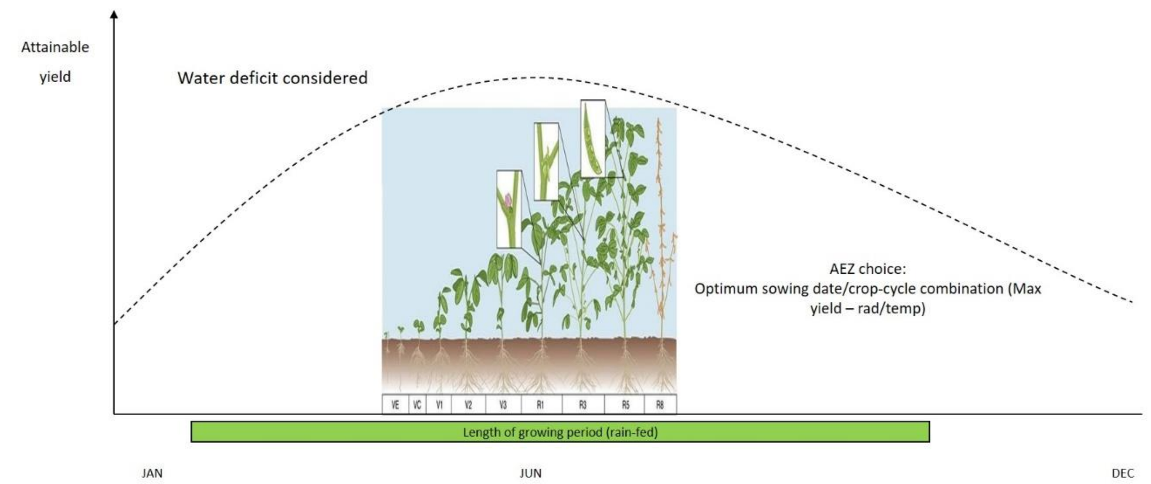
where HI_{max} and LAI_{max} denote the reference parameter values specified for growing conditions where the full growth cycle is possible.

Crop calendar

The crop calendar (i.e., sowing and harvesting dates) for a given LUT and grid-cell is determined by identifying within the permissible window of time the sowing date that leads to the highest attainable yield. GAEZ tests all possible LUTs/sowing dates within each grid-cell, separately for rain-fed and irrigated conditions.

For each LUT, the total crop cycle expected for the 'average climate' (30-year time period from 1961–1990 or 1981–2010) is given in days as an input parameter. For the average base climate, an accumulated temperature sum (TS_5) is calculated for each crop LUT. This crop-specific value of TS_5 is assumed to represent for a location the specific crop cycle requirement of the LUT. When simulating individual years, the crop cycle is adjusted until the specific TS_5 is reached, as calculated for average climate conditions, e.g. is shortened in years warmer than normal.

Figure 4-3 Optimum crop calendar (FAO and IIASA 2012)



For each grid cell and LUT the algorithm determines the highest attainable yield, which then defines the respective outcome for that location

For rain-fed production GAEZ calculates potential crop yields by shifting computed calendars within the permissible part of the LGP and selects the start date of the crop when yield is the highest. This optimum crop calendar for rain-fed conditions is reflecting, for a crop/LUT, the optimum combination of radiation regime, temperature regime and soil moisture availability, as shown in Figure 4.3.

For irrigated production GAEZ tests all possibilities of crop yield performance in LGP_{t5} (i.e., in the period during the year when Ta >5^{0}C) and selects the period with highest attainable yields, thus driven mainly by radiation and temperature regime. The calendar search in GAEZ is flexible and alternatively could also use a selection criterion which would account for the trade-off between additional irrigation water use and additional yield generated.

Grid cell analysis Module II

Results of the biomass and yield calculation procedures in Module II are presented for a sample grid cell in Appendix 4-7. The example provides output data for rain-fed cereal production under high inputs and advanced management for reference climate (1981–2010) for a grid cell near Ilonga, Tanzania.

Description of Module II outputs

The output of Module II records for each grid-cell and LUT the relevant results of the biomass calculation, including potential yields, yield-reducing factors, accumulated temperatures, actual crop evapotranspiration, water deficits and crop calendar information.

The process generates thousands of maps which are named using a 4-character crop acronym and a 3-character map type acronym. The types of mapped information provided by Module II/III is listed in Table 4-2. The 4-character crop name acronyms are shown in Table 4-3.

To illustrate the mapped outcomes of Module II/III the Figure 4-4 and Figure 4-5 show agro-climatic potential yields of rain-fed wheat simulated under high inputs and advanced management assumptions for (i) reference climate conditions of 1981–2010 and a soil with assumed available water capacity (AWC) of 200 mm (see Figure 4-4) and for (ii) an ensemble mean in period 2070–2099 calculated using climate projections of five earth system models under reference concentration pathway RCP8.5 (see Figure 4-5).

Table 4-2 Mapped output produced by Module II/III analysis

Type	Description	Unit
cbd	LUT crop cycle starting date	Day-of-year
cyl	Cycle length of selected crop/LUT	Days
eta	Actual crop evapotranspiration from precipitation (i.e., excluding irrigation)	mm
fc0	Combined temperature, soil moisture and agro-climatic constraint factor	Scalar
fc_1	Yield reduction factor due to temperature profile evaluation	Scalar

fc_2	Yield reduction factor due to soil moisture deficits during LUT growth cycle	Scalar
fc_3**	Yield reduction factor due to agro-climatic constraints evaluation	Scalar
idx	Sequence number of LUT selected to define grid cell crop results	Class
Tsc	Accumulated temperature during LUT crop cycle	∑°C
wde	LUT water deficit/net irrigation requirement during crop cycle	mm
yld	Agro-climatic potential yield	Kg/ha*

** For most crops the yields are given in kg dry weight per hectare. For alfalfa, miscanthus, napier grass, reed canary grass, pasture legumes and grasses the yields are in 10kg dry weight per hectare. For sugar beet and sugar cane the yields are in kg sugar per hectare and for olive and oil palm in kg oil per hectare. Cotton yields are given as kg lint per hectare.*
*** Agro-climatic constraint factor fc_3 is computed in Module III as discussed in the next chapter.*

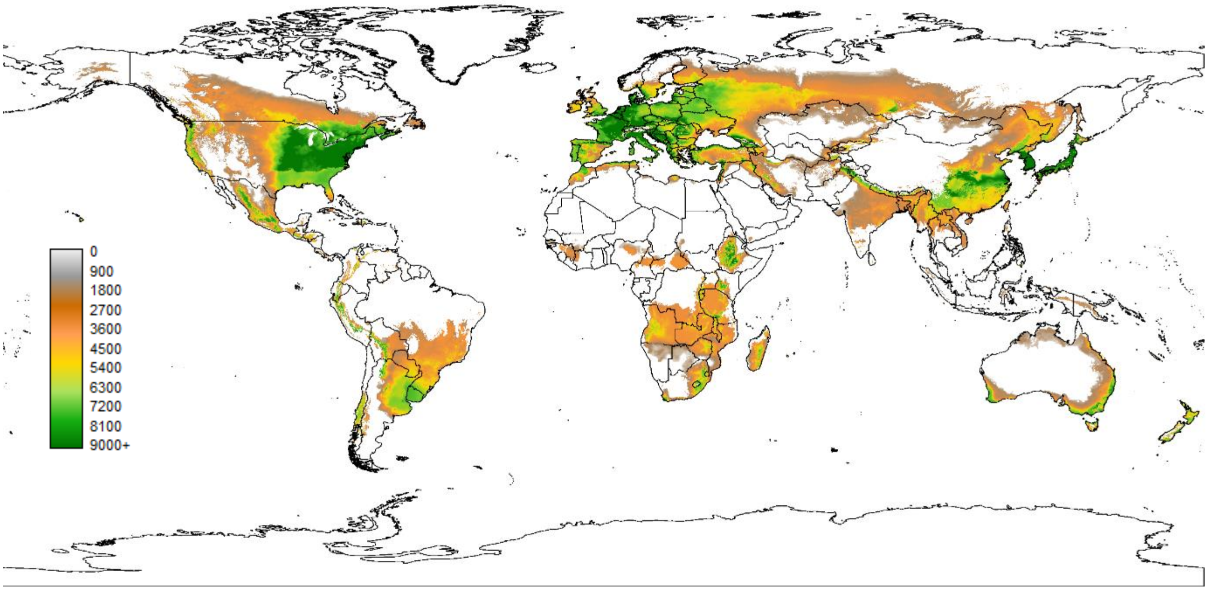
Table 4-3 Crop name acronyms used in GAEZ v4 file names of Module II/III mapped outputs

Acronym	Crop name	Acronym	Crop name
alfa	Alfalfa	bana	Banana
barl	Barley (the better of sbrl and wbrl)	bckw	Buckwheat
bean	Phaseolous bean	bhsg	Biomass highland sorghum
blsg	Biomass lowland sorghum	bsrg	Biomass sorghum (best blsg, bhsg and btsg)
btsg	Biomass temperate sorghum	cabb	Cabbage
carr	Carrot	casv	Cassava
chck	Chickpea	citr	Citrus
cocc	Cacao (comum)	coch	Cacao (hybrid)
cocn	Coconut	coco	Cacao (the better of comum and hybrid)
cofa	Coffee arabica	coff	Coffee (the better of arabica and robusta)
cofr	Coffee robusta	cott	Cotton
cowp	Cowpea	cyam	Cocoyam
dpea	Dry peas	flax	Flax fibre
fmlt	Foxtail millet	gras	Pasture grasses
grlg	Pasture legumes	grnd	Groundnut
gram	Gram	gyam	Greater yam
hmze	Highland maize (tropics)	hsrg	Highland sorghum (tropics)
jatr	Jatropha	lmze	Lowland maize
lsrg	Lowland sorghum	maiz	Maize (best of lmze, hmze and tmze)
misc	Miscanthus	mllt	Millet (better of fmlt and pmlt)
mzsi	Silage maize	napr	Napier grass
oats	Oat	oilp	Oil palm
oliv	Olive	onio	Onion

Acronym	Crop name	Acronym	Crop name
pigp	Pigeon pea	pmlt	Pearl millet
prub	Para-rubber	rape	Rapeseed
rcgr	Reed canary grass	ricd	Dryland rice
ricw	Wetland rice	ryes	Rye (the better of srye and wrye)
sbrl	Spring barley	sorg	Sorghum (best of lsrg, hsrg and tsrg)
soyb	Soybean	spot	Sweet potato
srye	Spring rye	sugb	Sugar beet
sugc	Sugar cane	sunf	Sunflower
swhe	Spring wheat	swgr	Switchgrass
teas	Tea (best of China, Assam and hybrid types)	tmze	Temperate/sub-tropical maize
toba	Tobacco	toma	Tomato
tsrg	Temperate/sub-tropical sorghum	wbrl	Winter, sub-tropical and tropical highland barley
whea	Wheat (the better of swhe and wwhe)	wpot	White potato
wrye	Winter rye	wwhe	Winter, sub-tropical and tropical highland wheat
wyam	White yam	yams	Yam (best of wyam, gyam, yyam and cyam)
yyam	Yellow yam		

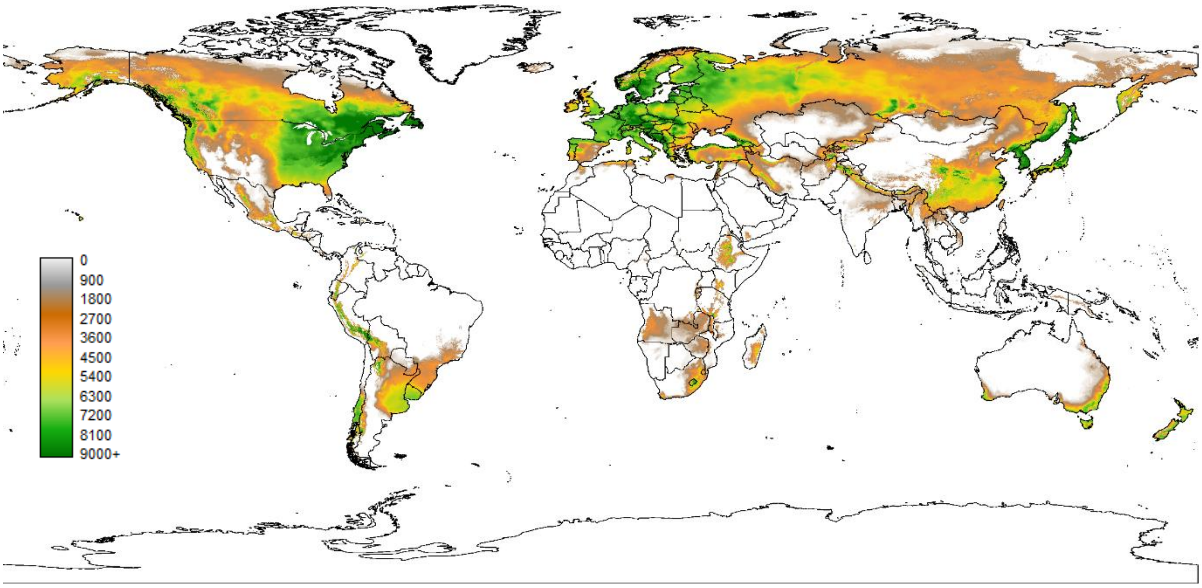
As is visible in these maps, substantial global warming projected under RCP8.5 will cause a clear geographical shift of the agro-climatic potential wheat yields toward higher latitudes and will largely wipe out the potential of current wheat types in the tropics, as is very noticeable in the tropical highlands of sub-Saharan Africa and the northern part of South Asia where wheat is grown widely in the Rabi season.

Figure 4-4 Agro-climatic potential yield (kg DW/ha) of rain-fed wheat, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

Figure 4-5 Agro-climatic potential yield (kg DW/ha) of rain-fed wheat, high inputs, climate of 2070–2099



Source: FAO and IIASA, 2021

5. Module III (Agro-climatic constraints)

Introduction

When computing potential biomass and yields in Module II, initially no account is taken of the climate related impacts affecting production potential through pests and diseases, and unfavorable working conditions in the field. Such effects need to be included to arrive at realistic estimates of agro-climatic potential crop yields. Precise estimates of these impacts are very difficult to obtain for a global study. Here it has been approximated by quantifying the constraints in terms of reduction ratings, according to different types of constraints and their severity for each crop/LUT. Ratings vary by moisture regime, temperature regime and by level of inputs/management. The latter subdivision is necessary to take account of the fact that some constraints, such as bollworm on cotton, are present under low input conditions but are controllable under high input conditions in certain moisture regimes. While some constraints are common to all input levels, others (e.g., poor workability because of excess moisture) are more likely to affect operations under high input assumptions with fully mechanized cultivation. The main purpose of Module III is to evaluate crop growing conditions for possible agro-climatic constraints and to determine a respective yield reduction factor.

Agro-climatic constraints cause direct or indirect losses in the yield and quality of produce. Yields losses in a rain-fed crop due to agro-climatic constraints have been formulated based on principles and procedures originally proposed in FAO (1978) and successively expanded and updated from specialized literature, field data and CABI - Distribution Maps of Plant Pest and Diseases. Agro-climatic constraint updates were implemented repeatedly, e.g. FAO (FAO, 1980); FAO/UNDP (1982); Brammer *et al.* (1988); Kassam *et al.* (1991); UNDP/SSTC/FAO/SLA (1994); EISD/SRI (1999); FAO/IIASA (2000); Fischer, G., H. van Velthuizen (2002); FAO/IIASA (2012) and WWF/IIASA (2018).

Four different yield constraints (i.e., yield-reducing factors) are accounted for[4]:

- Pests, diseases, and weeds damage on plant growth ('b' group);
- Pests, diseases, and weeds damage on quality of produce ('c' group);
- Climatic factors affecting the efficiency of farming operations ('d' group), and
- Frost hazards ('e' group).

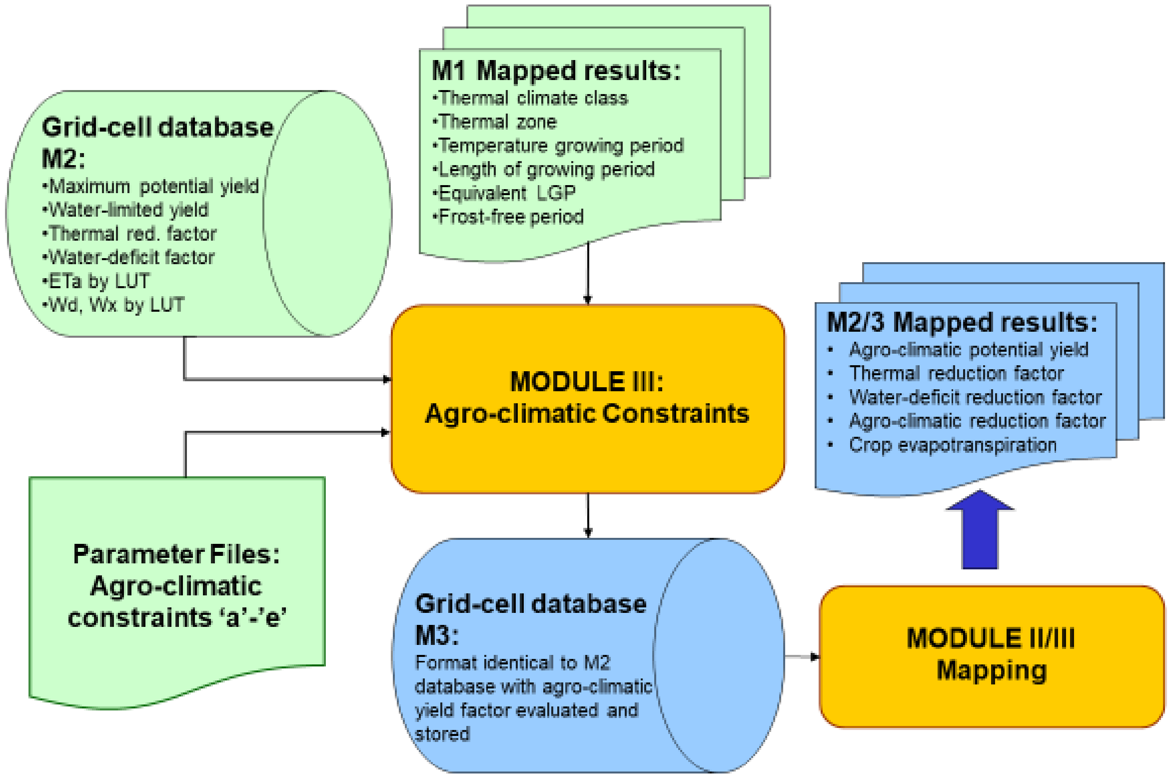
Although the constraints of group 'd' are not direct yield losses, such constraints do mean, for example, that the high input level mechanized cultivator cannot get onto the land to carry out operations. In practice, such limitations operate like yield reductions. Similarly, for the low input cultivator, for example, excessive wetness could mean that the produce is too wet to handle and remove, and again losses would be incurred even though the produce may be

[4] Originally there were five groups with the "a" group corresponding with yield reductions due to rainfall variability. In GAEZ v4 rainfall variability is already taken into account in Module II and therefore is not considered here.

standing in the field. Also included in this group, are constraints due to the cultivator having to use longer duration cultivars to enable harvesting in dry conditions. The use of such cultivars may incur yield restrictions, and such circumstances under wet conditions have therefore been incorporated in the severity ratings of agro-climatic constraints in group ‘d’.

The relationships between the occurrence of these constraints and quantified agro-climatic conditions, such as moisture stress and excess air humidity, and risk of early or late frost, are varying by location, between agricultural activities as well as by use of control measures. It has therefore been attempted to approximate the impact of these yield constraints on the basis of location-specific climatic conditions. The efficacy of control of these constraints (e.g. pest management) is accounted for through varying impact factors by levels of inputs/management.

Figure 5-1 Information flows of Module III



Still, there is relatively high level of uncertainty and therefore this quantification of agro-climatic constraints has been applied separately in Module III, such that effects are transparent, well separated and GAEZ assessments can be done with and without these constraints. This makes it also easy to apply alternative correction factors in studies where additional information on pests and diseases has been documented. Figure 5-1 gives an overview of the information flow in Module III.

In general, with increasing length of growing period and wetness, constraints due to pests and diseases (groups ‘b’ and ‘c’) become increasingly severe particularly to low input cultivators. As the length of growing period gets very long, even the high input level cultivator cannot always keep these constraints under control and they become severe yield reducing factors at all three levels of inputs. Other factors, such as poor pod set in soybean or poor quality in short lengths of growing period zones, are of similar severity for all three levels of inputs. Difficulties in lifting root crops under dry soil conditions (short lengths of growing periods group 'd') are rated more severely under the high level of inputs (mechanized) than under intermediate and low level of inputs. Agro-climatic constraints thus aim to represent any such additional direct or indirect losses of the yield and in the quality of produce. An explanation of the main yield-reducing components addressed by agro-climatic constraints is provided in the following sections.

Conceptual basis of agro-climatic constraint factors

The purpose of this section is to explain the conceptual basis of agro-climatic constraint factors considered in the model i.e., crop growth cycle and the length of growing period, water-stress during the growing period, pests, diseases, and weeds, climatic factors and frost hazard.

Mismatch between crop growth cycle and the length of the growing period

When the growing period is shorter than the growth cycle of the crop, from sowing to full maturity, there is loss of yield. The biomass and yield calculations account for direct losses by appropriately adjusting LAI and harvest index. However, the loss in the marketable value of the produce due to poor quality of the yield as influenced by incomplete yield formation (e.g., incomplete grain filling in grain crops resulting in shriveled grains or yield of a lower grade, incomplete bulking in root and tuber leading to a poor grade of ware), is not accounted for in the biomass and yield calculations. This loss is to be considered as an agro-climatic constraint in addition to the quantitative yield loss due to curtailment of the yield formation period. Yield losses can also occur when the length of the growing period is much longer than the length of the crop growth cycle, e.g. because of increased pest, disease and weed burden, excess wetness at harvest, or climatic conditions affecting the efficiency of farming operations.

Water-stress during the growing period

Water-stress generally affects crop growth, yield formation and quality of produce. The yield reducing impacts of water-stress vary from crop to crop. The total yield impact can be considered in terms of (i) the effect on growth of the whole crop, and (ii) the effect on yield formation and quality of produce. For some crops, the latter effect can be more severe than the former, particularly where the yield is a reproductive part (e.g., cereals) and yield formation depends on the sensitivity of floral parts and fruit set to water-stress (e.g., silk drying in maize).

Pests, diseases, and weeds

To assess the agro-climatic constraints of the pest, disease and weed complex, the effects on yields that operate through loss in crop growth potential (e.g., pest and diseases affecting vegetative parts in grain crops) are considered separately from effects on yield that operate directly on yield formation and quality of produce (e.g., cotton stainer affecting lint quality, grain mould in sorghum affecting both yield and grain quality).

Climatic factors directly or indirectly reducing yield and quality of produce

These include problems of poor seed set and/or maturity under cool or low temperature conditions, problems of seed germination in the panicle due to wet conditions at the end of grain filling, problems of poor quality lint due to wet conditions during the time of boll opening period in cotton, problems of poor seed set in wet conditions at the time of flowering in some grain crops, and problems of excessive vegetative growth and poor harvest index due to high night-time temperature or low diurnal range in temperature.

Climatic factors affecting the efficiency of farming operations and costs of production

Farming operations include those related to land preparation, sowing, cultivating and crop protection during crop growth, and harvesting (including operations related to handling the produce during harvest and the effectiveness of being able to dry the produce). Agro-climatic constraints in this category are expressed as workability constraints, which primarily account for excessive wetness conditions during necessary field operations. Limited workability can cause direct losses in yield and quality of produce, and/or impart a degree of relative unsuitability to an area for a given crop from the point of view of how effectively crop cultivation and produce handling can be conducted at a given level of inputs.

Frost hazard

The risk of occurrence of late and early frost increases substantially when mean temperatures drop below 10°C (Fischer, G., H. van Velthuizen, 2002). Hence, length of the thermal growing period with temperatures above 10°C (LGP_{t10}) in a grid-cell has been compared with growth cycle length of frost sensitive crops. When the crop growth cycle is only slightly shorter than LGP_{t10} the constraints related to frost risk are adjudged moderate, when the growth cycle is very close or equal to LGP_{t10}, the constraints have been adjudged as severe.

The availability of historical rainfall data has made it possible to derive the effect of rainfall variability through year-by-year calculation of yield losses due to water stress. Therefore the ‘a’ constraint, related to rainfall variability is no longer applied. Nevertheless, the ‘a‘ constraints have been retained in the agro-climatic constraints database for use with data sets containing only average rainfall data and for backward compatibility with earlier published AEZ information.

The ‘b’ and ‘d’ constraints and partly the ‘c’ constraint are closely related to wetness. The ratings of these constraints have been linked to indicators of wetness conditions, in Module I expressed by the number of growing period days (LGP) and/or as annual or seasonal moisture availability index *P/ETo*. While LGP may be curtailed in cooler climates by low temperatures despite of prevailing wetness, a high *P/ETo* ratio will capture conditions when precipitation tends to exceed evaporative demand and thereby indicate wetness. The ‘e’ constraint dealing with frost hazards is expressed in relation to the frost-free period LGP_{t10}.

Box 5-1 Agro-climatic constraints context

In general, with increasing length of growing period and wetness, constraints due to pests and diseases (groups 'b' and 'c') become increasingly severe particularly to low input cultivators. As the length of growing period gets very long, even the high input level cultivator cannot keep these constraints under control and they become severe yield reducing factors at all three levels of inputs. Other factors, such as poor pod set in soybean or poor quality in short lengths of growing period zones, are of similar severity for all three levels of inputs. Difficulties in lifting root crops under dry soil conditions (short lengths of growing periods group 'd') are rated more severely under the high level of inputs (mechanized) than under intermediate and low level of inputs. For irrigated production the 'c' constraint is applied only at the wet end, i.e., above 270 days in the example for winter wheat shown in Table 5-1.

Although the constraints of group 'd' are not direct yield losses in reality, such constraints do mean, for example, that the high input level mechanized cultivator, due to wetness, cannot get onto the land to carry out operations. In practice, this results in yield reductions. Similarly, for the low input cultivator, for example, excessive wetness could mean that the produce is too wet to handle and remove, and again losses would be incurred even though the produce may be standing in the field. Also included in this group are constraints due to the cultivator having to use longer duration cultivars to enable harvesting in dry conditions. The use of such cultivars incurs yield restrictions, and such circumstances under wet conditions have therefore been incorporated in the severity ratings of agro-climatic constraints in group 'd'.

In areas with year-round temperature growing periods, for example in the tropics and most of the sub-tropical thermal climate, the 'b', 'c' and 'd' agro-climatic constraints have been expressed for a big part in relation to LGP, in temperate and boreal climates equivalent LGP days are used as explanatory variable, which are calculated by an empirically estimated function of P/ETo ratios (see section 3.5.2).

The wetness indicator used to interpolate damage factors from the look-up table (see Table 5-1) is based on both LGP and LGP_{eq}, as follows:

$$LGP_{agc} = \begin{cases} \min(120, \max(LGP, LGP_{eq})) & if\ LGP \leq 120 \\ LGP & if\ 120 < LGP \leq 210 \\ \max(210, \min(LGP, LGP_{eq})) & if\ LGP > 210 \end{cases}$$

Table 5-1 presents an example of agro-climatic constraints for rain-fed winter wheat. For irrigated production only the agro-climatic constraints related to excess wetness apply, as listed in the right half of the reduction factor table for LGP_{agc} above 240 days. A listing of the agro-climatic constraint parameters considered for GAEZ crop/LUTs are presented in Appendix 5-1.

Table 5-1 Agro-climatic constraints for rain-fed winter wheat

Agro-climatic loss factors (in %) for rain-fed winter wheat, 40 days pre-dormancy +120 days post-dormancy												
LGP/LGP$_{eq}$	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365	365^{+}
Low inputs												
b	0	0	0	0	0	0	10	10	10	10	10	10
c	10	10	10	0	0	0	0	0	10	10	30	30
d	0	0	0	0	0	0	0	0	0	10	30	30
High inputs												
b	0	0	0	0	0	0	0	0	10	10	10	10
c	10	10	0	0	0	0	0	0	0	10	10	30
d	0	0	0	0	0	0	0	10	10	10	30	30
LGP$_{t10}$	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365	
All input levels												
e	100	50	25	0	0	0	0	0	0	0	0	

The 'a' constraint (yield losses due to rainfall variability) is not applied in the current assessment. This constraint has become redundant due to explicit quantification of yield variability through the application of year-by-year historical rainfall data sets.

Calculation procedures

The yield reduction factors for agro-climatic constraints were parameterized in lookup tables (Appendix 5-1) organized according to:

i. Crop LUT;

ii. Thermal climate class;

iii. Number of actual/equivalent growing period days (LGP/LGP$_{eq}$) for the 'b', 'c' and 'd' agro-climatic constraints;

iv. Length of the frost-free period (LGP$_{t10}$) for the 'e' constraint, and

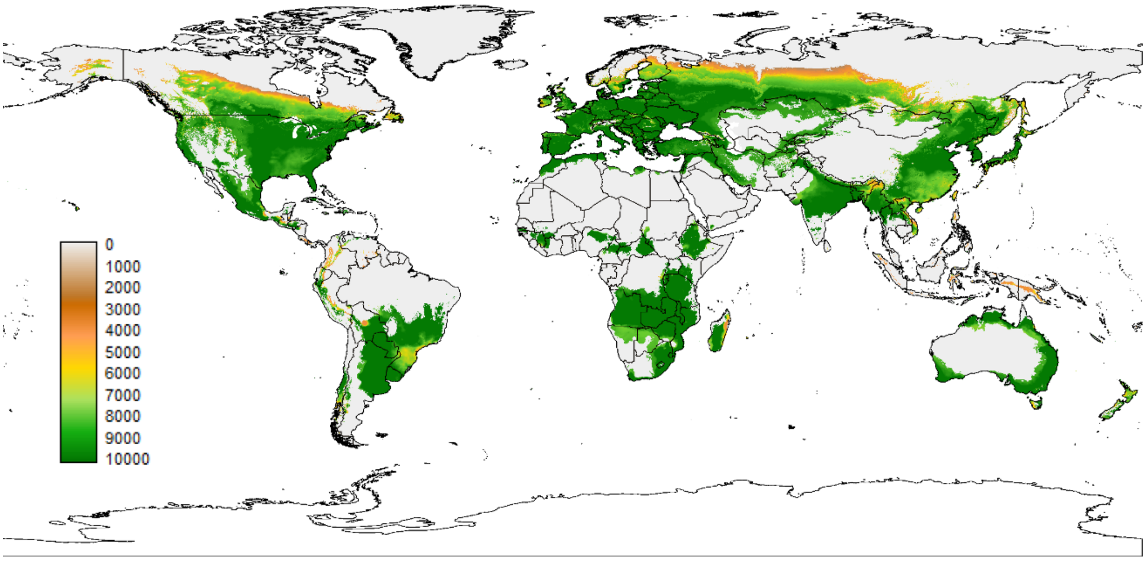
v. Input level.

By combining the individual agro-climatic constraint factors ($fct_b, \ldots, fct_e$) for constraint types 'b' to 'e', an overall yield reduction factor (*fc$_3$*) is calculated for each LUT:

$$fc_3 = \{(1 - fct_b) \times \ (1 - fct_c) \times (1 - fct_d), 1 - fct_e\}$$

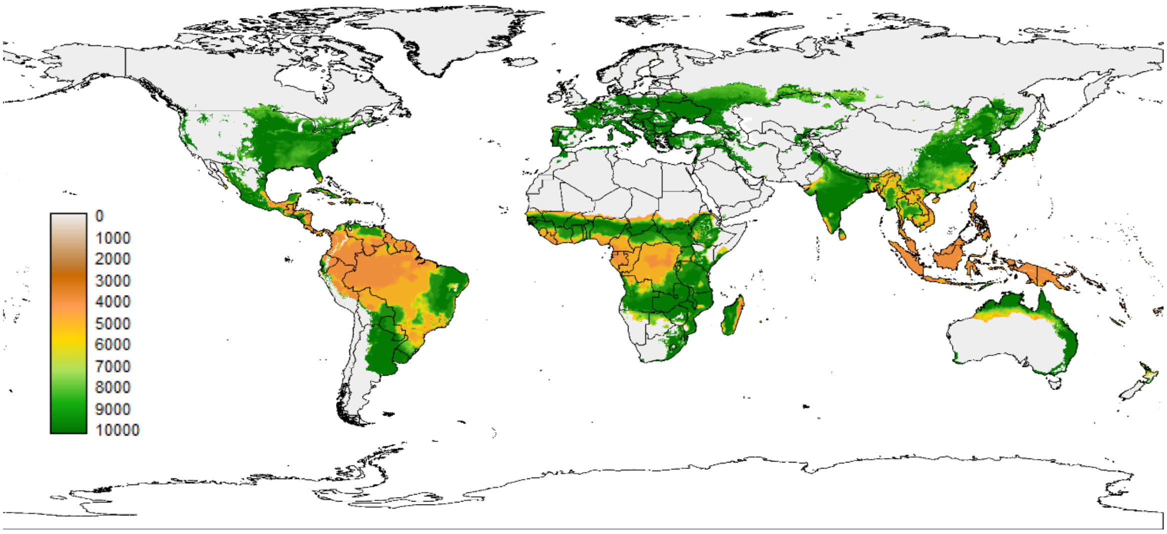
With agro-climatic constraints evaluated, all three yield reduction factors (*fc1* for thermal profile conditions and *fc2* for soil moisture deficit calculated in Module II, *fc3* for agro-climatic constraints calculated in Module III) are fully quantified and the agro-climatic potential crop yields are generated and mapped. Note that the evaluation of *fc2* and *fc3* is done separately for rain-fed and irrigated conditions. Factor fc1, though in principle the same for rain-fed and irrigated crops, can also vary by water source because crop calendars may differ between rain-fed and irrigated conditions and the selected defining LUT may differ as well.

Figure 5-2 Agro-climatic yield reduction factor (fc3) for wheat, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

Figure 5-3 Agro-climatic yield reduction factor (fc3) for grain maize, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

Figure 5-2 presents an example for wheat showing the global distribution of the overall yield reduction factor fc_3 expressing the expected wheat production losses due to agro-climatic constraint hazards of constraint types ‘b’ to ‘e’. The indicator value ranges from 0 to 10000. The latter, shown as dark green, indicates no expected losses due to agro-climatic hazards, indicator values below 5000 mean that half the yield or more may be lost due to unfavorable agro-climatic hazards. Figure 5-3 presents a map of factor fc_3 for maize where quite large impacts are indicated especially in humid tropical areas.

Calculation examples

As in previous chapters, we provide a grid cell example of the calculation of agro-climatic constraint factors fc_3. The location represented is a grid cell in the tropical lowlands in Tanzania. At 882 mm annual rainfall (average of 1981–2010) the moisture conditions are classified as sub-humid. The mean annual temperature is 24.3°C and the agro-climatic constraint loss factors are chosen from the parameter set for warm tropics. Table 5-2 and Table 5-3 provide the information necessary for calculating factor fc_3 for respectively rain-fed cotton and rain-fed grain maize.

Of the different constraints, the 'e' constraint (due early or late frost) is not applicable in lowland tropics. The 'd' constraint (due to moisture conditions affecting workability in the field) is evaluated as having no or very minor consequences. However, especially in the case of cotton an expected damage due to pest, disease and weed pressure results in a substantial loss factor, notably under low input assumptions.

Table 5-2 Estimation of agro-climatic constraints for 150-day rain-fed cotton (tropical cultivar)

Basic characteristics of grid cell	Agro-climatic indicators (Appendix 3-4)
IROW/ICOL1: 1160 (of 2160) 2605 (of 4320)	Thermal climate: tropical lowland
ALAT/ALNG: -6.63 (latitude) 37.04 (longitude)	Thermal zone: warm tropics
ALT: 645 m (altitude)	Mean annual temperature: 24.3 (°C)
Admin1 ID: 257 Tanzania	Mean temperature in coldest month: 21.3 (°C)
Admin2 ID: 220 Tanzania	Mean temperature in warmest month: 26.1 (°C)
Soil-MPU ID: 27116	Frost free period 365 (days)
YEAR: 1981–2010 (reference climate)	Annual rainfall: 882 (mm)
	Annual reference evapotranspiration: 1449 (mm)
	Annual precipitation/ET0 ratio: 61 (%)
	Number of growing period days: 235
	Number of growing periods: 1
	Equivalent LGP = 170 days (Section 3.5.2)

Agro-climatic loss factors (in %) for rain-fed cotton (tropical cultivars), growth cycle 150 days												
LGP_{agc}	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365**	**365+**
Low inputs												
'b' constraint	0	25	25	25	25	25	25	25	50	50	50	50
'c' constraint	0	25	25	25	25	25	25	50	50	50	50	50
'd' constraint	0	0	0	0	0	0	0	10	10	30	30	30

High inputs												
'b' constraint	0	0	0	0	0	25	25	25	25	50	50	50
'c' constraint	0	0	0	0	0	25	25	50	50	50	50	50
'd' constraint	0	0	0	0	0	0	10	10	30	30	30	30

N.B. Yield losses due to occurrence of early or late frost are not applicable in tropical lowland environments. Note, for interpolation the parameter values shown in each column refer to the mid-point of the respective interval. The columns of the look-up table, which are used for calculating the results of this example (by linear interpolation), are marked in green.

For the climatic conditions of the grid cell at Ilonga we obtain LGP_{agc} = 210 days. Therefore, the agro-climatic constraints result in yield loss factors for 150-day rain-fed cotton at low inputs as follows:

- 25% to account for 'b' constraints (yield losses due to the effect of pests, diseases and weed constraints on crop growth);
- 25% to account for 'c' constraints (yield losses due to water-stress, pest and diseases constraints on yield components and yield formation of produce), and
- No loss due to 'd' constraint (yield losses due to workability constraints e.g., wetness rendering produce handling difficulties).

In a similar way, we estimate for high inputs: 12.5% reduction each for 'b' and 'c' constraints and zero impact due to the 'd' constraint. Finally, in tropical lowland there is no risk of any early or late frost (i.e., the 'e' constraint is zero).

By combining the individual factors for constraint types 'b' to 'e', an overall yield factor (fc_3) is calculated. For low inputs this result in fc_3 = 0.75 x 0.75 x 1.0 = 0.5625, that is. a combined loss of 43.6%. The estimated constraint factor under high inputs is fc_3 = 0.875 x 0.875 x 1.0 = 0.7656, or a combined loss of 23.5%.

Proceeding as explained in the example for cotton, the agro-climatic constraints result in yield loss factors for 105-day rain-fed grain maize at low inputs as follows:

- 12.5% to account for 'b' constraints (yield losses due to the effect of pests, diseases and weed constraints on crop growth);
- 0% loss for 'c' constraints (yield losses due to water-stress, pest and diseases constraints on yield components and yield formation of produce), and
- 0% loss due to 'd' constraints (yield losses due to workability constraints e.g., wetness rendering produce handling difficulties).

In a similar way we estimate for high inputs: 0% reduction each for 'b' and 'c' constraints and 5% reduction due to the 'd' constraint. Finally, in tropical lowland there is no risk of any early or late frost (i.e., the 'e' constraint is zero).

By combining the individual factors for constraint types 'b' to 'e', an overall yield factor (fc_3) is calculated. For low inputs this result in fc_3 = 0.875 x 1.0 x 1.0 = 0.875, i.e., a combined loss of 12.5% caused by expected yield impacts of pests and diseases. The estimated constraint factor under high inputs is fc_3 = 1.0 x 1.0 x 0.95 = 0.95, or a combined loss of 5%, here caused by slight workability limitations.

Table 5-3 Estimation of agro-climatic constraints for 105-day rain-fed grain maize (lowland cultivar)

Basic characteristics of grid cell	Agro-climatic indicators (Appendix 3-4)
IROW/ICOL1: 1160 (of 2160) 2605 (of 4320)	Thermal climate: tropical lowland
ALAT/ALNG: -6.63 (latitude) 37.04 (longitude)	Thermal zone: warm tropics
ALT: 645 m (altitude)	Mean annual temperature: 24.3 (°C)
Admin1 ID: 257 Tanzania	Mean temperature in coldest month: 21.3 (°C)
Admin2 ID: 220 Tanzania	Mean temperature in warmest month: 26.1 (°C)
Soil-MPU ID: 27116	Frost free period 365 (days)
YEAR: 1981–2010 (reference climate)	Annual rainfall: 882 (mm)
	Annual reference evapotranspiration: 1449 (mm)
	Annual precipitation/ET0 ratio: 61 (%)
	Number of growing period days: 235
	Number of growing periods: 1
	Equivalent LGP = 170 days (Section 3.5.2)

Agro-climatic loss factors (in %) for rain-fed grain maize (lowland cultivars), growth cycle 105 days

LGP_{agc}	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365	365^{+}
Low inputs												
'b' constraint	25	25	25	0	0	25	25	25	25	25	25	50
'c' constraint	50	25	0	0	0	0	0	0	0	25	25	50
'd' constraint	0	0	0	0	0	0	10	10	10	30	30	30
High inputs												
'b' constraint	0	0	0	0	0	0	25	25	25	25	25	25
'c' constraint	50	25	0	0	0	0	0	0	0	25	25	50
'd' constraint	0	0	0	0	0	10	30	30	30	30	30	30

N.B. Yield losses due to occurrence of early or late frost are not applicable in tropical lowland environments. Note, for interpolation the parameter values shown in each column refer to the mid-point of the respective interval. The columns of the look-up table, which are used for calculating the results of this example (by linear interpolation), are marked in green.

.

6. Module IV (Agro-edaphic suitability)

Introduction

Module IV estimates yield reductions due to the constraints induced by prevailing soil and terrain-slope conditions. Crop yield impacts resulting from sub-optimum conditions for soils and for terrain-slopes are assessed separately.

The Harmonized World Soil Database (HWSDv1.2; Nachtergaele *et al.*, 2012[5]) served as source for soil resources data that was used for spatially detailed evaluation of soil qualities for edaphic crop suitability assessments. An example of the parameters extracted from HWSD v1.2 is given in Table 6-1.

Table 6-1 Example of SMU in HWSD v1.2

<table>
<tr><td>Location</td><td colspan="8">Tanzania, Ilonga</td></tr>
<tr><td>Coverage</td><td colspan="8">SOTWIS</td></tr>
<tr><td>Soil mapping unit</td><td colspan="8">27116</td></tr>
<tr><td>Dominant soil group</td><td colspan="8">AC - Acrisols</td></tr>
<tr><td>Soil unit symbol (FAO 90)</td><td colspan="2">ACu</td><td colspan="2">NTu</td><td colspan="2">LXf</td><td colspan="2">LPe</td></tr>
<tr><td>Soil unit name (FAO 90)</td><td colspan="2">Humic acrisols</td><td colspan="2">Humic nitisols</td><td colspan="2">Ferric lixisols</td><td colspan="2">Eutric leptosols</td></tr>
<tr><td>Share soil unit in soil mapping unit (%)</td><td colspan="2">55</td><td colspan="2">15</td><td colspan="2">15</td><td colspan="2">15</td></tr>
<tr><td>Topsoil textural class</td><td colspan="2">Medium</td><td colspan="2">Fine</td><td colspan="2">Medium</td><td colspan="2">Medium</td></tr>
<tr><td>Reference soil depth (cm)</td><td colspan="2">100</td><td colspan="2">100</td><td colspan="2">100</td><td colspan="2">30</td></tr>
<tr><td>Soil PHASE</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td></tr>
<tr><td>Reference drainage class (0–0.5% slope)</td><td colspan="2">Moderately Well</td><td colspan="2">Moderately Well</td><td colspan="2">Moderately Well</td><td colspan="2">Imperfectly</td></tr>
<tr><td>Reference AWC class(mm)</td><td colspan="2">150</td><td colspan="2">150</td><td colspan="2">150</td><td colspan="2">50</td></tr>
<tr><td>Gelic properties</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td></tr>
<tr><td>Vertic properties</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td></tr>
<tr><td>Petric properties</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td><td colspan="2">No</td></tr>
<tr><td>Soil profile characteristics</td><td colspan="4">Topsoil</td><td colspan="4">Subsoil</td></tr>
<tr><td>Soil unit symbol (FAO 90)</td><td>ACu</td><td>NTu</td><td>LXf</td><td>LPe</td><td>ACu</td><td>NTu</td><td>LXf</td><td>LPe</td></tr>
</table>

[5] Note that the basic soil information used in GAEZ v4 is very similar to the one used in GAEZ v3. However, algorithms for estimating soil qualities and soil unit suitability ratings have been updated and the calculation procedures for available soil water has been enhanced (Section 6.5). Procedures for assigning removable soil phases in cultivated land have been revisited and revised.

Sand fraction (%)	62	24	47	59	49	18	50	
Silt fraction (%)	19	27	23	24	17	21	17	
Clay fraction (%)	19	49	30	17	34	61	33	
USDA texture classification	sandy loam	clay (light)	sandy clay loam	sandy loam	sandy clay loam	clay (heavy)	sandy clay loam	
Gravel content (%)	0	1	0	0	0	1	0	
Organic carbon (% weight)	1.4	2.5	1.1	1.5	0.4	1.0	0.7	
pH (H_2O)	6.4	5.3	6.4	5.6	5	5.4	6.4	n.a.
CEC (clay) (cmol/kg)	21	23	37	192	16	27	47	
CEC (soil) (cmol/kg)	9	20	15	38	7	20	18	
Base saturation (%)	79	27	80	56	32	29	82	
TEB (cmol/kg)	7.1	5.4	12	21.3	2.2	5.8	14.8	
Calcium carbonate (% weight)	0	0	0	0	0	0	0	
Gypsum (% weight)	0	0	0	0	0	0	0	
Sodicity (ESP) (%)	1	1	1	1	1	1	2	
Salinity (ECe) (dS m^{-1})	0.1	0.0	0,0	0,0	0,0	0,0	0,0	

The agro-edaphic suitability estimations are crop/LUT-specific and are implemented for three basic levels of inputs and management (Section 6.1.1) and rain-fed and irrigated water supply systems (Section 6.1.2).

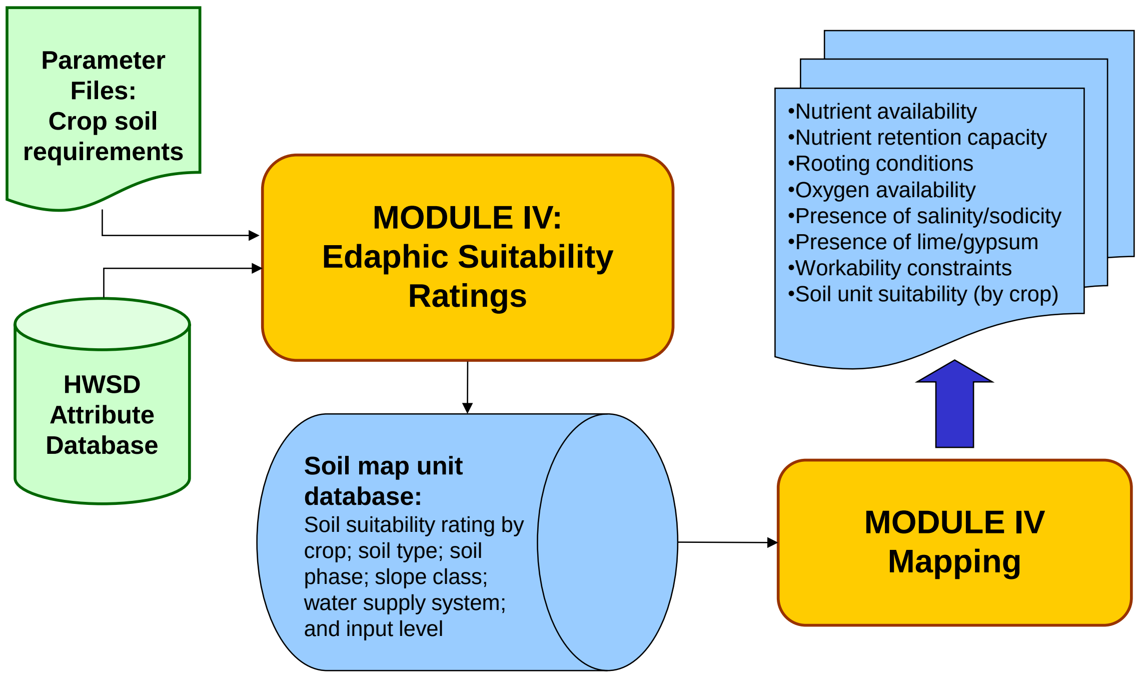
Soil suitability (Section 6.2 – 6.4) is assessed through crop/LUT specific evaluations of seven major soil qualities relevant for agriculture[6] namely: (1) soil nutrient availability; (2) soil nutrient retention capacity; (3) soil rooting conditions; (4) soil oxygen availability for roots; (5) presence of soil salinity and sodicity; (6) presence of lime and gypsum, and (7) soil workability. These are estimated from soil characteristics available in HWSD v1.2. These qualities are assessed for each crop and input/management level and for four water supply systems (rain-fed, gravity irrigated, sprinkler irrigation and drip irrigation) and result in a crop and input specific suitability rating. Available soil water is assessed considering soil depth, soil volume and salinity (Section 6.5).

Terrain suitability (Section 6.6) 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. Module IV evaluates soil units and terrain-slopes separately. Soil resources and terrain-slope conditions are aligned and integrated at 30 arc-second grid cell level (AEZ soil and terrain-slope databases) by ranking soil types regarding occurrence in different slope classes (see Module V). In this chapter, the framework used to assess the soil and terrain suitability for irrigated agriculture (Section 6.7) and for defining water collecting sites, areas which are prone to seasonal waterlogging and

[6] 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. In this module the concept of soil quality is restricted to soil properties relevant for agricultural production.

flood risks, is described. These sites with very specific soil water regimes are set aside for separate assessment (Section 6.8). The need for fallow periods is soil and climate related and is assessed in Section 6.9. The agro-edaphic assessment of Module IV is schematically presented in Figure 6-1.

Figure 6-1 Information flow in Module IV



Level of inputs and management

Individual soil and terrain characteristics have been related to requirements and tolerances of crops at three basic levels of inputs and management circumstances, namely: high, intermediate and low.

Low-level inputs/traditional management

Under the low input, traditional management assumption, the farming system is largely subsistence based and not necessarily market oriented. Production is based on the use of traditional cultivars (if improved cultivars are used, they are treated in the same way as local cultivars), labor intensive techniques, and no application of nutrients, no use of chemicals for pest and disease control and minimum conservation measures.

Intermediate-level inputs/improved management

Under the intermediate input, improved management assumption, the farming system is partly market oriented. Production for subsistence plus commercial sale is a management objective. Production is based on improved varieties, on manual labor with hand tools and/or animal traction and some mechanization. It is medium labor intensive, uses some fertilizer application and chemical pest, disease and weed control, adequate fallow and some conservation measures.

High-level inputs/advanced management

Under the high input, advanced management assumption, the farming system is mainly market oriented. Commercial production is a management objective. Production is based on improved high yielding varieties, is fully mechanized with low labor intensity and uses optimum applications of nutrients and chemical pest, disease and weed control.

Water supply systems

Four water supply systems have been separately evaluated. Apart from evaluating crop production systems based on rain-fed cultivation, specific soil requirements for three major irrigation systems have been established namely for gravity, sprinkler and drip irrigation. Table 6-2 presents an example of the water supply system/crop associations that are considered in the assessment. Appendix 6-1 lists for all crops all combinations considered.

Table 6-2 Examples of combining crops, input levels and water supply systems in GAEZ v4

Input levels	Water supply systems			
	Rain-fed	Irrigation		
		Gravity	Sprinkler	Drip
	H, I, L	H, I	H, I	H, I
Crops				
Wheat	v	corrugation/border	v	-
Wetland rice	v	basin	-	-
Maize	v	furrow	v	-
Cassava	v	-	-	-
Oil palm	v	-	-	v
Olive	v	basin/furrow	-	v

Soil and terrain suitability assessment procedures

In the GAEZ approach, land qualities are assessed in several steps involving specific procedures. The land qualities related to climate and climate-soil/terrain interactions (flooding regimes, soil erosion and soil nutrient maintenance) are treated separately from those land qualities specifically related to soil chemical properties and conditions that directly affect crop growth and production (Table 6-3).

Table 6-3 Land qualities and corresponding AEZ assessment procedures

Land quality	AEZ procedure (chapter/section)
Climate regime (temperature, moisture, radiation)	Climatic suitability assessment (Module II)
Soil physical and chemical properties	Soil suitability assessment (Section 6.2, 6.3 and 6.4))
Terrain slope	Assessment of sustainable use of sloping terrain (Section 6.5 and Section 6.6).
Soil nutrient maintenance	Fallow period requirement assessments (Section 6.7)
Flooding regime	Moisture regime analysis of water collecting sites (Section 6.8)

Soil suitability assessment procedure

Procedures and activities employed in the soil suitability assessment are schematically represented below in Figure 6-2.

In the GAEZ approach, first individual soil qualities are defined and quantified. Table 6-4 below provides an overview of the seven soil qualities in relation to relevant soil characteristics, including soil drainage characteristics and soil phase occurrences. The soil qualities influencing crop performance considered in the assessment include: nutrient availability (SQ1); nutrient retention capacity (SQ2); rooting conditions (SQ3); oxygen availability to roots (SQ4); presence of salinity and sodicity (SQ5); presence of lime and gypsum (SQ6), and workability (SQ7). The seven soil qualities (SQ1–7) are estimated from specific soil characteristics, the prevalence of soil phases, soil drainage characteristics, vertic and petric soil units, and gelic soil conditions.

Figure 6-2 Soil suitability rating procedures

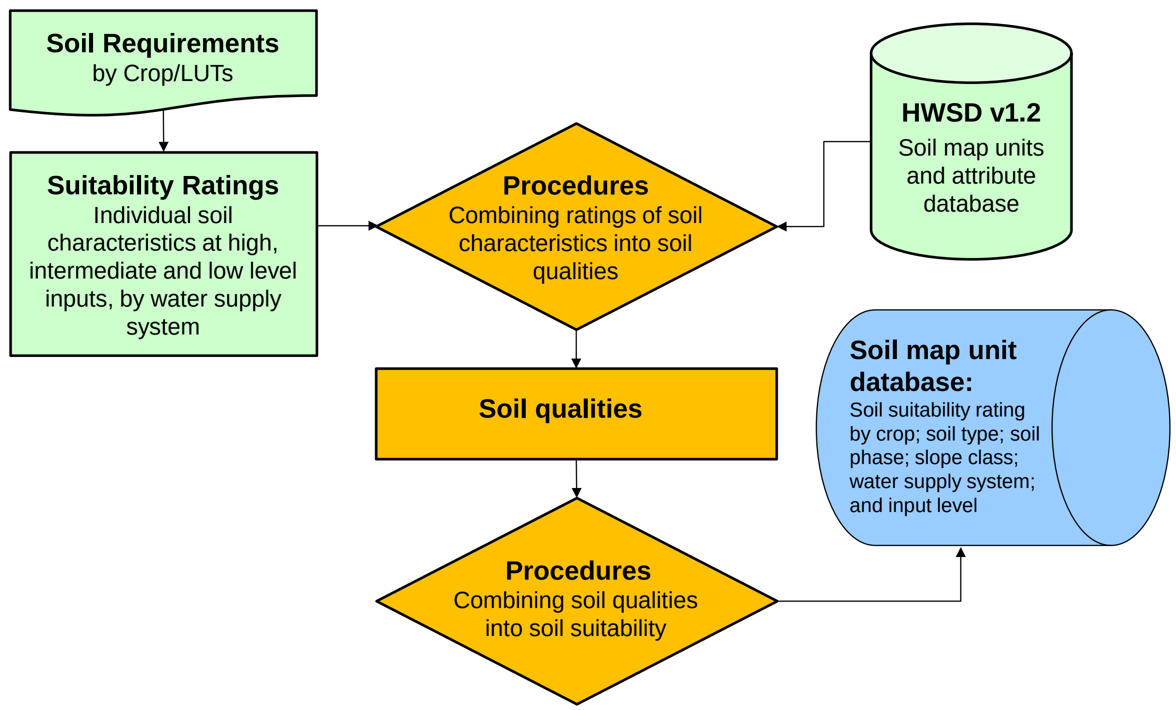


Table 6-4 Soil qualities and soil characteristics

Soil qualities		Soil quality related soil profile characteristics, soil drainage conditions and soil phase characteristics
SQ1	Nutrient availability.	Soil texture, soil organic carbon, soil pH, total exchangeable bases.
SQ2	Nutrient retention capacity.	Soil texture, base saturation, cation exchange capacity of soil and of clay fraction.
SQ3	Rooting conditions.	Soil texture, coarse fragments, vertic soil properties and soil phases affecting root penetration and soil depth and soil volume.
SQ4	Oxygen availability to roots.	Soil drainage and soil phases affecting soil drainage
SQ5	Presence of salinity and sodicity	Soil salinity, soil sodicity and soil phases influencing soil salinity and sodicity conditions.
SQ6	Presence of lime and gypsum	Calcium carbonate and Gypsum.
SQ7	Workability (constraining field management).	Soil texture, effective soil depth/volume, and soil phases constraining soil management (soil depth, rock outcrops, stoniness, gravel/concretions and hardpans).

Soil characteristics

Chemical and physical soil profile characteristics considered for both top-soil (0–30 cm) and sub-soil (30–100cm), include: the soil textural class; organic carbon content; pH, cation exchange capacity of soil and clay fraction; base saturation; total exchangeable bases; calcium carbonate contents; gypsum content; sodicity and salinity. For each soil unit these values are available from HWSD.

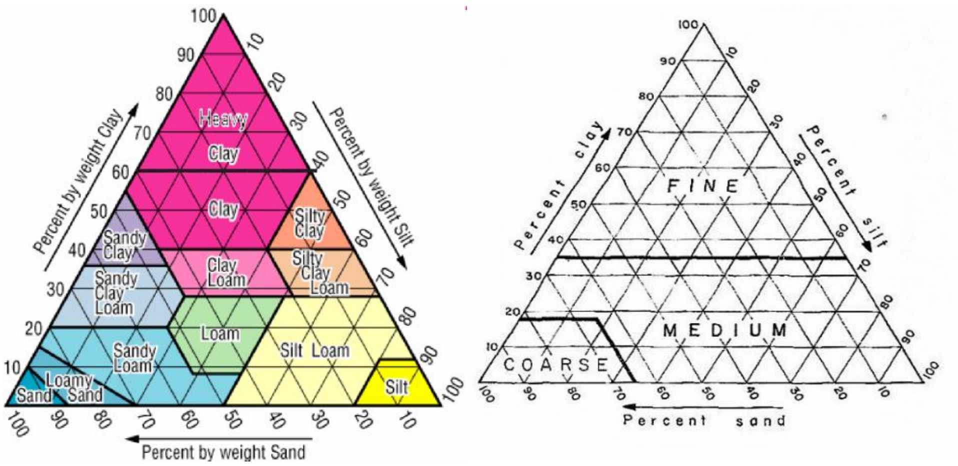
Soil texture classes (TXT) and soil textural groupings (1 - 3)

Soil texture[7] indicates the relative content of particles of various sizes, such as sand, silt and clay in the soil. Texture influences the ease with which soil can be worked, the amount of water and air it holds, and the rate at which water can enter and move through soil and as such it influences the following soil qualities: nutrient availability (SQ1), nutrient retention (SQ2), rooting conditions (SQ3) and soil workability (SQ7). Soil texture is also an important factor for determining soil drainage (Section 6.2.2).

There are 13 soil textural classes defined on the basis of their sand, silt and clay percentages: sand (S); loamy sand (LS); sandy loam (SL); loam (L); silt loam (SiL); silt (Si); sandy clay loam (SCL); clay loam (CL); silty clay loam (SiCL); sandy clay (SC); silty clay (SiC); clay (C), and heavy clay (Ch). These classes can be grouped into 3 main soil textural groupings corresponding approximately with soil texture classes: coarse (S, LS) with symbol 1, fine (C, Ch, SiC, SC) with symbol 3 and medium (all other textures) with symbol 2. Soil textural classes and Soil textural groupings are illustrated in Figure 6-3.

[7] Soil textures generally are associated with specific soil structures and mineralogy.

Figure 6-3. Soil texture classes (a) and Soil textural groupings (b)



(a) (b)

Gravel content (GRC)

While texture refers to the granulometry of particles less than 2mm in diameter, gravel concerns the soil fraction that has particles larger than 2mm. HWSD contains an estimate of the gravel content of each soil unit.

Soil Organic carbon content (SOC)

Soil organic carbon (SOC) is the main component of soil organic matter (SOM) that consists of plant and animal detritus at various stages of decomposition, cells and tissues of soil organisms, and substances that soil organisms synthesize. SOM provides numerous benefits to the physical and chemical properties of soil and its capacity to provide regulatory ecosystem services. SOM is especially critical for soil functions and soil health. Organic carbon is, the best simple indicator of SOM and moderate to high amounts of organic carbon are associated with fertile soils with a good structure and a good nutrient availability (SQ1).

Soil acidity and alkalinity (pH value)

The pH, measured in a soil-water solution, is a measure for the acidity and alkalinity of the soil. The pH has a strong effect on the availability of nutrients to the plant (SQ1). Optimum pH values range between 5.5 and 7.0. Very low pH values are associated with Aluminum toxicity.

Cation exchange capacity of clay (apparent CEC)

The apparent CEC gives an indication of the weathering stage of soils and is associated with the absence or presence of mineral reserves that influences the retention of nutrients and water. Weathering stages are also associated with clay minerals that have typical cation exchange capacities, with kaolinites generally having the lowest at less than 16 cmol/kg, while smectites have one of the highest with 80 cmol/kg or more. This is a good indicator for nutrient retention (SQ2).

Cation exchange capacity of soil (CEC)

The total nutrient fixing capacity of a soil is well expressed by its Cation Exchange Capacity (CEC). Soils with low CEC have little resilience and cannot build up stores of nutrients. Many sandy soils have CEC less than 4 cmol/kg. The clay content, the clay type and the organic matter content all determine the total nutrient storage capacity. Values in excess of 10 cmol/kg are considered satisfactory for most crops. The CEC is an excellent indicator for soil nutrient availability (SQ1).

Base saturation (BS)

The base saturation measures the sum of exchangeable cations (nutrients) Na, Ca, Mg and K as a percentage of the overall exchange capacity of the soil (including the same cations plus H and Al). High base saturation is associated with higher pH and high availability of nutrients.

Total exchangeable bases (TEB)

Total exchangeable bases represent for the sum of exchangeable cations in a soil: Sodium (Na), Calcium (Ca), Magnesium (Mg) and Potassium (K). TEB, as the CEC of the soil, is a good indication of nutrient availability (SQ1)

Calcium carbonate (CCB)

Calcium carbonate is a chemical compound (a salt), with the chemical formula $CaCO_3$. It is a common substance found as rock in all parts of the world and is the main component of shells of marine organisms, snails, and eggshells. Calcium carbonate is the active ingredient in agricultural lime and is usually the principal cause of hard water. It is quite common in soils particularly in drier areas and it may occur in different forms as mycelium-like threads, as soft powdery lime, as harder concretions or cemented in petrocalcic horizons. Low levels of calcium carbonate enhance soil structure and are generally beneficial for crop production. At higher concentrations they may induce iron deficiency and when cemented limit the water storage capacity of soils. It is of direct relevance to match CCB with the tolerance of crops for lime and gypsum (SQ6).

Calcium sulphate (GYP)

Gypsum is a chemical compound (a salt) which occurs occasionally in soils particularly in dryer areas. Research indicates that up to 2% gypsum in the soil favors plant growth, between 2 and 25% has little or no adverse effect if in powdery form, but more than 25% can cause substantial reduction in yields. It is of direct relevance to match GYP with the tolerance of crops for lime and gypsum (SQ6).

Exchangeable sodium percentage (ESP)

The exchangeable sodium percentage (ESP) has been used to indicate levels of sodium in soils. Sodium influences negatively soil structure and soil permeability. The tolerance of crops for sodium is variable avocado and nuts are extremely sensitive and show toxicity symptoms with ESP as low as 10%, while wheat, cotton and date palm for instance can stand ESP up till 40%. It is of direct relevance to match ESP with the tolerance of crops for sodicity (SQ5).

Electrical conductivity (EC)

Coastal and desert soils in particular can be enriched with water-soluble salts or salts more soluble than gypsum. Crops vary considerably in their resistance and response to salt in soils. Some crops will suffer at values as little as 2 $dS.m^{-1}$ (beans, radish, pear, apples) others can stand up to 16 $dS.m^{-1}$ (sugar beet, spinach, date palm). It is of direct relevance to match EC with the tolerance of crops for salinity (SQ5).

In addition to these soil characteristics three other soil characteristics are considered that are contained in the soil unit name. These are:

Vertic soil units and properties

Vertic soil units are those that have clayey textures which at some time in most years show one or more of the following: cracks, slickensides, wedge-shaped or parallel-piped structural aggregates that are not sufficiently expressed to qualify as Vertisols. Like Vertisols these characteristics unfavourably affect the workability of soils (SQ7) (FAO, Unesco and ISRIC, 1990).

Petric soil units

Petric Calcisols and Petric Gypsisols have respectively petrocalcic and petrogypsic horizons within 100cm of the surface, affecting SQ3 (rooting conditions), SQ6 (presence of lime and gypsum) SQ7 (workability) and available soil water (Section 6.5).

Gelic soil units

Gelic soil units are those that have permafrost within 200 cm of the surface (FAO, Unesco and ISRIC, 1990). Permafrost areas are unsuitable for crop growing and excluded from evaluation.

Reference Soil Depth (RSD)

The reference soil depth is set at 100 cm for all soil units except for Lithosols (10cm), Rankers (30cm), Rendzinas (30cm) and Leptosols (30cm). The reference soil depth is consequently adjusted as a function of impermeable layers or hardened layers and pans that occur within 100 cm of the surface.

Soil drainage

Soil drainage refers to the natural capability of a soil to remove excess water. The drainage capacity of a soil depends on the soil type, its texture, the presence or absence of impermeable layers and the slope on which the soil occurs.

The rate at which water drains into the soil has a direct effect on the amount and timing of runoff, what crops can be grown, and where wetlands form. In soils with low drainage rates, water will pond on the soil's surface. Poorly drained soils are desirable when growing crops like rice where the fields are flooded during cultivation, but other crops need better drained soils. Seven classes are recognized (FAO, 1995):

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

Drainage characteristics for each soil are generally included in national soil surveys. In HWSD a reference drainage class is given based on soil textural class; no soil phase and flat terrain is assumed. For the suitability assessment local occurrences of soil phases and terrain slope conditions are accounted for (for an example see Table 6-5).

Soils characterized by permanent or frequent high-water tables (such as most Histosols, Gleysols, and gleyic units of other soils) that generally occur on flat to gently sloping terrain had the poorest drainage (ranging between very poor to imperfectly drained). Soils with a high clay content (Vertisols) or soils characterized by an abrupt textural change (Planosols) or an anthraquic phase have similar poor drainage classes.

Soils characterized by coarse textures that occur on gentle slopes such as most Arenosols, Regosols and (non-gleyic) Podzols are partly excessively and partly somewhat excessively drained.

Shallow soils such as Leptosols and soils with plinthite or with a petrocalcic, petrogypsic, petroferric or duripan phase are imperfectly drained when having medium or fine textures and moderately well drained when having a coarse topsoil texture. In general, steep slopes and coarse topsoil texture, improve drainage conditions. An example of the drainage estimation is given in Table 6-5.

Table 6-5 Example of soil drainage estimation by soil unit, textural class and slope class

Soil unit	Textural class	Slope %							
		0 – 0.5	0.5 - 2	2 - 5	5 - 8	8 - 16	16 - 30	30 - 45	> 45
Gelic histosol (HSi)	All	VP	VP	VP	VP	VP	VP	VP	VP
Eutric gleysols (Gle)	1	P	P	P	I	I	I	I	I
	2	P	P	P	P	I	I	I	I
	3	VP	VP	VP	VP	P	P	P	P
Vertisols	1	P	P	I	I	I	I	I	I
	2	P	P	P	I	I	I	I	I
	3	P	P	P	P	I	I	I	I
Calcaric fluvisols (FLc)	1	MW	MW	MW	W	W	W	W	W
	2	MW	MW	MW	MW	W	W	W	W
	3	I	I	I	I	MW	MW	MW	MW
Cambic arenosols	1	SE	SE	SE	E	E	E	E	E

The soil drainage evaluation for each soil unit / slope class / texture group / phase combination is presented in Appendix 6-2.

Soil phases

Phases are subdivisions of soil units based on characteristics that are significant for the use or management of the land, but were not diagnostic for the separation of the soil units themselves at the time they were mapped (Since then soil classification changes have incorporated several of these phases in the soil unit name). In HWSD 33 different soil phases are recognized but only a smaller number of them have sufficient extent and have a direct link with the soil suitability to be discussed here. Some of the phases, mapped by different agencies (CEC, 1985; FAO and Unesco, undated; ISRIC and FAO, 2006; Shi *et al.*, 2004) can be grouped as they stand for very similar characteristics. In addition to the definition of the phases the link with the soil quality impact is given.

The soil phases (except Anthraquic) are also used for adjustments of the available water storage capacity of the soils in which they occur (AWC, see section – 6.5).

Stony/rudic/concretionary phases

These phases mark areas where the presence (> 35%) of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable. Hand tools or simple mechanical equipment may to some extent be used provided other conditions are favorable. Fragments up to 7.5 cm are considered as gravel; larger fragments are stones and boulders. These soil phases affect in the first place the workability of the soil (SQ7) but also the soil volume and rooting conditions (SQ3).

Lithic phase

This phase is used when continuous coherent and hard rock occurs within 50 cm of the soil surface. For Leptosols the lithic phase is not shown as it is implied in the soil unit name. This characteristic clearly affects the soil depth and consequently the rooting conditions (SQ3) and the workability (SQ7).

Petric and gravelly phases

The gravelly and petric phases refers to soil material which contains more than 40 % coarse fragments or oxidic concretions within 100 cm of the soil surface. The coarse material is embedded at less shallow depth compared to the stony phase but also affect the workability of the soil (SQ7) and the soil volume and rooting conditions (SQ3).

Skeletic phase

The skeletic phases refers to soil material which contains more than 40 % coarse fragments or oxidic concretions within 50 cm of the soil surface. Coarse material affects workability of soils (SQ7), and soil volume and rooting conditions (SQ3).

Petrocalcic phase

Marks soils in which the upper part of a petrocalcic horizon (> 40% lime, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface. The limitation in soil depth and the high concentration of lime implies constraints related to lime and gypsum (SQ6), but also the soils depth (SQ3) and the workability (SQ7) are affected.

Petrogypsic phase

Used for soils in which the upper part of a petrogypsic horizon (> 60% gypsum, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface. This high concentration of gypsum in an indurated layer implies constraints related to lime and gypsum (SQ6), but also the soils depth (SQ3) and the workability (SQ7) are affected.

Petroferric phase

The petroferric phase marks soils with a continuous layer of indurated material in which iron is important cement and organic matter is absent within 100 cm of the soil surface. These characteristics affect the workability of the soil (SQ7) and the soil volume and rooting conditions (SQ3).

Fragipan phase

The fragipan phase marks soils which have the upper level of the fragipan occurring within 100 cm of the surface. The fragipan is a loamy subsurface horizon with a high bulk density relatively to the horizon above it. It is hard or very hard and seemingly cemented when dry. Dry fragments slake or fracture in water. A fragipan is low in organic matter and is only slowly permeable. These characteristics limit the soil depth and the soil volume and affect the rooting conditions (SQ3).

Duripan phase

The duripan phase marks soils in which the upper level of a duripan occurs within 100 cm of the soil surface. A duripan is a subsurface horizon that is cemented by silica and contains often accessory cements mainly iron oxides or calcium carbonate. These characteristics limit the soil depth and the soil volume and affect the rooting conditions (SQ3).

Saline/salic phases

The saline and salic phase marks soils in which in some horizons within 100 cm of the soil surface show electric conductivity values higher than 4 dS m^{-1}. The saline phase is not shown for Solonchaks because their definition implies a high salt content. These concentrations of soluble salts are harmful for salt -sensitive crops and affects SQ5.

Sodic phase

The sodic phase marks soils which have more than 6 % saturation with exchangeable sodium in some horizons within 100 cm of the soil surface. The sodic phase is not shown for Solonetz because their definition implies a high ESP. These concentrations of sodium are harmful for Na -sensitive crops and affects SQ5.

Anthraquic phase

The anthraquic phase marks soils showing stagnic properties within 50 cm of the surface due to surface water logging associated with long continued irrigation, particularly of rice. This affects the rooting conditions of crops (SQ3).

Soil suitability ratings

The soil suitability assessment considers soil profile attributes, soil texture, soil drainage and soil phases.

Rating of soil characteristics

Soil characteristics suitability ratings are empirical coefficients that reflect the effect the value of the soil characteristic has on the yield potential of a specific crop. The rating system is adapted from Sys *et al.* (1991). The individual ratings themselves draw on extensive compilation of results of research farm experiments and empirical knowledge among others summarized by Sys *et al*. (1993), Nachtergaele (1988) and Nachtergaele and Bruggeman (1986). The ’Sys’ system uses six constraint classes namely:

- S0 - No constraint (100)
- S1 - Slight constraint (90)
- S2 - Moderate (70)
- S3 - Severe constraint (50)
- S4 - Very severe constraint (30)

- N - Not suitable (10)

The effect of soil characteristics often goes in a single direction: the lower the value the higher the constraint level (organic carbon is an example), or the higher the value the higher the constraint level (salinity and sodicity are examples). There are also characteristics that have an optimum value below and above which the constraints level increases (pH is an example). Note that for some characteristics, thresholds are built in that limit the constraint levels to be used. For instance, even at zero organic carbon content the maximum constraint is set at 70. For intermediate values of soil characteristics, the lower rating is selected. For instance, a pH value of 8.4 in rain-fed maize high input gets a rating of 50. A coarse fragments content of 60 % for workability (SQ7) is rated 10.

The ratings have been compiled by input level (high, intermediate and low) and by the four water supply systems (rain-fed, gravity irrigation, sprinkler irrigation and drip irrigation systems). The soil profile characteristics ratings account for soil characteristics, *gelic* soil conditions and *vertic* soil properties.

The ratings presented below (Table 6-6 and Table 6-7) refer to the rain-fed production of maize at high levels of inputs and wetland rice at low levels of inputs respectively. The full table for all crops at three input levels and by water supply systems are given in Appendix 6-3, 6-4 and 6-5. Soil characteristics and properties are organized by the soil quality to which they apply, some are used for more than one soil quality.

Table 6-6 Soil characteristics ratings for rain-fed maize at high input level

Soil characteristics, vertic soil properties and gelic conditions	Soil quality	Soil characteristics ratings					
		S0	S1	S2	S3	S4	N
		100[8]	90	70	50	30	10
Organic carbon	Nutrient availability (SQ1)	>1.2	0.8	0.5	0	0	0
TEB	Nutrient availability (SQ1)	>5	3.5	2	0	999	999
Low pH (H_2O)	Nutrient availability (SQ1)	>5.8	5.5	5.2	4.7	4.4	3.9
High pH (H_2O)	Nutrient availability (SQ1)	≤7	7.8	8.2	8.5	999	8.6
Low pH (H_2O)	Nutrient retention (SQ2)	>5	3.5	2	0	999	999
High pH (H_2O)	Nutrient retention (SQ2)	>5.8	5.5	5.2	4.7	4.4	3.9
CEC (clay)	Nutrient retention (SQ2)	>16	0	999	999	999	999
Base saturation (%)	Nutrient retention (SQ2)	50	35	20	0	999	999
CEC soil	Nutrient retention (SQ2)	>8	4	2	999	999	999
Vertic properties	Rooting conditions (SQ3)	-	X	-	-	-	-

[8] Ratings are given in percentages for ease of calculation when multiplying ratings of all soil qualities.

Gelic conditions	Rooting conditions (SQ3)	-	-	-	-	-	X
Rooting depth (cm)	Rooting conditions (SQ3)	>100	85	70	35	20	0
Coarse fragments	Rooting conditions (SQ3)	≤15	35	55	65	999	100
Electric conductivity	Presence of salinity (SQ5)	≤2	4	6	8	12	100
ESP (%)	Presence of sodicity (SQ5)	≤8	15	20	25	999	100
$CaCO_3$ (%)	Presence of lime (SQ6)	≤6	15	25	35	999	500
Gypsum (%)	Presence of gypsum (SQ6)	≤2	4	10	20	999	100
Rooting depth (cm)	Workability (SQ7b)	>100	85	70	35	20	0
Coarse fragments	Workability (SQ7b)	≤15	35	55	65	999	100

Table 6-7 Soil characteristics ratings for rain-fed wetland rice at low input level

Soil characteristics, vertic soil properties and gelic conditions	Soil quality	Soil characteristics ratings					
		S0	S1	S2	S3	S4	N
		100[9]	90	70	50	30	10
Organic carbon	Nutrient availability (SQ1)	>2	1.5	0.8	0	-	-
TEB	Nutrient availability (SQ1)	>6.5	4	2.8	1.6	0	999
Low pH (H_2O)	Nutrient availability (SQ1)	>6	5.5	5	4.5	4.1	3.6
High pH (H_2O)	Nutrient availability (SQ1)	<7	8.2	8.5	9	999	9.1
Low pH (H_2O)	Nutrient retention (SQ2)	>6	5.5	5	4.5	4.1	3.6
High pH (H_2O)	Nutrient retention (SQ2)	<7	8.2	8.5	9	999	9.1
CEC (clay)	Nutrient retention (SQ2)	>24	16	0	999	999	999
Base saturation (%)	Nutrient retention (SQ2)	80	50	35	20	0	999
CEC soil	Nutrient retention (SQ2)	>8	6	3	2	0	999
Vertic properties	Rooting conditions (SQ3)	X	-	-	-	-	-
Gelic conditions	Rooting conditions (SQ3)	-	-	-	-	-	X
Rooting depth (cm)	Rooting conditions (SQ3)	>90	70	35	30	999	0
Coarse fragments	Rooting conditions (SQ3)	<3	15	35	999	999	100
Electric conductivity	Presence of salinity (SQ5)	1	2	4	6	12	100

[9] Ratings are given in percentages for ease of calculation when multiplying ratings of all soil qualities.

ESP (%)	Presence of sodicity (SQ5)	10	20	30	40	999	100
CaCO3 (%)	Presence of lime (SQ6)	<3	6	15	25	999	100
Gypsum (%)	Presence of gypsum (SQ6)	<1	3	10	15	999	100
Rooting depth (cm)	Workability (SQ7a)	>85	70	999	35	999	0
Coarse fragments	Workability (SQ7a)	<3	15	35	999	999	100

Soil texture ratings

Soil texture conditions are influencing the various soil qualities (SQ1, SQ2, SQ3 and SQ7). In addition, texture is used in the determination of soil drainage conditions and therefore indirectly used for SQ4 as well. The table below provides example soil texture ratings for rain-fed production of wheat for individual soil qualities. Soil workability ratings differ for high (H) and intermediate and low inputs (L+I) and are provided separately. Soil texture ratings are compiled for individual water supply systems. Table 6-8 presents soil texture ratings for 13 texture classes for rain-fed maize.

Table 6-8 Soil texture ratings for rain-fed maize

Soil texture ratings for rain-fed production of maize													
Soil qualities and input level	Clay (heavy)	Silty clay	Clay (light)	Silty clay loam	Clay loam	Silt	Silt loam	Sandy clay	Loam	Sandy clay loam	Sandy loam	Loamy sand	Sand
	1	2	3	4	5	6	7	8	9	10	11	12	13
Nutrient availability, SQ1 (L)	100	100	100	100	100	100	100	100	100	100	90	70	30
Nutrient retention capacity, SQ2 H)	100	100	100	100	100	100	100	100	100	100	90	70	30
Rooting conditions, SQ3 (H+I+L)	90	100	100	100	100	100	100	100	100	100	100	100	100
Workability constraints, SQ7b (H)	100	100	100	100	100	100	100	100	100	100	100	100	100
Workability constraints, SQ7a (L+I)	50	100	100	100	100	100	100	100	100	100	100	100	100

Soil texture ratings for all crops are provided for four water supply systems and three levels of inputs (see Appendix 6-3, 6-4 and 6-5).

Soil drainage ratings

Reference soil drainage (on flat land) is characterized in the Harmonized World Soil Database in 7 classes and corrected for slope conditions. These classes are in a next step corrected as a function of the slope on which they occur (section 6.2.2).

Soil drainage ratings are varying by crop and may vary by prevalent soil texture conditions. Table 6-9 presents soil drainage ratings for rain-fed maize. Assumptions for artificial soil drainage differ by input levels. High level inputs assume full and adequate artificial drainage systems are installed while low and intermediate inputs assume no artificial drainage.

Soil drainage ratings for all crops and water supply systems are provided in Appendices 6-3 to 6-5.

Table 6-9 Soil drainage ratings for rain-fed maize

Fine, medium and coarse textural classes							
Drainage classes	VP	P	I	MW	W	SE	E
Low inputs*	10	50	90	100	100	100	100
Intermediate inputs**	10	50	90	100	100	100	100
High inputs***	90	100	100	100	100	100	100

** Low input drainage ratings assume no artificial drainage*
*** Intermediate input drainage ratings assume no artificial drainage (For organic farming or other sophisticated management types with reduced agro-chemical inputs, high input drainage ratings are to be applied in the model*
**** High input drainage ratings assume that full and adequate artificial drainage systems are installed*

Soil phases ratings

The soil phase ratings available from published and unpublished data sets have been compiled by input level (high, intermediate and low) and by the four water supply systems (rain-fed, gravity irrigation, sprinkler irrigation and drip irrigation systems).

The ratings presented below (Table 6-10) refer to the rain-fed production of maize. The ratings represent constraints implied by the occurrence of soil phases in percentage (100% rating no constraint to 0% rendering a soil totally unsuitable).

The soil phases are organized by soil quality to which they apply and by level of input and management and water supply system[10]. Two rating types have been used: "*full*" indicating that the soil phase rating would apply to 100% of the extent of the soil unit to which the soil phase is attributed and *"split"*, where the soil phase rating is assumed to affect 50% of the soil to which it is attributed while the other 50% is assumed not to be affected.

[10] Constraint ratings for stony, petric, petroferric, fragipan, duripan, rudic, skeletic, gravelly and concretionary soil phases have not been applied for cropland.

Table 6-10 Soil phase ratings for rain-fed maize at 3 input levels

Soil quality	Rating type*	Soil phases (HWSD)	INPUT LEVEL		
			HIGH	INT	LOW
SQ3 Rooting conditions	Full	Anthraquic	70	70	70
		Stony, rudic	75	75	75
		Lithic	50	50	50
	Split	Petric, petrocalcic, petrogypsic, petroferric, skeletic,gravelly, concretionary	60	60	60
		Fragipan, duripan,	100	85	70
SQ4 Oxygen availability	Full	Anthraquic	100	100	100
SQ5 Presence of salinity/sodicity	Split	Saline / salic	20	20	20
		Sodic	35	35	35
SQ6 Presence of lime/gypsum	Split	Petrocalcic	50	50	50
		Petrogypsic	35	35	35
SQ7 Workability	Full	Stony, rudic	50	75	75
		Lithic	30	50	75
	Split	Petric, petrocalcic, petrogypsic, petroferric, skeletic,gravelly, concretionary	50	50	50
		Fragipan, duripan,	100	100	100

**Rating type: Full = Total area affected by constraints as indicated; Split = 50% of area with constraints as indicated and 50% without constraints*

In the European Soil Database (ESDB) three additional characteristics have been recognized related to the available rooting depth, the occurrence of an impermeable layer and the water saturation of the soil during the year. The ratings for these additional characteristics in relation to three relevant soil qualities for maize, at three input levels are given in Table 6-11**.**

Table 6-11 ESDB Soil phase ratings for rain-fed maize at 3 input levels

Soil quality	SQ3			SQ4			SQ7		
Soil limitation / input level	L	I	H	L	I	H	L	I	H
No information (ROO= 0)	100	100	100				100	100	100
No obstacle to roots between 0 and 80 cm (ROO=1)	100	100	100				100	100	100
Obstacle to roots between 60 and 80 cm depth (ROO=2)	70	70	70				100	100	100
Obstacle to roots between 40 and 60 cm depth (ROO=3)	60	60	60				100	75	50

Obstacle to roots between 20 and 40 cm depth (ROO=4)	40	40	40				75	50	30
Obstacle to roots between 0 and 80 cm depth (ROO=5)	50	50	50				75	75	50
Obstacle to roots between 0 and 20 cm depth (ROO=6)	0	0	0				0	0	0
No information (IL=0)	100	100	100	100	100	100	100	100	100
No impermeable within 150 cm (IL=1)	100	100	100	100	100	100	100	100	100
Impermeable between 80 and 150 cm (IL=2)	100	100	100	100	100	100	100	100	100
Impermeable between 40 and 80 cm (IL=3)	60	60	80	100	100	100	100	75	60
Impermeable within 40 cm (IL=4)	30	30	30	100	100	100	75	50	30
Not wet within 80 cm for over 3 months, nor wet within 40 cm for over 1 month (WR=1)				100	100	100			
Wet within 80 cm for 3 to 6 months, but not wet within 40 cm for over 1 month (WR=2)				100	100	100			
Wet within 80 cm over 6 months, but not wet within 40 cm for over 11 months (WR=3)				100	100	100			
Wet within 40 cm depth for over 11 months (WR=4)				100	100	100			

Soil phase ratings for all crops are provided for all input levels and the four water supply systems in the Appendices 6-3 to 6-5.

Soil quality and soil suitability

This section deals with soil suitability classification procedures, following a two-step approach:

i. Crop responses to individual soil attribute conditions and relevant soil drainage and phase conditions are combined into soil quality (SQ) ratings, and

ii. Soil qualities are combined into crop specific soil suitability ratings, by input and management level and by water supply system.

Soil qualities

The procedures used to derive the soil qualities[11]: (SQ1–7) from various combinations of soil attributes are described below.

Let $(x_1,\dots,x_m)$ be a vector of soil attributes relevant for a particular soil quality SQ and $(\tau(x_1),\dots,\tau(x_m))$ the vector of respective soil attribute ratings, $0 \le \tau(x_j) \le 100$.

Further, let j_o denote the soil attribute with the lowest rating such that:

$$\tau(x_{jo}) \le \tau(x_j),\ j = 1,\dots,m.$$

Then we define soil quality SQ as a weighted sum of soil attribute ratings, as follows:

$$SQ = f_{SQ}(x_1,\dots,x_m) = \frac{\tau(x_{j_0}) + \frac{1}{m-1}\sum_{j\neq j_0} \tau(x_j)}{2}.$$

Nutrient availability (SQ1)

Natural availability of nutrients is decisive for successful low-level inputs farming and to some extent also for intermediate input levels. Diagnostics related to nutrient availability are manifold. Important soil characteristics of the topsoil (0–30 cm) are: soil texture/mineralogy/structure (TXT), soil organic carbon (OC), soil pH and total exchangeable bases (TEB). For the subsoil (30–100 cm) these are: texture/mineralogy/structure, pH and total exchangeable bases.

The soil profile attributes relevant to soil nutrient availability are related. For SQ1 the attribute with the lowest suitability rating is combined with the average of the remaining ones. The relationships shown below represent topsoil and subsoil separately using the soil attributes and ratings for the respective soil layers and input levels.

$$SQ1_{topsoil} = f_{SQ}\ (TXT, OC, pH, TEB)$$

$$SQ1_{subsoil} = f_{SQ}\ (TXT, pH, TEB)$$

[11] The soil qualities are separately estimated for topsoil (0–30 cm) and subsoil (30–100 cm) and combined by weighing factors according to crop specific rooting depth. While active roots are generally most present in the topsoil and to better account for crop-soil specific rooting patterns, for next GAEZ updates, new applications as well as for national AEZ applications, enhanced topsoil and subsoil weighing factors for soil qualities are recommended (Nachtergaele and van Velthuizen, unpublished).

Nutrient retention capacity (SQ2)

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

Nutrient retention capacity 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, organic matter 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 capacity in two ways, through its effects on available exchange sites on the clay minerals and by soil permeability.

The soil characteristics used for topsoil are respectively soil texture/mineralogy/structure (TXT), base saturation (BS), cation exchange capacity of soil (CEC_{soil}), and for the subsoil soil TXT, pH, BS, and cation exchange capacity of clay fraction (CEC_{clay}). Soil pH serves as indicator for aluminum toxicity and for micro-nutrient deficiencies.

For SQ2 the attribute with the lowest suitability rating is combined with the average of the remaining ones. Separately for high and intermediate inputs and management, and for topsoil and subsoil, the following relationships are used:

$$SQ2_{topsoil} = f_{SQ}\ (TXT, BS., CEC_{soil})$$

$$SQ2_{subsoil} = f_{SQ}\ (TXT, pH, BS, CEC_{clay})$$

Rooting conditions (SQ3)

Rooting conditions include effective soil depth (cm) accounting for impermeable layers, pans or indurated horizons in the soil and effective soil volume (vol. %) accounting for the presence of gravel and stones. Rooting conditions may be affected by the presence of a soil phase, either limiting the effective rooting depth or decreasing the effective volume accessible for root penetration. Rooting conditions influence crop growth in various ways:

- Adequacy of foothold, i.e., sufficient soil depth for the crop for anchoring;
- 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), in particular affecting root and tuber crops

Soil depth and volume limitations affect root penetration and constrain yield formation for roots and tubers. Rooting conditions (SQ3) are estimated by combining the reference soil depth rating with the soil property or soil phase that is most severely rated with regard to soil depth and volume conditions.

Relevant soil properties considered are: Reference soil depth, soil properties, i.e., soil texture/ mineralogy / structure, vertic properties, gelic properties, petric properties[12] and presence of coarse fragments.

The following soil phases are considered for SQ3:

- FAO 74 soil phases: Stony, lithic, petric, petrocalcic, petrogypsic, petroferric, fragipan and duripan.
- FAO 90 soil phases: Rudic, lithic, pertroferric, skeletic, fragipan and duripan.

ESDB (FAO 85) soil phases and other soil depth/volume related characteristics include: Stony, lithic, petrocalcic, petroferric, fragipan and duripan, and presence of gravel or concretions, obstacles to roots (six classes) and impermeable layers (four classes).

$$SQ3 = \tau\ (RSD)*\min[(\tau\ (SPR), \tau\ (SPH), \tau\ (OSD)]$$

where, τ (RSD) is reference soil depth rating, τ (SPR) is soil property rating, τ (SPH) is soil phase rating and τ (OSD) is other soil depth/volume related characteristics rating. OSD rating is derived from obstacles to roots and impermeable layers, both occurring in ESDB coverage in HWSD. Note, SQ3 is evaluated separately for topsoil and subsoil characteristics.

Oxygen availability (SQ4)

Oxygen availability in soils is largely defined by 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. For low and intermediate input 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 through the occurrence of specific soil phases. These include for the FAO '74 classification soil phases indicating phreatic conditions, and for the FAO '90 classification soil phases indicating anthraquic conditions.

SQ4 has been defined as the most limiting rating for a specific crop of either soil drainage or soil phase. Soil quality differs between farming input levels due to the different assumptions regarding artificial drainage. SQ4 is evaluated separately for topsoil and subsoil attributes.

$$SQ4 = \min[\tau(DRG), \tau(SPH)]$$

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

[12] Petric Calcisols and Petric Gypsysols (FAO 1990).

Presence of salinity and sodicity (SQ5)

Accumulation of salts may cause salinity. Excess of free salts, referred to as soil salinity, measured as electric conductivity (EC) or as saturation of the exchange complex with sodium ions. This then is referred to as sodicity or sodium alkalinity (it often occurs with very high pH values) and is measured as exchangeable sodium percentage (ESP).

Salinity affects crops through inhibiting the uptake of water. Moderate salinity affects growth and reduces yields; high salinity levels might kill the crop. Sodicity causes sodium toxicity and affects soil structure leading to massive or coarse columnar structure with low permeability. Apart from soil salinity and sodicity, saline (salic) and sodic soil phases affect crop growth and yields.

In case of simultaneous occurrence of saline (salic) and sodic soils the limitations are combined. Subsequently the most limiting of the combined soil salinity and/or sodicity conditions and occurrence of saline (salic) and/or sodic soil phase is selected. This soil quality is assumed independent of level of input and management. SQ5 is evaluated separately for topsoil and subsoil attributes.

$$SQ5 = \min[\tau\,(ESP)^{*}\,\tau(EC), \tau(SPH)]$$

where, τ( ) is the respective attribute rating function evaluated separately for topsoil and subsoil attributes.

Presence of lime and gypsum (SQ6)

Low pH leads to acidity related toxicities e.g., aluminum, iron, manganese toxicities and to deficiencies of, for instance, phosphorus and molybdenum. Calcareous soils exhibit generally micronutrient deficiencies of, e.g., iron, manganese, and zinc and in some cases toxicity of molybdenum. Gypsum (GYP) strongly limits available soil moisture. Tolerance of crops to calcium carbonate (CCB) and gypsum varies widely (FAO, 1990; Sys *et al.*, 1993).

Low pH and high CCB and GYP are mutually exclusive. The acidity (pH) related toxicities and deficiencies are accounted in SQ1, nutrient availability, and SQ2, nutrient retention capacity respectively.

In SQ6, the most limiting of the combination of excess calcium carbonate and gypsum in the soil and occurrence of petrocalcic and petrogypsic soil phases is assessed. This soil quality is assumed independent of level of input and management. SQ6 is evaluated separately for topsoil and subsoil attributes.

$$SQ6_{topsoil/subsoil} = \min[\tau(CCB)^{*}\tau(GYP), \tau(SPH)].$$

where, τ ( ) is the respective attribute rating function.

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, structure, organic matter content, soil consistence/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, other soils are only manageable at a specific moisture status, for hand cultivation or light machinery. Irregular soil depth, gravel and stones in the profile and rock outcrops, might prevent the use of heavy farm machinery. The soil constraints related to soil texture and soil structure are particularly affecting low and intermediate input farming LUTs, while the constraints related to irregular soil depth and stony and rocky soil conditions are foremost affecting mechanized land preparation and harvesting operations of high-level input mechanized farming LUTs. Workability constraints are therefore handled separately for low/intermediate and high inputs.

In the GAEZ rating procedure, the workability (SQ7) is influenced by (i) physical hindrance to cultivation and (ii) limitations to cultivation imposed by texture/clay mineralogy. In all cases, SQ7 is derived by combining the most limiting soil/soil phase attribute with the average of the remaining attribute response ratings. Soil phases considered are from FAO '74 classification: stony, lithic, petric, petrocalcic, petroferric, fragipan and duripan, and from FAO '90 classification: duripan, fragipan, lithic, petroferric, rudic and skeletic. SQ7 is evaluated by input level separately for topsoil and subsoil attributes.

$$SQ7 = f_{SQ}(\tau(RSD), \tau(GRC), \tau(SPH), \tau(TXT), \tau(VSP))$$

where, τ( ) is the respective input level specific attribute rating function, GRC is soil gravel content rating and VSP is vertic soil properties rating; other attributes as defined before.

In addition, for FAO'74 soil classification system: "Shifting sand, Rock debris, Outcrops, Dunes, Salt flats, Lakes and Ice caps" miscellaneous units are considered to render soils unsuitable for crop production, and for FAO'90 soil classification system these are: "Gelundic, Takyric, Yermic, Desert and Gobi" miscellaneous units.

Soil suitability

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

- Nutrient availability and nutrient retention capacity are key soil qualities;
- 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 intermediate level inputs farming;

- Nutrient availability and nutrient retention capacity are strongly related to rooting depth and soil volume available, and
- Oxygen available to roots, presence of salinity and sodicity, presence of lime and gypsum, and workability are regarded as equally important soil qualities, and the combination of these four soil qualities is best achieved by multiplication of the most limiting rating with the average of the ratings of the remaining three soil qualities.

Following the above principles for individual crops by three levels of inputs and four different water supply systems, each soil unit suitability rating (SR) has been estimated. The functional relationships for respectively low, intermediate and high input farming are presented below.

The procedures used to derive the soil ratings for low, intermediate and high levels of input and management: (*SRlow*, *SRint* and *SRhigh*) from various combinations of soil qualities are described as:

Let $(SQ_1,\ldots,SQ_m)$ be a vector of soil attributes relevant for a particular soil rating SR and $(\tau(SQ_1),\ldots, \tau(SQ_m))$ the vector of respective soil quality values, $0 \leq \tau(SQ_j) \leq 100$.

Further, let j_o denote the soil quality with the lowest value such that:

$\tau(SQ_{jo}) \leq \tau(SQ_j)$, j = 1,…,m.

Then we define f_{SR}, as:

$$f_{SR}(x_1,\ldots,x_m) = \frac{\tau(SQ_{j_0}) + \frac{1}{m-1}\sum_{j\neq j_0} \tau(SQ_j)}{2}$$

Low input farming:

SRlow = SQ1*SQ3*fSR(SQ4, SQ5, SQ6, SQ7)

Intermediate input farming:

SRint. = 0.5 * (SQ1+SQ2)*SQ3* fSR(SQ4, SQ5, SQ6, SQ7)

High input farming:

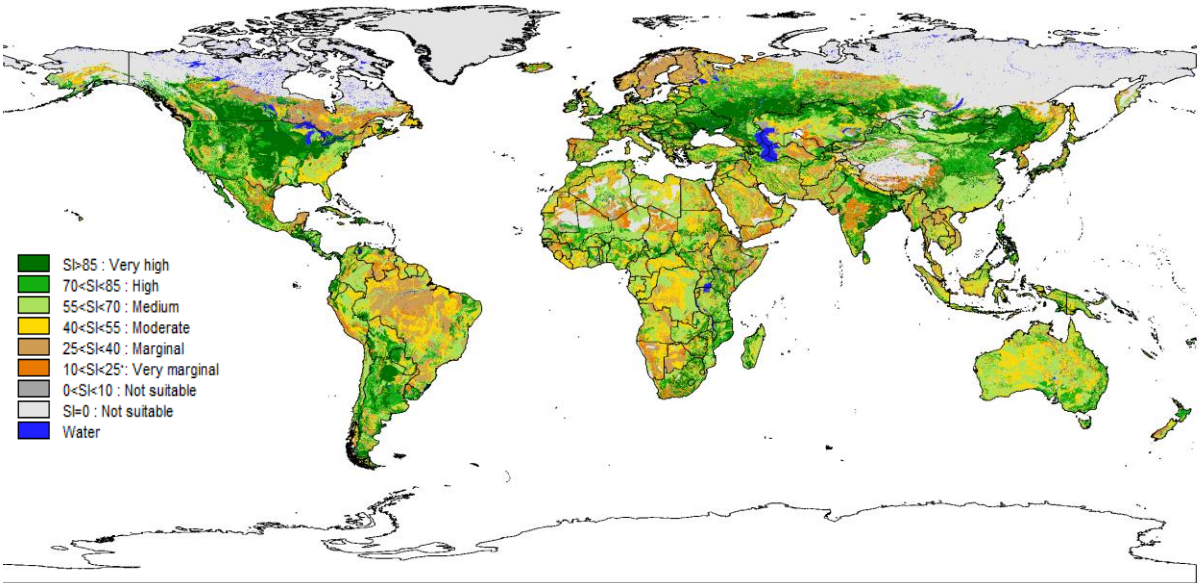
SRhigh = SQ2*SQ3* fSR(SQ4, SQ5, SQ6, SQ7)

The results of the soil unit suitability assessments have been tabulated by each crop/soil-unit/slope class/input level/water supply system combination for integration with the results of the agro-climatic suitability assessment[13]. Appendix 6-6 presents examples of soil suitability assessment for rain-fed maize at respectively high level of inputs/advanced management and for low level of inputs/traditional management. Figure 6-4 and Figure 6-5 present soil

[13] In Module V (Chapter 7), soil resources and terrain-slope conditions are integrated by ranking all soil types in each soil map unit with regard to occurrence in different slope classes. Module V also combines LUT specific results of the agro-climatic evaluation for biomass and yield calculated in Module II/III with edaphic ratings generated in Module IV and applies those to each soil/slope combination to estimate agro-ecological attainable yields and related variables.

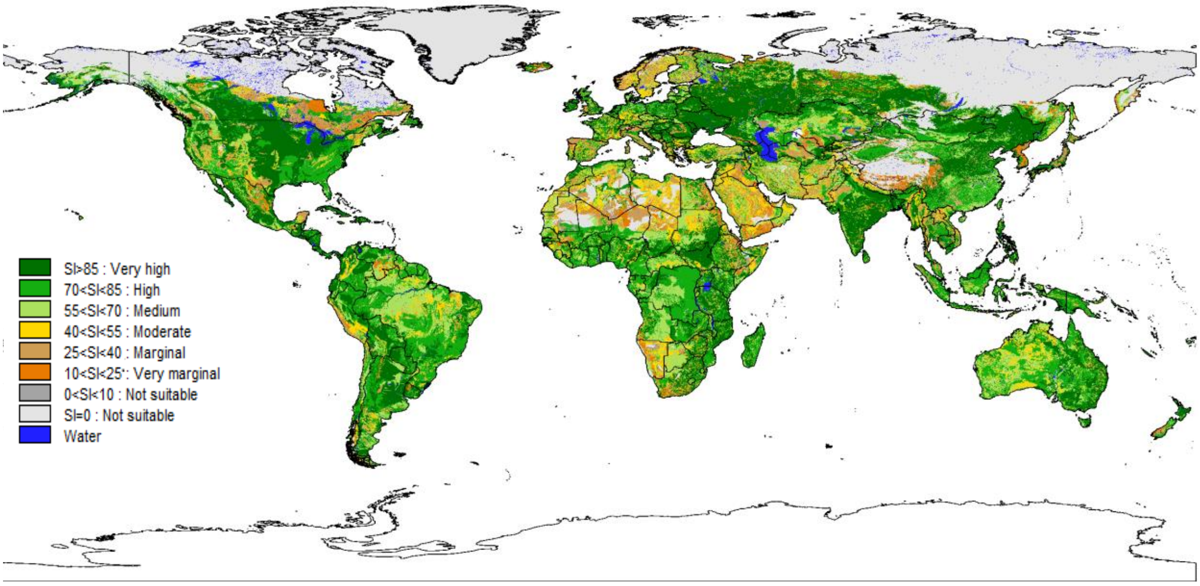
suitability for rain-fed maize assuming low level inputs and traditional management, respectively, high level inputs and advanced management.

Figure 6-4 Soil suitability for rain-fed maize, low level inputs



Source: FAO and IIASA, 2021

Figure 6-5 Soil suitability for rain-fed maize, high level inputs



Source: FAO and IIASA, 2021

Available soil water

The growing period for most crops continues beyond the rainy season and, to a greater or lesser extent, crops mature on moisture stored in the soil profile. However, the amount of soil moisture stored and available to a crop, varies, e.g., with depth of the soil, physical characteristics, and the rooting pattern of the crop. Depletion of soil moisture reserves causes the actual evapotranspiration to fall short of the potential rate. Available soil water capacity depends on physical and chemical characteristics, but above all on effective depth or volume (FAO, 1995).

As a first step soils are grouped in eight sets which reflect fundamental differences in soil depth, textural changes with depth, influence of parent material or seasonal flooding conditions:

i. Histosols, Fluvisols and Gleysols: which are considered as wetlands or water collecting sites (Section 6.9);

ii. Andosols: which due to parent material influence have a relatively high available soil water capacity (AWC) (except Vitric Andosols);

iii. Vertisols: specific characteristics set this group of soils apart;

iv. Lithosols and miscellaneous land units: Lithosols and 'rock' units are characterized by a very limited soil depth;

v. Rendzinas and Rankers: both these soil groups are, by definition, shallow;

vi. Soil groups and soil units with no implied clay increase with depth: this group combines soils in which the topsoil texture is considered representative of the whole profile. These are: Solonchaks, Regosols, Podzols, Cambisols, Arenosols, Vitric Andosols, Greyzems and the non-luvic soil units of the Xerosols, Yermosols, Kastanozems, Chernozems and Phaeozems;

vii. Soil groups and soil units with an implied clay increase with depth: this set combines soils in which subsoil texture is finer than the topsoil texture. These are Solonetz, Podzoluvisols, Nitisols, Acrisols, Ferralsols and luvic units of the Xerosols, Yermosols, Kastanozems, Chernozems and Phaeozems, and

viii. Planosols: This soil group is considered to have a fine textured subsoil regardless of the topsoil texture which separates these soils from those discussed under vi and vii.

Water availability to plants grown on Histosols, Gleysols and Fluvisols is mainly a function of groundwater or surface water levels and flooding. These soils are considered here as occurring in 'water collecting sites' and are treated separately. Tropical soils (Ferralsols, Acrisols, Nitisols, Ferralic Cambisols and Ferric Luvisols) have specific mineralogy. AWC for these soils, compared to similar textural classes for other soils is substantially lower and have been reduced by an assumed 10%. Estimated available soil water capacity (AWC) by soil units and by topsoil texture groupings for FAO'74 and FAO'90 soil classifications for reference soil depths are presented in the Appendix 6-7.

Gravel, stones, boulders, and rock fragments when present in the profile reduce considerably the capacity of a soil to store moisture. The FAO74 legend uses this criterion when defining the stony phase reflecting the presence of coarse fragments in the surface layers or at the surface to an extent that it reduces effective soil volume and therefore AWC significantly. For water balances used in AEZ, AWC is assumed to be reduced in the order of 50% when Stony or Rudic soil phases occur (Fischer, G., H. van Velthuizen, 2002).

Another soil phase affecting soil volume is the Lithic soil phase which occurs within 50 cm of the soil surface. In case of soils with a Lithic soil phase effective soil volume and AWC are assumed to be reduced with 65% (Fischer, G., H. van Velthuizen, 2002).

Other soil volume limiting soil phases, i.e., Petric, Petrocalcic, Petrogypsic, Petroferric, Duripan, Skeletic, Gravelly and Concretionary soil phases, occur anywhere between soil surface and 100 cm depth. Depth of occurrence defines both effective soil volume and AWC. It has therefore been assumed that in 50% of the extent of the soil unit with such soil phase the upper part of the soil phase occurs between 50 and 100 cm from the soil surface and in the other 50% in less than 50 cm depth. Accordingly, AWC has been reduced by 25% in 50% of the extent, respectively by 65 % in the other 50% (see Box 6-1, Example 2) (Fischer, G., H. van Velthuizen, 2002). In addition, the ESDB part of HWSD defines soil volume limiting impermeable layers (IL). There is no effect for IL = 1 (impermeable layer not within top 150 cm) and IL = 2 (impermeable layer between 80 – 120 cm). For IL = 3 (impermeable layer between 40–80 cm) a soil volume reduction factor of 40% is used and for IL=4 (impermeable layer between 20–40) 70%.

Apart from soil volume reducing soil phases, effective soil volume and AWC may significantly be affected by coarse fragment occurrences, as for example in Vitric Andosols, Rankers, Rendzinas and Lithosols /Leptosols. In other soils, such as Ferralsols, Regosols, Acrisols, Petric Calcisols and Petric Gypsisols coarse fragment occurrences are common but largely dependent on local conditions.

Coarse fragments (gravel) contents in topsoil and subsoil, systematically available from HWSD, have been used to adjust AWC. The AWC adjustment follows procedures recommended by USDA and NCRS (1967). The procedures are based on linear relationships between coarse fragment content and AWC. The relationships have been established by USDA soil texture classes. Adjustments of AWC due to coarse fragments of topsoil and subsoil have been derived separately and averaged before applying. Table 6-12 presents AWC adjustments for coarse fragments content by texture class.

Table 6-12 AWC adjustments for coarse fragments by texture class

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	0,300	0,233
Silty clay	1,000	0,875	0,750	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	0,250
Silty clay loam	1,000	0,900	0,800	0,700	0,600	0,500	0,425	0,325	0,300
Clay loam	1,000	0,900	0,800	0,700	0,600	0,500	0,425	0,325	0,300
Sandy clay loam	1,000	0,867	0,800	0,700	0,600	0,500	0,433	0,367	0,300

Silt loam	1,000	0,900	0,800	0,700	0,600	0,500	0,425	0,325	0,300
Loam	1,000	0,882	0,794	0,706	0,618	0,500	0,441	0,324	0,294
Sandy loam	1,000	0,917	0,792	0,667	0,625	0,500	0,458	0,375	0,292
Loamy sand	1,000	0,857	0,786	0,714	0,643	0,500	0,429	0,357	0,286
Sand	1,000	0,917	0,833	0,667	0,583	0,500	0,417	0,333	0,250

The same USDA source provides adjustments to AWC as a function of soil electrical conductivity. In a similar way as for coarse fragment contents, adjustments are made by USDA soil texture classes.

Table 6-13 presents AWC adjustments for soil salinity levels by texture class. As can be seen from the table, AWC relates in a quadratic polynomial fashion with soil salinity.

Table 6-13 AWC adjustments for soil salinity by texture class

USDA Texture class	Soil salinity (dS m-1)							
	0	2	4	6	8	10	12	14
Clay	1,000	0,933	0,867	0,800	0,733	0,667	0,500	0,300
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	0,950	0,875	0,800	0,725	0,625	0,475	0,325
Clay loam	1,000	0,950	0,875	0,800	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	0,950	0,875	0,800	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

Topsoil and subsoil adjustment factors are derived separately and have been averaged before applying to the soil units in question. Unlike soils with volume and soil depth reducing soil phases which are treated separately, for the estimation of salinity-based AWC adjustment factors, saline and salic phases are not considered to avoid double counting.

Box 6-1 AWC calculation examples

Example 1

The dominant soil unit in the Ilonga example (HWSD v1.2.1) is an Umbric Acrisol (ACu) – FAO'90 classification - with a SL (sandy loam) topsoil texture (0–30cm) and a SCL (sandy clay loam) subsoil texture (30–100 cm), gravel content is zero throughout the soil profile, while the salinity is negligible at 0.1 dS/m. No soil phases occur. In that case the AWC would be equal to the reference AWC, i.e., 162 mm for ACu with medium topsoil texture (see Appendix 6-7, Table A6-7a).

Example 2

A Calcic Cambisol (Bk) – FAO'74 classification - with a SiCL (silty clay loam) texture throughout and slightly saline; in the topsoil electric conductivity is 2 dS m^{-1} and 4 dS m^{-1} in the subsoil. This soil has a petrocalcic soil phase. Reference AWC (see Appendix 6-7, Table A6-7b) for a Bk soil with medium topsoil texture is 180 mm. The petrocalcic soil phase - occurrence of a petrocalcic horizon (>40% lime, cemented, usually thicker than 10 cm with upperpart within 100 cm of the soil surface) - decreases AWC. It is assumed that in 50% of the extent of this Bk soil unit (part A) the upper level of the petrocalcic horizon occurs between 50 and 100 cm depth. In this case AWC is reduced with 25%; i.e., AWC is estimated to be 135 mm. The other 50% (part B) assumes that the upper level of the petrocalcic horizon occurs within 50 cm from the soil surface. In this case AWC is reduced with 65%, i.e., AWC is estimated to be 63 mm. When accounting for topsoil and subsoil salinity, further reductions are applied namely for the topsoil with extra 5% and subsoil with extra 12.5 % (Table 6-13). The overall reduction to soil salinity is taken as the average between topsoil and subsoil being 8.25%. For Part A of the Bk soil unit this results in AWC = 135 × 0.9175 = 124 mm, and for Part B of the Bk soil unit AWC = 63 × 0.9175 = 58 mm.

Example 3

A Ferralic Arenosol (ARo) – FAO'90 classification- with S (sand) topsoil texture and LS (loamy sand) subsoil texture contains 10% coarse fragments in the topsoil and 30% in the subsoil.

Reference AWC (see Appendix 6-7, Table A6-7a) for a ARo soil with coarse topsoil texture is 95 mm. Topsoil and subsoil coarse material content reduces effective soil volume, therefore further reductions are applied namely for the topsoil extra 8.3 % and subsoil extra 28.6 % (Table 6-12). The overall reduction due to coarse fragments in this ARo soil is taken as the average between topsoil and subsoil being 18.5 %. This results for the ARo soil unit in an estimate of AWC = 95 × 81.5 = 77 mm.

Terrain suitability assessment procedures

The influence of topography on agricultural land use is manifold. Farming practices are by necessity adapted to terrain slope, slope aspect, slope configuration and micro-relief. For instance, steep irregular slopes are not practical for mechanized cultivation, while these slopes might very well be cultivated with adapted machinery and hand tools.

Sustainable agricultural production on sloping land is foremost concerned with the prevention of erosion of topsoil and decline of fertility. Usually this is achieved by combining special crop management and soil conservation measures. Cultivated sloping land may provide inadequate soil protection and without sufficient soil conservation measures, cause a considerable risk of accelerated soil erosion. In the short term, cultivation of slopes might lead to yield reductions due to loss of applied fertilizer and fertile topsoil. In the long term, this will result in losses of land productivity due to truncation of the soil profile and consequently reduction of natural soil fertility and of available soil moisture.

Rain-fed annual crops are the most critical to cause topsoil erosion, because of their particular cover dynamics and management. The terrain-slope suitability rating used in the Global AEZ study captures the factors described above which influence production and sustainability. This is achieved through: (i) defining for the various crops permissible slope ranges for cultivation, by setting maximum slope limits; (ii) for slopes within the permissible limits, accounting for likely yield reduction due to loss of fertilizer and topsoil, and (iii) distinguishing among farming practices ranging from manual cultivation to fully mechanized cultivation.

Ceteris paribus, i.e., under similar crop cover, soil erodibility and crop and soil management conditions, soil erosion hazards largely depend on amount and intensity of rainfall. Data on rainfall amount is available on a monthly basis for all grid cells in the climate inventory. Rainfall intensity or energy, as is relevant for soil erosion, is not estimated in these data sets.

To account for clearly existing differences in both amount and within-year distribution of rainfall, use has been made of the modified Fournier index (Fm), which reflects the combined effect of rainfall amount and distribution (FAO/UNEP, 1977), as follows:

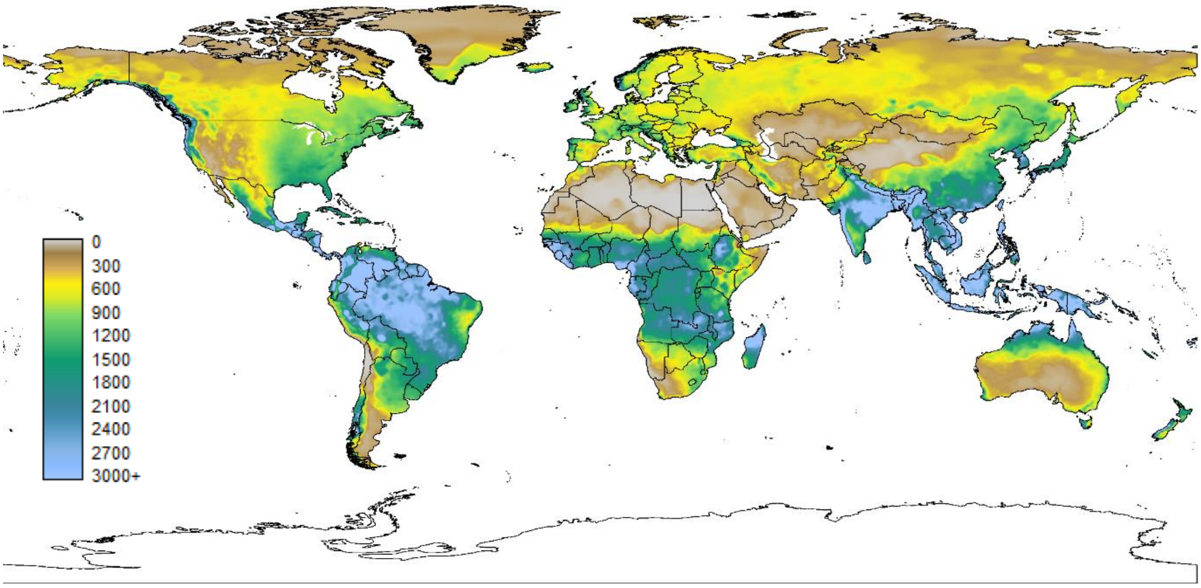
$$Fm = \frac{12\sum_{i=1}^{12} P_i^2}{\sum_{i=1}^{12} P_i}$$

where P_i is the precipitation of month i

When precipitation is equally distributed during the year, i.e., in each month one-twelfth of the annual amount is received, then the value of Fm is equal to the annual precipitation. On the other extreme, when all precipitation is received within one month, the value of Fm amounts to twelve times the annual precipitation. Hence, Fm is sensitive to both total amount and distribution of rainfall and is limited to the range 1 to 12 times the annual precipitation.

The Fm index has been calculated for all grid cells of the 5 arc-minute climatic inventory in Module I (see Chapter 3). The results have been grouped in six classes, namely: Fm < 1300, 1300–1800, 1800–2200, 2200–2500, 2500–2700, and Fm > 2700. These classes were determined on basis of regression analysis, correlating different ranges of length of growing period zones with levels of the Fournier index Fm. This was done to incorporate the improved climatic information on within year rainfall distribution into GAEZ while keeping consistency with earlier procedures of the methodology, which were originally defined by LGP classes. Figure 6-6 presents the global distribution of the Modified Fournier index.

Figure 6-6 Modified Fournier index (Fm)



Source: FAO and IIASA, 2021

Slope ratings are defined for the eight slope range classes used in the land resources database, namely: 0–0.5% very flat, 0.5–2% flat, 2–5% gently sloping, 5–8 % undulating, 8–16% rolling, 16–30% hilly, 30–45% steep, and > 45% very steep. The following suitability rating classes are employed:

Table 6-14 presents terrain-slope ratings for rain-fed conditions for eight crop groups and at three levels of inputs and management, as used for the lowest class of the Fournier index, i.e., Fm< 1300. Appendix 6-8 presents terrain slope ratings for the other classes of Fm, namely: Fm 1300–1800, Fm 1800–2200, Fm 2200–2500, Fm 2500–2700 and Fm >2700.

Table 6-14 Terrain-slope ratings for rain-fed conditions (Fm< 1300)

High inputs

Slope gradient classes	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	> 45%
Annuals 1	S1	S1	S1	S1	S1/S2	S2/N	N	N
Annuals 2	S1	S1	S1	S1	S1/S2	S2/N	N	N
Annuals 3	S1	S1	S1/S2	S2	S2/N	N	N	N
Perennials 1	S1	S1	S1	S1	S2	S2/N	N	N
Perennials 2	S1	S1	S1	S1	S1/S2	S2/N	N	N
Perennials 3	S1	S1	S1	S1	S1/S2	S2/N	N	N
Perennials 4	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 5	S1	S1	S1	S1	S1/S2	S2/N	N	N
Forest	S1	S1	S1	S1	S1	S1	S1/S2	N

***S1**: Optimum conditions; **S2**: Sub-optimum conditions; **S1/S2**: 50% optimum and 50% sub-optimum conditions; **S1/N**: 50% optimum and 50% not suitable conditions; **S2/N**: 50% sub-optimum and 50% not suitable conditions; **N**: Not suitable conditions*
***Annuals 1**: wheat, barley, rye, oat, buckwheat; **Annuals 2**: maize, sorghum, pearl millet, foxtail millet, dryland rice, potato, white potato, sweet potato, phaseolus bean, chickpea, cowpea, gram, dry pea, pigeon pea, rapeseed, soybean, groundnut, sunflower, cotton, sugar beet, rape, flax, white yam, greater yam, tobacco, cabbage, carrot, onion, tomato; **Annuals 3**: wetland rice; **Perennials 1**: sugar cane; **Perennials 2**: olive, citrus; **Perennials 3**: cassava, oil palm, banana, yellow yam, cocoyam, cocoa, coffee, coconut, jatropha; **Perennials 4**: pasture legumes, grasses, tea; **Perennials 5**: alfalfa, switchgrass, miscanthus, reed canary grass; **Forest**: para rubber*

Intermediate inputs

Slope gradient classes	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	> 45%
Annuals 1	S1	S1	S1	S1	S1	S2	S2/N	N
Annuals 2	S1	S1	S1	S1	S1/S2	S2	S2/N	N
Annuals 3	S1	S1	S1	S1/S2	S2/N	N	N	N
Perennials 1	S1	S1	S1	S1	S1/S2	S2	S2/N	N
Perennials 2	S1	S1	S1	S1	S1	S2	S2/N	N
Perennials 3	S1	S1	S1	S1	S1	S2	S2/N	N
Perennials 4	S1	S1	S1	S1	S1	S1	S2	N
Perennials 5	S1	S1	S1	S1	S1	S2	S2/N	N
Forest	S1	S1	S1	S1	S1	S1	S1/S2	S2/N

***S1**: Optimum conditions; **S2**: Sub-optimum conditions; **S1/S2**: 50% optimum and 50% sub-optimum conditions; **S1/N**: 50% optimum and 50% not suitable conditions; **S2/N**: 50% sub-optimum and 50% not suitable conditions; **N**: Not suitable conditions*
***Annuals 1**: wheat, barley, rye, oat, buckwheat; **Annuals 2**: maize, sorghum, pearl millet, foxtail millet, dryland rice, potato, white potato, sweet potato, phaseolus bean, chickpea, cowpea, gram, dry pea, pigeon pea, rapeseed, soybean, groundnut, sunflower, cotton, sugar beet, rape, flax, white yam, greater yam, tobacco, cabbage, carrot, onion, tomato; **Annuals 3**: wetland rice; **Perennials 1**: sugar cane; **Perennials 2**: olive, citrus; **Perennials 3**: cassava, oil palm, banana, yellow yam, cocoyam, cocoa, coffee, coconut, jatropha; **Perennials 4**: pasture legumes, grasses, tea; **Perennials 5**: alfalfa, switchgrass, miscanthus, reed canary grass; **Forest**: para rubber*

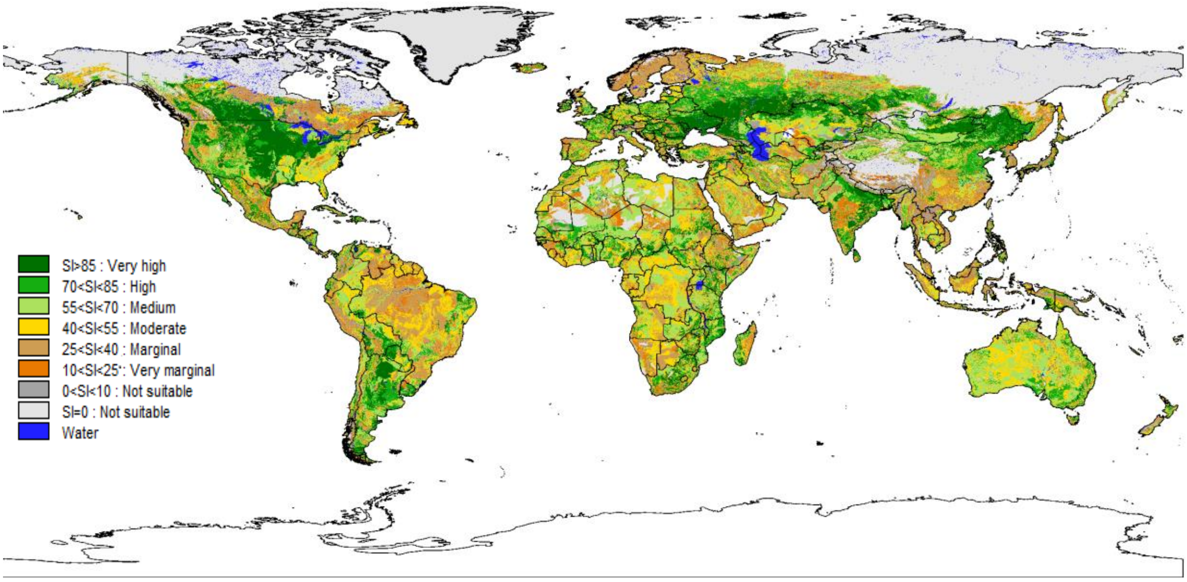
Low inputs

Slope gradient classes	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	> 45%
Annuals 1	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Annuals 2	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Annuals 3	S1	S1	S1	S1/S2	S2	S2/N	N	N
Perennials 1	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 2	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 3	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 4	S1	S1	S1	S1	S1	S1	S1	S1/N
Perennials 5	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Forest	S1	S1	S1	S1	S1	S1	S1/S2	S2/N

***S1**: Optimum conditions; **S2**: Sub-optimum conditions; **S1/S2**: 50% optimum and 50% sub-optimum conditions; **S1/N**: 50% optimum and 50% not suitable conditions; **S2/N**: 50% sub-optimum and 50% not suitable conditions; **N**: Not suitable conditions*
***Annuals 1**: wheat, barley, rye, oat, buckwheat; **Annuals 2**: maize, sorghum, pearl millet, foxtail millet, dryland rice, potato, white potato, sweet potato, phaseolus bean, chickpea, cowpea, gram, dry pea, pigeon pea, rapeseed, soybean, groundnut, sunflower, cotton, sugar beet, rape, flax, white yam, greater yam, tobacco, cabbage, carrot, onion, tomato; **Annuals 3**: wetland rice; **Perennials 1**: sugar cane; **Perennials 2**: olive, citrus; **Perennials 3**: cassava, oil palm, banana, yellow yam, cocoyam, cocoa, coffee, coconut, jatropha; **Perennials 4**: pasture legumes, grasses, tea; **Perennials 5**: alfalfa, switchgrass, miscanthus, reed canary grass; **Forest**: para rubber*

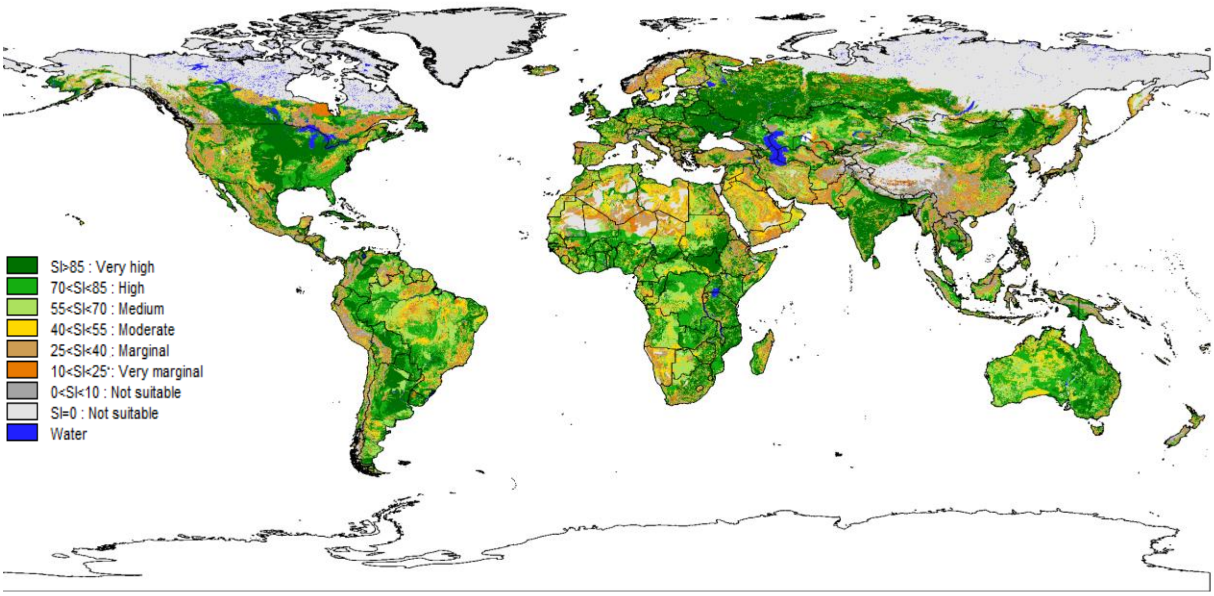
Figure 6-7 and Figure 6-8 present soil and terrain slope suitability for rain-fed maize assuming low level inputs and traditional management, respectively, high level inputs and advanced management.

Figure 6-7 Soil and terrain suitability for rain-fed maize, low level inputs



Source: FAO and IIASA, 2021

Figure 6-8 Soil and terrain suitability for rain-fed maize, high level inputs



Source: FAO and IIASA, 2021

Soil and terrain suitability assessment for irrigated conditions

Apart from evaluating rain-fed crop production systems, specific soil requirements for three major irrigation systems have been established namely for gravity, sprinkler and drip irrigation.

Soil suitability for irrigated conditions

The suitability evaluation procedures for irrigated crop production cover dry-land crops and wetland rice, at intermediate and high levels of inputs. Crop-specific soil limitations for rain-fed production, such as limitations imposed by soil rooting conditions, soil nutrient availability, soil nutrient retention capacity, soil toxicity is similar to those for rain-fed suitability. Examples of water supply system specific soil evaluation criteria are soil salinity and soil alkalinity that are separately evaluated for drip irrigation systems and gypsum content, which is separately evaluated for gravity irrigation (Fischer, G., H. van Velthuizen, 2002).

The following land and soil characteristics have been interpreted specifically for the irrigation suitability classification: topography; soil drainage; soil texture; surface and sub-surface stoniness; calcium carbonate levels; gypsum status; and salinity and alkalinity conditions. The main literature sources used in the interpretation include Sys *et al.* (1993), Sys and Riquier (1980), FAO (1985), FAO (1996), FAO (FAO, 1976), FAO and Unesco (1974), and FAO *et al.* (1990). Details of the application of standard or adapted ratings are presented by water supply system in Table 6-15.

Terrain suitability for irrigated conditions

The dominant terrain factor governing the suitability of an area for any water supply system is terrain slope. Other topographic factors, such as micro-relief, have partly been accounted for in the soil unit and soil phase suitability classifications.

Permissible slopes depend on type of water supply system and assumed level of inputs and management. Terrain suitability ratings for individual water supply systems and input levels, for eight slope classes and eight crop groups, are presented by the six Fournier index classes varying from Fm < 1300 to Fm > 2700, in the Appendix 6-8.

Table 6-15 Soil and terrain evaluation ratings by water supply system

SOIL AND TERRAIN EVALUATION					
Water supply systems		**Rain-fed**	**Irrigated**		
			Gravity irrigation	**Sprinkler irrigation**	**Drip irrigation**
Input levels		H, I., L	H, I.	H, I	H, I
Deviations from rain-fed soil parameter rating					
SQ7	Texture/minerarology	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
SQ3	Rooting depth	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
SQ4	Drainage	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
SQ6	CaCO3	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
SQ6	CaSO4	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
SQ5	Salinity	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	adapted ratings
SQ5	Sodicity	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
Deviations from rain-fed slope parameter rating					
Other	Slopes	standard (rain-fed)	standard (irrigated)	standard (rain-fed)	standard (rain-fed)
Deviations from rain-fed soil phase parameter rating					
SQ4	Phreatic	n.a.	standard (rain-fed)	n.a.	n.a.
	Anthraquic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Inundic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Excessively drained	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Flooded	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	0 No information (IL=0)	n.a.	n.a.	n.a.	n.a.
	1 No impermeable within 150 cm (IL=1)	n.a.	n.a.	n.a.	n.a.
	2 Impermeable between 80 and 150 cm (IL=2)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
	3 Impermeable between 40 and 80 cm (IL=3)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	4 Impermeable within 40 cm (IL=4)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)

SOIL AND TERRAIN EVALUATION						
Water supply systems		Rain-fed	Irrigated			
			Gravity irrigation	Sprinkler irrigation	Drip irrigation	
	0 No information (WR=0)	n.a.	n.a.	n.a.	n.a.
	1 Not wet within 80 cm for over 3 months, nor wet within 40 cm for over 1 month (WR=1)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
	2 Wet within 80 cm for 3 to 6 months, but not wet within 40 cm for over 1 month (WR=2)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	3 Wet within 80 cm over 6 months, but not wet within 40 cm for over 11 months (WR=3)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	4 Wet within 40 cm depth for over 11 months (WR=4)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
SQ5	Saline	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	adapted ratings
	Sodic	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
	Salic	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	adapted ratings
SQ6	Petrocalcic	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)	standard (rain-fed)
	Petrogypsic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
SQ7	Stony	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Lithic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Petric	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Petrocalcic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Petrogypsic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Petroferric	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Fragipan	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Duripan	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Rudic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
	Skeletic	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)

SOIL AND TERRAIN EVALUATION				
Water supply systems	**Rain-fed**	**Irrigated**		
		Gravity irrigation	**Sprinkler irrigation**	**Drip irrigation**
Erosion	n.a.	n.a.	n.a.	n.a.
No limitation to agricultural use	n.a.	n.a.	n.a.	n.a.
Gravelly	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Concretionary	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
No information (ROO= 0)	n.a.	n.a.	n.a.	n.a.
No obstacle to roots between 0 and 80 cm (ROO=1)	n.a.	n.a.	n.a.	n.a.
Obstacle to roots between 60 and 80 cm depth (ROO=2)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Obstacle to roots between 40 and 60 cm depth (ROO=3)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Obstacle to roots between 20 and 40 cm depth (ROO=4)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Obstacle to roots between 0 and 80 cm depth (ROO=5)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Obstacle to roots between 0 and 20 cm depth (ROO=6)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
No information (IL=0)	n.a.	n.a.	n.a.	n.a.
No impermeable within 150 cm (IL=1)	n.a.	n.a.	n.a.	n.a.
Impermeable between 80 and 150 cm (IL=2)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Impermeable between 40 and 80 cm (IL=3)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)
Impermeable within 40 cm (IL=4)	standard (rain-fed)	adapted ratings	standard (rain-fed)	standard (rain-fed)

Suitability of water-collecting sites

In water-collecting sites substantially more water can be available to plants as compared to upland situations. Water-collecting sites are difficult to locate in a global study but can be approximately determined on basis of prevalence of specific soil types. Fluvisols[14] and to a lesser extent Gleysols[15] are typically representing the flat terrain of alluvial valleys and water-collecting sites. Figure 6-9 presents percentage occurrences of water collection sites. Histosols[16], partly occurring in water collecting sites as well, are not considered.

The cultivation of Fluvisols (under unprotected natural conditions) is determined by frequency, duration and depth of flooding. The flooding attributes are generally controlled by external factors such as a river's flood regime which in turn is influenced by hydrological features of the catchment area and catchment/site relations, rather than by the amount of 'on site' precipitation.

Therefore, with exception of wetland crops, the cultivation of these soils is mainly confined to post-flood periods, with crops growing on residual soil moisture. The flooding regime in arid and semi-arid zones is erratic. Some years, severe flash floods may occur, in other years no floods occur at all. In sub-humid and humid zones flooding is more regular but duration and depth of flooding may vary widely from year to year. Gleysols are not directly affected by river flooding. These soils are however frequently situated in low-lying water-collecting sites and when not artificially drained, the Gleysols may be subject to waterlogging or even inundation as result from combinations of high groundwater tables and ponding rainwater. In arid and semi-arid areas these soils are cultivated in the later part and after rainy seasons; the crops grow and mature on residual soil moisture. In sub-humid and humid areas Gleysols without artificial drainage often remain waterlogged for extensive periods, rendering them unsuitable for cultivation of dryland crops.

On both, Fluvisols and Gleysols, crops of short duration that are adapted to growing and producing yields on residual soil moisture and which are tolerant to flooding, water-logging and high groundwater tables, can be found producing satisfactorily outside the growing period defined by the local rainfall regime. Therefore, a separate crop suitability classification for water-collecting sites is required. In compiling this classification, the logic of the original AEZ study (FAO, 1981) has been followed. This includes accounting for crop-specific tolerances to excess moisture (high groundwater, waterlogging and flooding/inundation) and the use of available estimates of flooding regimes of the Fluvisols. Since Gleysols are mostly, but not

[14] Fluvisols are, by definition, flooded by rivers. Fluvisols are young soils where sedimentary structures are clearly recognizable in the soil profile.

[15] Gleysols are generally not flooded by rivers. However, the soil profiles indicate regular occurrence of high groundwater tables through reduction (gley) features. Low-lying Gleysols may be ponded/water-logged by high groundwater and rainfall during the rainy season.

[16] Histosols are partly occurring in water collecting sites as well. When reclaimed, including artificial drainage and after mixing the histic topsoil with underlying mineral materials, Histosols may be turned in very productive soils for intensive forms of arable cropping/horticulture (Driessen and Dudal, 1991). Draining and reclaiming poorly drained Histosols is not recommended because they serve as important habitat for wetland ecosystems and are significant carbon reservoirs. Unreclaimed natural Histosols, due to low bearing capacities of upper histic horizon (bulk density < 0.1 Mg/m^3), generally poor drainage conditions and other unfavorable chemical and physical characteristics, are considered unfit to permit its use for arable purposes and therefore rendering possibilities of benefitting from additional water resources in water collecting sites irrelevant.

necessarily, subjected to waterlogging and inundation just like the 'natural Fluvisols', it was decided to treat Gleysols with terrain-slopes of less than 2% the same as Fluvisols.

In many parts of the world the flooding of Fluvisols is increasingly being controlled with dikes and other protection means. Fluvisols, in protected conditions, do not benefit additional water supply and regular fresh sediment deposits, nor do they suffer from flooding. The moisture regime of Fluvisols under these protected conditions are similar to other soils and therefore protected Fluvisols are treated according to the procedures used for crops in upland conditions.

In a similar way, Gleysols may be artificially drained, thereby diminishing a major limitation for the cultivation of these soils. For areas where the Gleysols have been drained, a revised (i.e., less severe) set of soil ratings is used and the rules for natural Fluvisols are not applied. Since spatial details of the occurrence of protected Fluvisols and artificial drainage of Gleysols are not available at the global scale these factors are assumed to be linked to the level of inputs/management. The application of Fluvisol suitability ratings and soil unit suitability ratings of artificially drained Gleysols are presented in Table 6-16.

Table 6-16 Application of fluvisol and gleysol suitability ratings by input level

Water source	Fluvisols		Gleysols	
	Natural conditions	Protected conditions	Natural conditions	Artificially drained conditions
RAIN-FED				
High level inputs	no	yes	no	yes
Intermediate level inputs	50%	50%	50%	50%
Low level inputs	yes	no	yes	no
IRRIGATION				
High level inputs	no	yes	no	yes
Intermediate level inputs	50%	50%	50%	50%

Moisture suitability ratings devised for unprotected Fluvisols and Gleysols without artificial drainage are organized in ten groups of crops with comparable growth cycle lengths and similar tolerances to high groundwater levels, waterlogging and flooding (see Appendix 6-9). An example is given in Table 6-17. A complete set of rating tables is provided in Appendix 6-9.

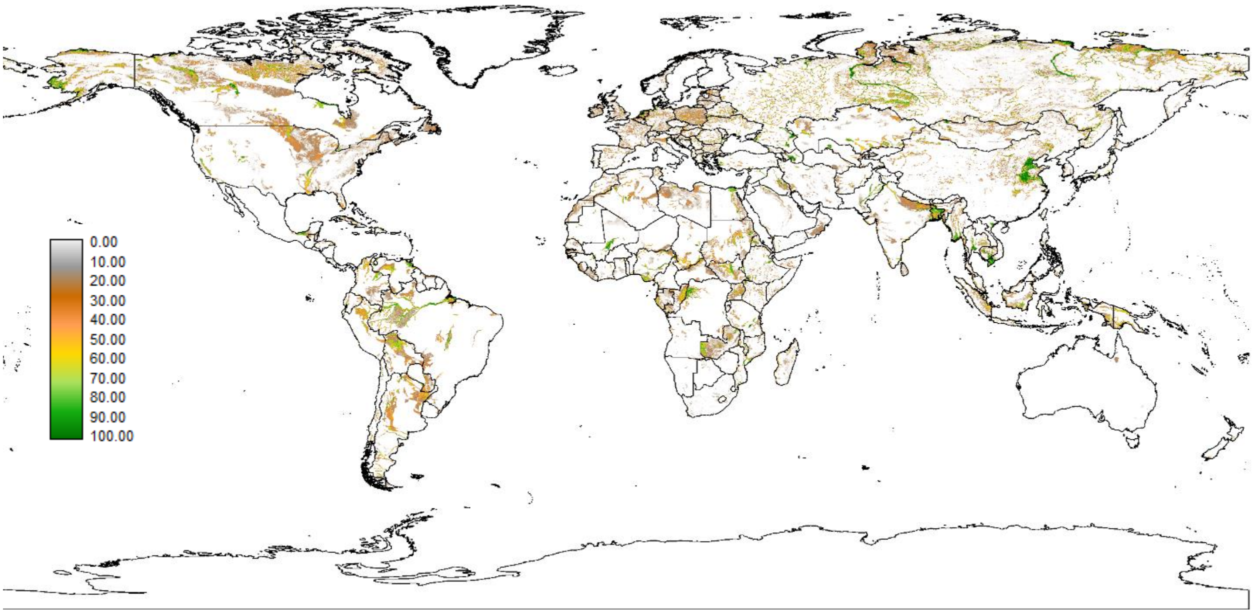
Short-term dry-land crops (I)

This group includes some short duration crops (wheat, barley, rye, oat, dryland rice, foxtail millet, chickpea, rape, and alfalfa) which are somewhat tolerant to excess moisture. For LGPs less than 30 days it is assumed there is on the average insufficient water to bring these crops to maturation and yield, especially since the contribution from rainfall is also almost non-existent. At LGPs longer than 120 days these crops will grow irrespective additional water. It has been assumed that the Fluvisols are too wet in LGPs over 300 days. Most of these crops are marginal to not suitable in humid areas. Agro-climatic constraints alone will render these long LGPs already marginal to not suitable.

Table 6-17 Suitability make up for short-term dryland crops in 'natural' (unprotected) water collecting sites without artificial drainage by LGP class

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	**1–29**	**30–59**	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365**	**365+**
VS						33	33	33	33	33	33				
S					33										
MS				33		33	33	33	33	33	33				
mS			33		33										
NS	100	100	67	67	34	34	34	34	34	34	34	100	100	100	100

Figure 6-9 Occurrence of water collecting sites (%of grid cell)



Source: FAO and IIASA, 2021

Fallow period requirements

In their natural state many tropical soils cannot be continuously cultivated without undergoing degradation. Such degradation is marked by a decrease in crop yields and a deterioration of soil structure, nutrient status and other physical, chemical and biological attributes. Under traditional low input farming systems, this deterioration is kept in check by alternating some years of cultivation with periods of fallow. The length of the necessary rest period is dependent on inputs applied, soil and climate conditions, and crops. Hence, the main reason for incorporating fallow into crop rotations is to enhance sustainability of production through maintenance of soil fertility.

Regeneration of nutrients and maintenance of soil fertility under low input cultivation is achieved through natural bush or grass fallow. At somewhat higher inputs to soils, the soil fertility is maintained through fallow, which may include for a portion of time a grass, grass-legume ley or a green-manure crop. Factors affecting changes in soil organic matter are reviewed in Nye and Greenland (1960) and Kowal (1978). They include temperature, rainfall, soil moisture and drainage, soil parent material, and cultivation practices. The fallow factors used in the present GAEZ land potentials assessments are based on earlier work done in the context of FAO's regional assessments (Young and Wright, 1980) and the Kenya AEZ study (Kassam *et al.*, 1991b).

The fallow factors have been established by main crop groups and environmental conditions. The crop groups include cereals, legumes, roots and tubers, and a miscellaneous group consisting of long-term annuals/perennials. The environmental frame consists of individual soil units, thermal regimes and moisture regimes. The thermal regimes are expressed in terms of annual mean temperatures of > 25°C, 20–25°C, 15–20°C and <15°C. The moisture regimes are expressed in terms of five broad LGP ranges: <60 days, 60–120 days, 120–180 days, 180–270 days, and > 270 days.

The fallow factors included in GAEZ are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow, foremost to maintain its soil fertility status. For the four crop groups: cereals, legumes, roots and tubers, and a miscellaneous group consisting of long-term annuals/perennials, at intermediate level of inputs, the fallow requirements are set at one third of the levels required under low level of inputs (see Appendix 6-10), and at high levels of inputs and management fallow requirements are uniformly set at 10%.

Exceptions to the above are:

i. For Fluvisols and Gleysols fallow factors are set lower because of their special moisture and fertility conditions;

ii. For wetland rice on Fluvisols, fallow requirements for all three input levels are set to 10%;

iii. For wetland rice on Gleysols, at high and intermediate inputs the fallow requirements are set to 10 % and at low inputs to 20%;

iv. For wetland rice on soils other than Fluvisols and Gleysols, fallow requirements are set as for crop group 1 (cereals), and

v. Fallow requirements have been assumed to be negligible for the perennial crops oilpalm, olive, citrus, cocoa, tea, coffee, jatropha, coconut, miscanthus, switchgrass, reed canary grass and alfalfa. For these perennials, no fallow requirements have been set.

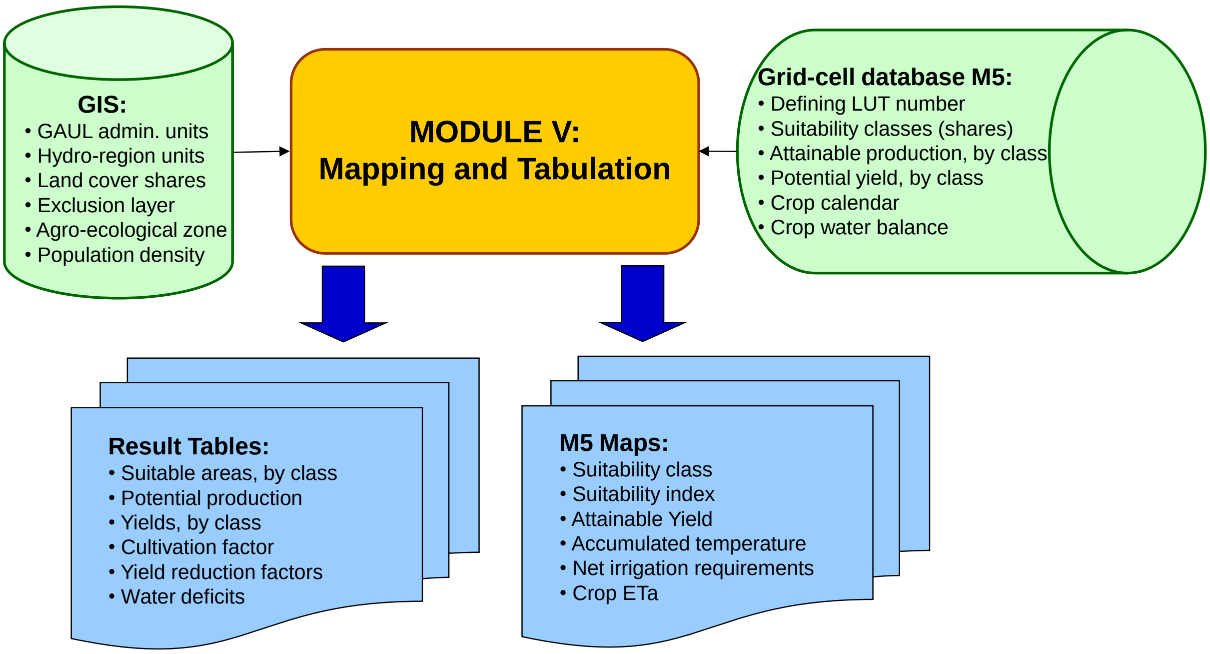
In GAEZ the fallow requirement factors are applied for the estimation of potential average annual production which can be achieved on a sustainable basis under the assumed level of inputs and management.

7. Module V (Integration of climatic and edaphic evaluation)

Introduction

Module V executes the final step in the GAEZ crop suitability and land productivity assessment. It reads the LUT specific results of the agro-climatic evaluation for biomass and yield calculated in Module II/III for different soil classes and it uses the edaphic rating produced for each soil/slope combination in Module IV to estimate agro-ecological attainable yields and related variables. The inventories of soil resources and terrain-slope conditions are integrated by ranking all soil types in each soil map unit with regard to occurrence in different slope classes. Considering simultaneously the slope class distribution of all grid cells belonging to a particular soil map unit results in an overall consistent distribution of soil-terrain slope combinations by individual soil association map units and 30 arc-sec grid cells. Soil unit ratings and terrain slope ratings are applied separately for each water supply system. The information flow in Module V is summarized in Figure 7-1.

Figure 7-1 Information flow in Module V



Description of Module V operation

Main processing steps in Module V

The algorithm in Module V steps through the 30 arc-seconds grid cells of the spatial soil association layer of the Harmonized World Soil Database (Nachtergaele *et al.*, 2012) and determines for each grid cell the respective make-up of land units in terms of soil types and slope classes. Each of these component land units is separately assessed and assigned a suitability rating and simulated attainable yield. The grid cell results are accumulated over all component land units in a grid cell.

Processing of soil and slope distribution information takes place for 30 arc-second grid cells. One hundred of these produce the edaphic characterization at 5 arc-minutes, which is the resolution used for providing GAEZ v4 results. Information stored for 5 arc-minute grid cells contains distributions resulting from the individual 30 arc-second sub-grid evaluations.

The main purpose of Module V is to compile a grid-cell database for each crop, which stores evaluation results and summarizes the processed sub-grid information. Computations include the following steps:

- Assign applicable agro-climatic yields calculated in separate crop water balances for eight broad soil AWC classes (simulated in Module II/III);
- Under low input conditions, apply AEZ rules for water-collecting sites (defined as Fluvisols and Gleysols on flat terrain; see Chapter 6, section 6.8);
- Apply yield reduction factors according to results of edaphic and terrain slope evaluation for the specific combinations of soil types/slope classes making up a grid cell (evaluated in Module IV);
- Apply yield adjustment factors to account for CO_2 fertilization effect according to crop, atmospheric CO_2 concentration and land suitability rating;
- Determine an applicable fallow requirement factor depending on climate characteristics, soil type, crop group and input level;
- Aggregate results of attainable yields, actual crop evapotranspiration and crop water deficits/net irrigation requirements over the component land units that make up a grid cell (soil type/slope combinations), and
- Map and tabulate results for each past and future 30-year period by crop, input level and water source.

The make-up of different land units (soil type/slope class combinations) within a 5 arc-minute grid cell usually involves multiple combinations of soil types and texture classes, each of which is assigned to the closest matching of the eight soil AWC classes used for simulation in Module II/III. The respective class results are then retrieved to represent for each component soil the agro-climatic potential yield and associated crop calendar and crop water balance indicators.

Results of the individual soil component evaluations are aggregated up to the 5 arc-minute grid cell level and stored as distributions of suitable areas and corresponding attainable yields.

Cropping activities are among the most critical in causing topsoil erosion, because of their management and the cover dynamics of annual crops. For this reason, GAEZ applies in Module V a terrain-slope suitability rating procedure to account for important factors that influence production sustainability (for details see Chapter 6, section 6.6). Terrain suitability is estimated according to grid-cell specific terrain-slope classes and location specific rainfall amounts and concentration characteristics. Soil and terrain characteristics are read by 30 arc-second grid-cells for which sub-grid soil and terrain combinations have been quantified in the database. These calculations are crop/LUT specific and are separately performed for three basic input levels for rain-fed and irrigated water supply systems.

The processing in Module V also accounts for fallow period requirements, which have been established for main crop groups, by level of inputs, and for different climatic conditions (for details see Chapter 6, section 6.9). The fallow factors included in GAEZ are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow, foremost to maintain its soil fertility status. In crop summary tabulations produced in Module V, the fallow requirement factors are applied for the estimation of attainable average annual production that can be achieved on a sustainable basis under the assumed level of inputs and management.

Module V mapping and tabulation

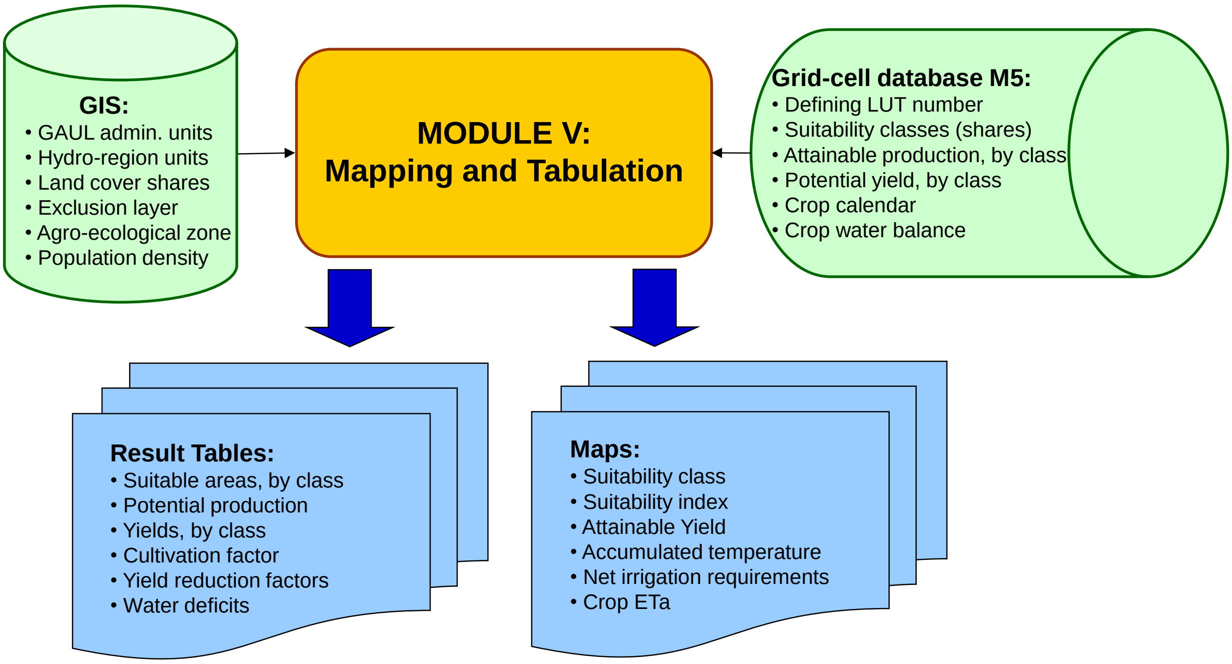
The results of crop evaluation in Module V are stored as separate databases, each organized in terms of 5 arc-minutes grid cells. Separate files are generated holding results by crop, input level, type of water supply and climate scenario/time period. Each of these crop databases contains sub-grid distribution information with regard to suitable extents, potential production, water deficit and fallow factors, with all information kept by suitability classes.

Various utility programs have been developed to aggregate and tabulate results by administrative or hydro-region units, or to map the contents of Module V crop databases in terms of a suitability index, suitable area shares, potential grid-cell production and related water balance variables. Appendix 7-1 provides maps of suitability for major crops under historical climate (1981–2010) and assumed high inputs and advanced management.

Crop summary tables provide standardized information for each crop by administrative units (country or country/province for a few major countries) and by broad hydro-regions. The comprehensive tables summarize by suitability class the suitable extents and attainable yields, various constraint factors (due to thermal regime, moisture deficits, agro-climatic constraints due to pest, disease and workability limitations and due to soil/terrain limitations) and aggregate simulated water deficits (see Appendix 7-2).

The information flow for tabulation and mapping of Module V outcomes is depicted in Figure 7-2, taking as input various GIS layers (to delineate territorial units) and the simulation results stored in numerous crop databases.

Figure 7-2 Tabulation and mapping of Module V results

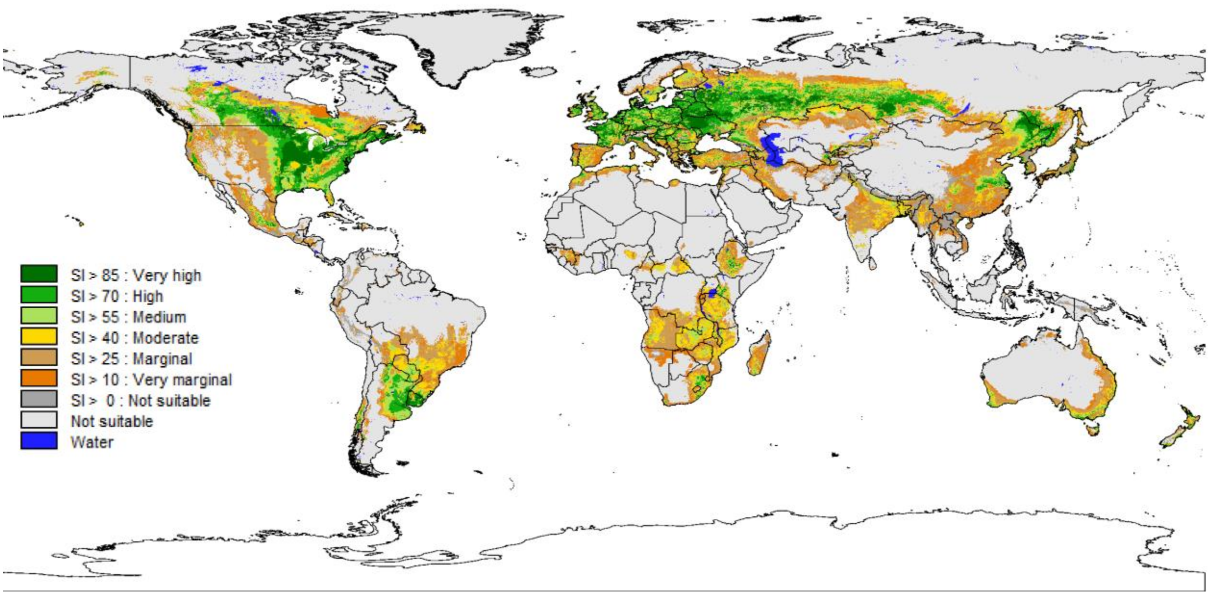


Following below, three examples of mapped outputs from Module V analysis are presented. Figure 7-3 shows a map of the agro-ecological suitability of rain-fed wheat under high inputs and advanced management. The mapped classes are based on the normalized suitability index *SI*:

$$SI = (90 \times VS + 70 \times S + 50 \times MS + 30 \times mS + 15 \times vmS + 0 \times NS)/0.9$$

where VS, S, …, NS are the area extents in a grid cell assessed as respectively very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS), very marginally suitable (vmS) and not suitable (NS).

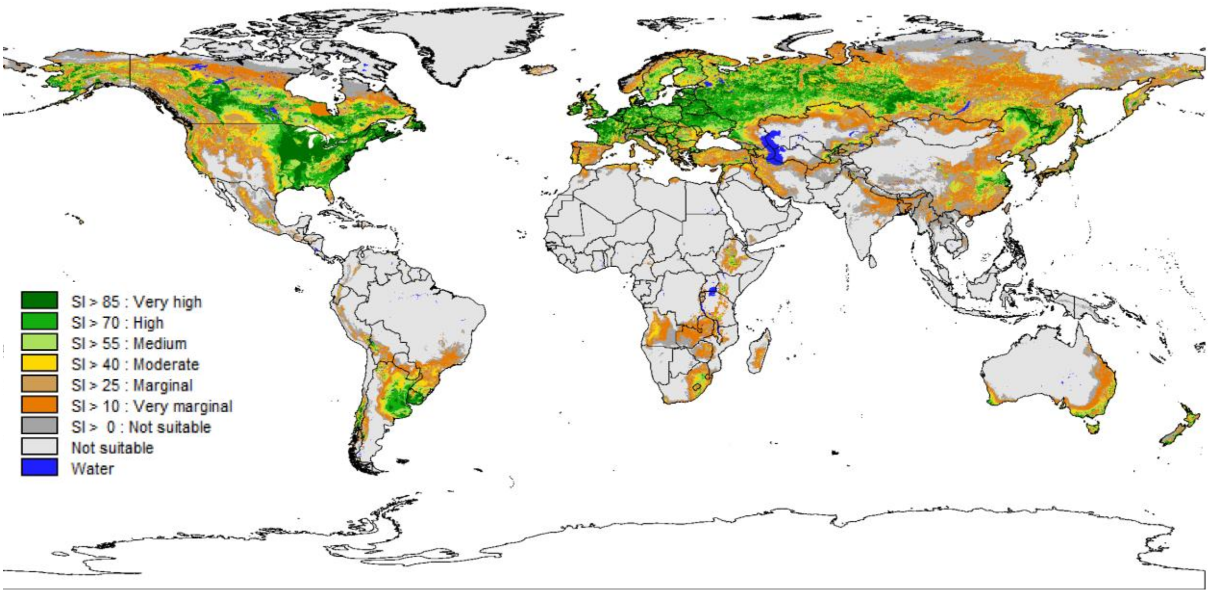
Figure 7-3 Suitability of rain-fed wheat, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

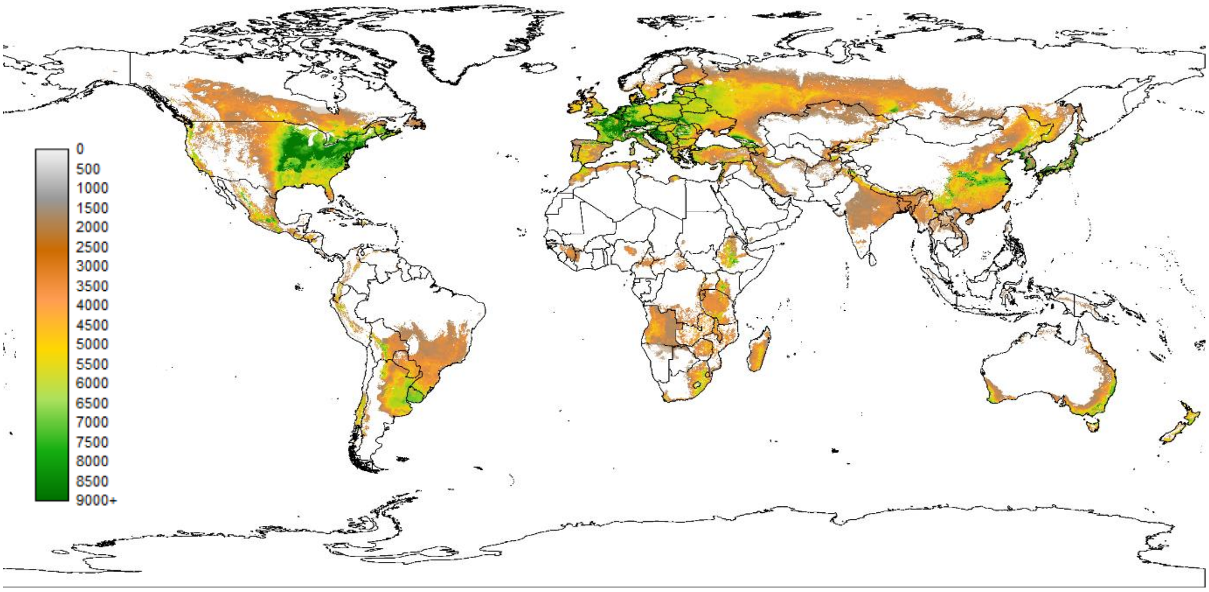
For comparison, Figure 7-4 shows rain-fed wheat suitability results for the end of this century, the ensemble mean of results computed for high input assumptions with projected climate of five earth system models for period 2070–2099 under representative concentration pathway RCP8.5.

Figure 7-4 Suitability of rain-fed wheat, high inputs, ensemble mean of 2070–2099 for RCP8.5



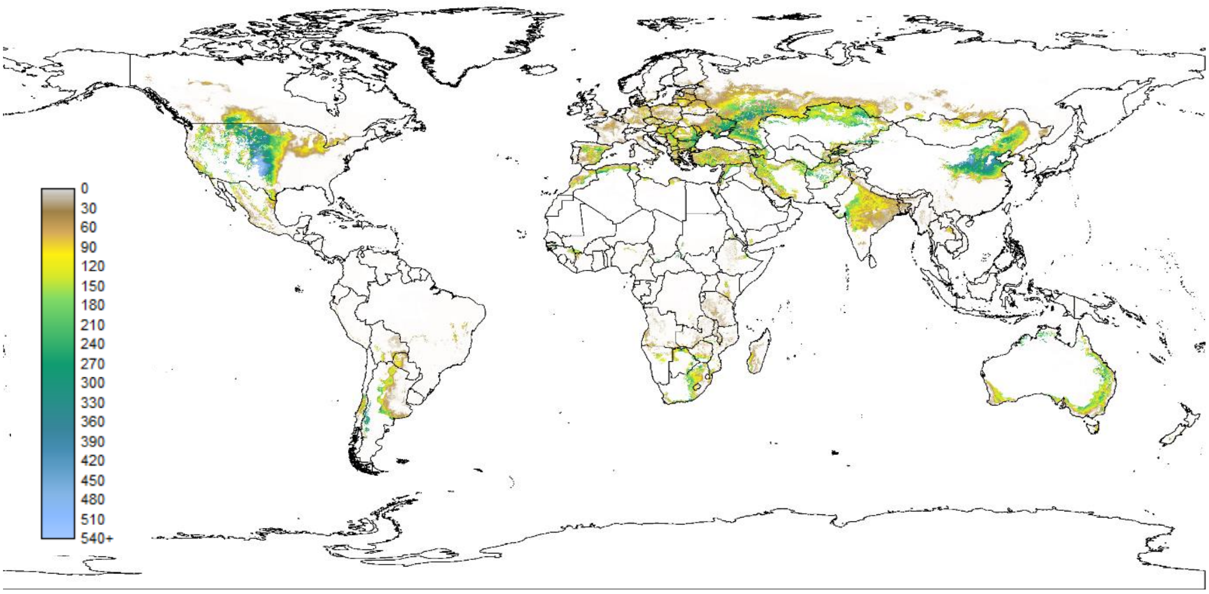
Source: FAO and IIASA, 2021

Figure 7-5 Attainable yield of rain-fed wheat, high inputs, period 1981–2010 (kg DW/ha)



Source: FAO and IIASA, 2021

Figure 7-6 Growth cycle crop water deficit of rain-fed wheat, high inputs, period 1981–2010 (mm)



Source: FAO and IIASA, 2021

The second example (see Figure 7-5) shows for current cropland and for the climate of 1981–2010 a map of rain-fed wheat yields attainable under high inputs and advanced management. The calculation of average attainable yields for current cropland assumes that in each grid cell the best suitable land will be used first, and results are averaged up to the share of land indicated as cropland. The mapping program also produces a map of the highest occurring class yields in a pixel and a map of average output density for the entire grid-cell.

The final example in this section relates to the crop water balance. Figure 7-6 shows for rain-fed wheat and the reference climate of 1981–2010 the simulated soil moisture deficit (mm) during the crop growth cycle of the respective best performing wheat LUT selected in a grid cell.

Impact of atmospheric CO_2 concentrations on crop yields

The "fertilization" effect of increasing atmospheric CO_2 on crop yields is accounted in GAEZ by the CO_2 yield-adjustment factor (f_{CO2}). Crop species respond differently to CO_2 depending on physiological characteristics such as photosynthetic pathway (e.g., C3 or C4 plants). These crop-specific responses are accounted in the parameterization of f_{CO2}:

$$f_{CO_2} = 1 + (a \times [CO_2]^2 + b) \times [CO_2] + c) \times f_{sui\_CO_2}$$

Where a, b and c are parameters (by broad crop groups) used to capture the different CO_2 responses of five broad crop groups (Table 7-1).

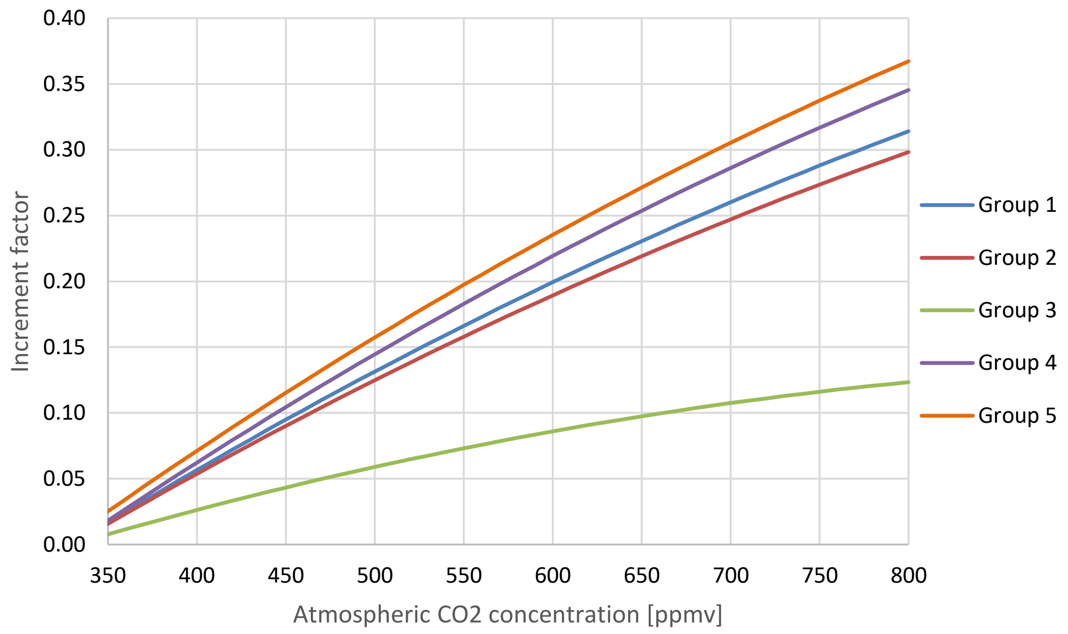
Table 7-1 Crop-specific coefficients for the calculation of CO_2 fertilization effect

Coefficients	Crop Group*				
	1	2	3	4	5
a	-0.0003500	-0.0003325	-0.0002800	-0.0003850	-0.0004025
b	0.10636	0.10104	0.057888	0.11700	0.12231
c	-31.2870	-29.7227	-16.0540	-34.4157	-35.9801

1: wheat, barley, rye, oat, buckwheat, temperate beans, chickpea, dry pea, rapeseed, flax, cabbage, carrot, onion, tomato, alfalfa.
2: rice, cassava, sweet potato, yam, lowland beans, cowpea, gram, pigeon pea, groundnut, sunflower, tobacco, banana, oil palm, olive, citrus, cocoa, coffee, coconut, red canary grass, jatropha, rubber, grass legumes.
3: maize, sorghum, millet, sugar cane, napier grass, miscanthus, switchgrass.
4: soybean.
5: white potato, sugar beet, cotton.

The factor f_{sui_CO2} is an empirical correction factor accounting for land suitability as explained below. The maximum yield increment due to CO_2 enrichment (i.e., without considering land suitability constraints) is shown in Figure 7-7.

Figure 7-7 Yield response to elevated ambient CO_2 concentrations



The local environment also influences the impact that CO_2 has on crop growth. Realization of the fertilization effect of CO_2 is adjusted when sub-optimum growth conditions are indicated by the suitability classification for a LUT in each grid-cell. Under very suitable conditions it is assumed that a fertilization effect equal to 85% of that derived from laboratory experiments could be realized in farmers' fields. For marginally suitable conditions this share is set to one-third (see Table 7-2). This mechanism and the functions used are broadly consistent with results reported in free-air CO_2 enrichment (FACE) experiments.

Table 7-2 Adjustment factors for CO_2 fertilization effect according to land suitability class

	Very Suitable (VS)	**Suitable (S)**	**Moderately Suitable (MS)**	**Marginally Suitable (mS)**
f_{sui_CO2}	0.850	0.667	0.500	0.333

In GAEZ various atmospheric CO_2 concentration pathways were simulated, as used for the IPCC AR5 (IPCC 2013) and quantified by different climate modeling groups. GAEZ runs were performed with different CO_2 concentrations for each scenario for three future time periods (2020s, 2050s and 2080s) as shown in Table 7-3.

Table 7-3 Atmospheric CO_2 concentrations (ppm) used to model the fertilization effect in GAEZ for different IPCC representative concentration pathways (RCP) and time points

Scenario(1)	Year(2)			
	1990s	2020s	2050s	2080s
RCP2p6	359.8	422.5	442.5	428.9
RCP4p5	359.8	422.7	498.5	531.5
RCP6p0	359.8	419.0	493.3	616.6
RCP8p5	359.8	431.5	570.5	801.0

(1) RCP: representative concentration pathway from IPCC AR5
(2) Corresponds to the CO_2 concentration at the mid-point of a 30-year period (e.g. year 2025 represents the 2020s and corresponds to the mid-point of the period from 2011 to 2040).

Description of Module V outputs

Module V records for each grid-cell and crop the relevant results of the assessment, including by suitability class the suitable extents, attainable yields, yield-reducing factors, accumulated temperatures, and water balance information.

Operation of Module V generates many maps which are named using a 3-character map type acronym and a 3-character crop acronym. Maps are by crop, map type, input level, water source, climate, concentration pathway, and time period. Since 5 arc-minute grid cells can be made up of multiple soil types and terrain slope classes, the assessment assigns an estimate to each of these components, to capture the heterogeneity of each grid cell, which produces a distribution of results falling into different suitability classes, as follows:

Acronym	suitability description	Farm economics
VS	Very suitable land (80–100 % of maximum attainable yield)	Prime land offering best conditions for economic crop production
S	Suitable land (60–80%)	Good land for economic crop production
MS	Moderately suitable land (40–60%)	Moderate land with substantial climate and/or soil/terrain constraints requiring high product prices for profitability
mS	Marginally suitable land (20–40%)	Commercial production not viable. Land could be used for subsistence production when no other land is available
vmS	Very marginally suitable (< 20%)	Economic production not feasible
NS	Not suitable	Production not possible

The mapping therefore generates different products that either average the results for an entire grid cell (see map types *etl*, *si*, *sx*, *wdl* and *yl* in Table 7-4) or relate to a fraction of the grid cell indicated by the land cover data as cropland (see map types *etc*, *sc*, *su*, *wdc* and *yc* in Table 7-4). For these maps it is assumed that farmers will have used the better part of the suitability distribution in a grid cell, e.g. when the cropland share is 20% of a grid cell then the top 20% of the suitability and yield distribution are used to define the map contents. In addition, the average yield of the highest occurring suitability class in a grid cell is mapped as well (map type *yx* in Table 7-4). Also, the maps of type *sx1* to *sx3* help to understand the make-up of a grid cell by summarizing components of the suitability distribution of each pixel. The different themes of mapped information provided by Module V are listed in Table 7-4.

Table 7-4 Mapped output produced by Module V analysis

Type	Crop indicator	Unit
etc	Actual crop evapotranspiration (excluding irrigation), average for current cropland	mm
etl	Actual crop evapotranspiration (excluding irrigation), average for grid cell	mm
sc	Suitability index class, current cropland	Class
si	Suitability index class, total grid cell	Class
su	Average suitability index of current cropland	Scalar
sx1	Share of grid cell assessed as VS or S	Scalar
sx2	Share of grid cell assessed as VS, S or MS	Scalar
sx3	Share of grid cell assessed as VS, S, MS or mS	Scalar
sx	Average suitability index of total grid cell	Scalar
wdc	LUT water deficit/net irrigation requirement during crop cycle, current cropland	mm
wdl	LUT water deficit/net irrigation requirement during crop cycle, total grid cell	mm
yc	Average attainable yield, current cropland	Kg/ha*
yl	Output density (= potential grid cell production/grid cell area), total grid cell	Kg/ha*
yx	Maximum attainable class yield in grid cell	Kg/ha*

** For most crops the yields are given in kg dry weight per hectare. For alfalfa, miscanthus, napier grass, reed canary grass, pasture legumes and grasses the yields are in 10kg dry weight per hectare. For sugar beet and sugar cane the yields are in kg sugar per hectare and for oil palm in kg oil per hectare. Cotton yields are given as kg lint per hectare.*

The 3-character crop name acronyms, which are used to generate file names in Module V, are listed in Table 7-5.

Table 7-5 Crop name acronyms used in GAEZ v4

Acronym	Crop name	Acronym	Crop name
alf	Alfalfa	*ban*	Banana
bck	Buckwheat	*brl*	Barley
bsg	Biomass sorghum	*cab*	Cabbage
car	Carrot	*chk*	Chickpea
cit	Citrus	*coc*	Cacao
cof	Coffee (best type)	*con*	Coconut
cot	Cotton	*cow*	Cowpea

csv	Cassava	*flx*	Flax fibre
fml	Foxtail millet	*grd*	Groundnut
grm	Gram	*jtr*	Jatropha
mis	Miscanthus	*mlt*	Millet (best type)
mze	Maize, grain	*mzs*	Silage maize
nap	Napier grass	*oat*	Oat
olp	Oil palm	*olv*	Olive
oni	Onion	*pea*	Dry pea
phb	Phaseolous bean	*pig*	Pigeonpea
pml	Pearl millet	*pst*	Pasture
rcd	Dryland rice	*rcg*	Reed canary grass
rcw	Wetland rice	*rsd*	Rapeseed
rub	Rubber	*rye*	Rye
sfl	Sunflower	*soy*	Soybean
spo	Sweet potato	*srg*	Sorghum, grain
sub	Sugar beet	*suc*	Sugar cane
swg	Switchgrass	*tea*	Tea (best type)
tob	Tobacco	*tom*	Tomato
whe	Wheat	*wpo*	White potato
yam	Yam (best type)		

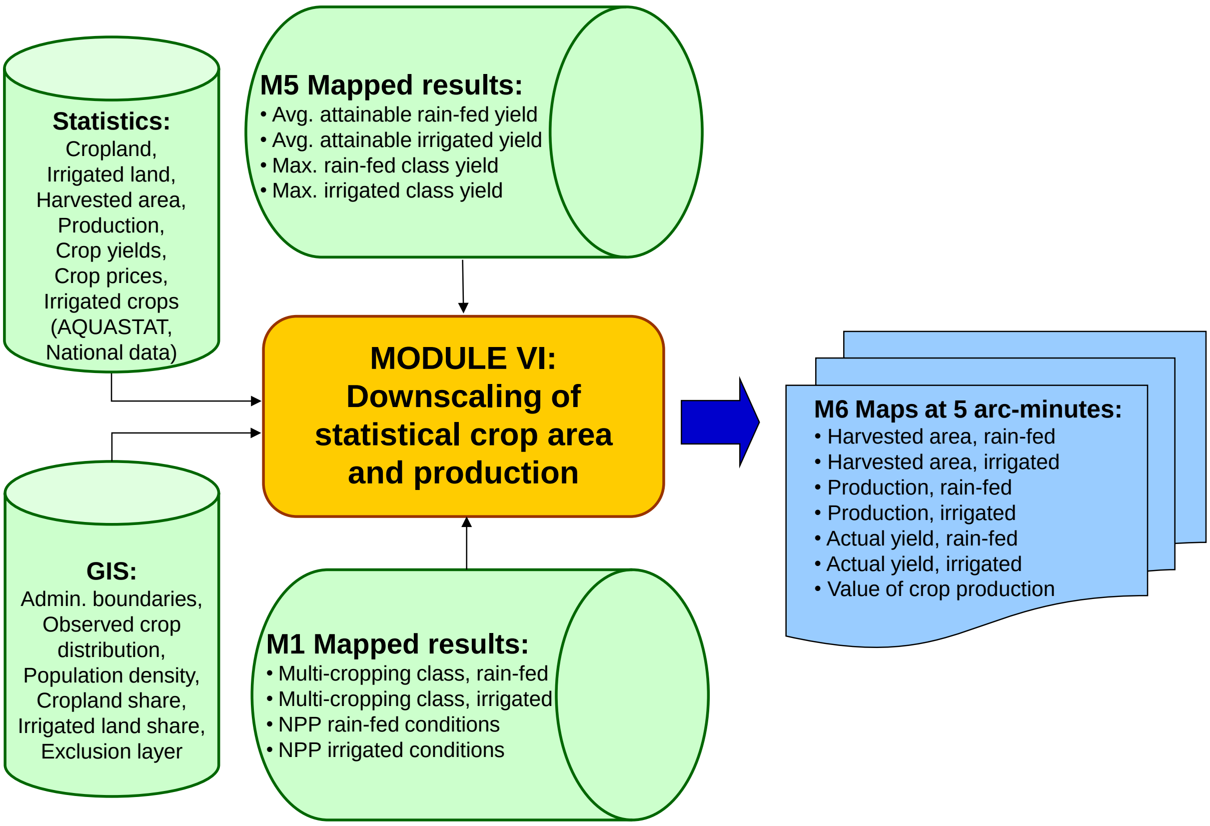
8. Module VI (Actual yield and production)

Introduction

Global change processes raise new estimation problems challenging the conventional statistical methods. These methods are based on the ability to obtain observations from unknown true probability distributions, whereas the new problems require recovering information from only partially observable or even unobservable variables. For instance, aggregate data exist at global and national level regarding agricultural production. 'Downscaling' methods in this case should achieve plausible estimation of spatial distributions, consistent with 'local' data obtained from remote sensing, available aggregate agricultural statistics, and other available evidence.

For this purpose, a flexible sequential downscaling method, based on iterative rebalancing, was developed at IIASA and implemented for use in GAEZ. The information flow associated with the spatial allocation of agricultural statistics is sketched in Figure 8-1.

Figure 8-1 Information flow in Module VI



Downscaling of agricultural statistics to grid cells

Agricultural production and land statistics are available at national scale from FAO, but these statistical data do not reflect the spatial heterogeneity of agricultural production systems at finer resolutions, e.g., grid cells, within country boundaries. In this case a "downscaling" method is needed for attribution of aggregate national production statistics to individual spatial units (grid cells) by applying formal methods that account for land characteristics, assess possible production options and can use available evidence from observed or inferred geo-spatial information, including remotely sensed land cover, soil, climate and vegetation distribution, population density and distribution, etc.

Land cover data products are classifications that provide detailed geographical information, amongst others of the distribution of cropland. Besides land cover/use data there exists other important information on factors, which significantly affect the patterns and intensities of crop production. For example, spatially explicit biophysical data related to land constraints, such as soil type and terrain slopes, and land productivity for specific agricultural activities, human population distribution, prices received by farmers, etc. Such data, in combination with GAEZ crop suitability and potential attainable yield layers, was used in the downscaling procedures to construct a prior distribution for allocation of agricultural cropping activities and production.

To achieve consistency of available data and estimates across scales, the sequential rebalancing procedures that were developed at IIASA rely on appropriate optimization principles (Fischer *et al.*, 2006a) and combine the available statistics with the calculated "prior" and other hard (accounting identities) and soft (expert opinion) constraint data.

To guide the spatial allocation of crops, GAEZ procedures for the calculation of potential yields and production have been applied to, respectively, rain-fed and irrigated cropland shares of individual 5 arc-minute grid cells. Rather than taking an average yield for the entire grid cell it is assumed that the cultivated land will occupy the better part of the suitability distribution determined in each grid cell. To estimate consistent spatial yield patterns of currently cultivated crops by grid cells requires joint downscaling of agricultural statistics for all crops simultaneously. The sequential downscaling consists of efficient iterative rebalancing procedures (Fischer *et al.,* 2006b) based on cross entropy maximization principles, thereby allocating production in crop statistics to appropriate tracts of rain-fed respectively irrigated cropland while providing realistic estimates of current yield and production for the cropland in individual grid cells, consistent with the land's spatial distribution and agronomic capabilities.

In summary, two main steps were involved in obtaining downscaled grid-cell level area, yield and production of main crops:

i. Compilation of calibrated shares of rain-fed and irrigated cropland by 30 arc-seconds (and aggregation to 5 arc-minute) grid cell, and

ii. Attribution of crop specific harvested area yield and production to the rain-fed and irrigated cropland of each grid cell.

Calibration of rain-fed and irrigated cropland shares

For the estimation of cropland shares in individual 5 arc-minute grid cells, data from GLC-Share (Latham *et al.*, 2014) and GMIA v5 (Siebert *et al.*, 2013) were combined. A population inventory for year 2010 has been used to estimate land required for housing and infrastructure (population density map developed by FAO-SDRN, based on spatial data derived from LandScan (Oak Ridge National Laboratory, 2013), with calibration to UN 2010 population figures undertaken at FAO-SDRN.

In step (i) the available land cover interpretations are combined to produce a quantification of each grid cell in the spatial raster in terms of twelve main land use/land cover shares. These shares are for: artificial surfaces (01), cropland (02), grassland (03), tree covered areas (04), shrubs covered areas (05), herbaceous vegetation, aquatic or regularly flooded (06), mangroves (07), sparse vegetation (08), bare soil (09), snow and glaciers (10), water bodies (11), and cropland equipped with full control irrigation (12).

The estimation of cropland shares by 30 arc-second grid cell used in GAEZ employs an approach to formally and consistently integrate up-to-date geographical data sets obtained from remote sensing with statistical information compiled by FAO and/or national statistical bureaus, as a basis for spatially detailed downscaling of agricultural production statistics to land units (grid cells) and subsequent yield gap analysis. This information is needed to prevent double counting of available resources and is essential for various environmental assessments requiring spatial detail.

An iterative calculation procedure was used to estimate land cover class weights, consistent with aggregate FAO land statistics and spatial land cover patterns obtained from remotely sensed data. The procedure involves a sequence of steps, as follows:

- Collection of national (and possibly sub-national) statistics on cropland;
- Integration of GMIA v5 and GLC-Share land cover data sets;
- Spatial aggregation of geographical land cover data to obtain distributions of land cover classes at the level of national and sub-national administrative units for which statistical data is available;
- Cross-sectional regressions of statistical cropland against land cover distributions derived from geographical land cover data sets to obtain reference weights for each land cover class in terms of cultivated land contained;
- Estimation of urban/built-up land shares based on an empirical relationship of per capita land requirements as a function of population density, by application to a spatially detailed population density dataset at 30 arc-seconds and aggregation of results to 5 arc-minute grid cells;
- Application of an iterative procedure for the adjustment of land cover class weights, starting from estimated reference values, to achieve consistency of geographical and statistical data, i.e., such that weighted summation of land cover classes of an allocation unit (country or sub-national administrative unit) results in the total cropland as reported in the statistical data. This procedure is first run to calibrate irrigated cropland

with AQUASTAT statistics and is then applied to cropland reported in FAOSTAT (keeping calibrated irrigated land fixed), and

- Adjustment of remaining land cover shares (i.e., excluding cropland, urban/built-up land and water bodies) to ensure consistency such that all land cover shares sum up to 100 % in each grid cell.

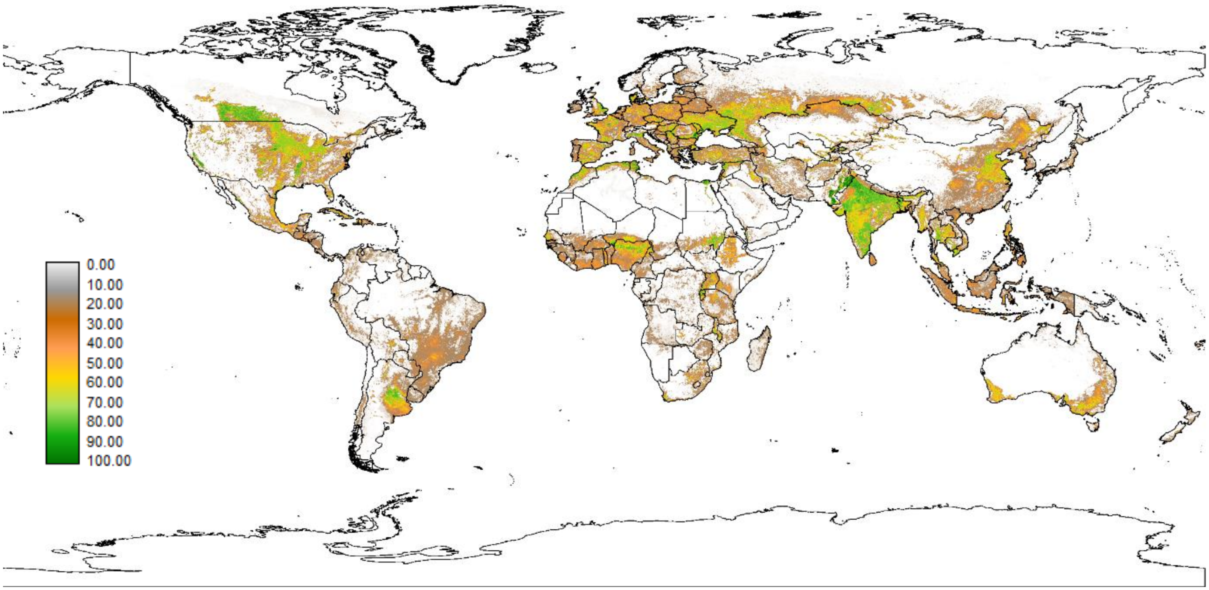
Land cover class weights define for each land cover class and spatial allocation unit (e.g., country) the contents of a land cover class in terms of cropland. Starting values of class weights for the cropland class used in the iterative procedure were obtained by cross-country regression of statistical data of cropland against aggregated extents of national land cover class distributions obtained from GIS.

The iterative algorithm for adjusting land cover weights is controlled by a parameter file specifying three levels of increasingly wider intervals within which the respective class weights can be adjusted. The ranges of permissible class weights for each land cover category were defined by (i) where possible, quantitative information contained in the GLC-Share legend class description, and (ii) expert judgment on the plausibility and possible magnitude of the presence of cultivated land in different land cover classes.

For instance, the weight used for cultivated land contained in the cropland class (02) would in a first step be adjusted in the interval [0.65, 0.85] and cultivated land content of all other classes is kept at 0. If this adjustment is insufficient then the interval [0.50, 0.95] is tested and small amounts of cropland can also be considered in grassland and shrubland areas. In the final step, the class weight for cropland are chosen from the interval [0.25, 1.00] and the permissible amount in some other classes will be increased. Note, in most countries this last step was not necessary and a solution was found in the first or second iteration. In this way the algorithm not only produces formally consistent results for each allocation unit but also provides an indication of the discrepancy between mapped land cover distributions and statistical amounts of cropland.

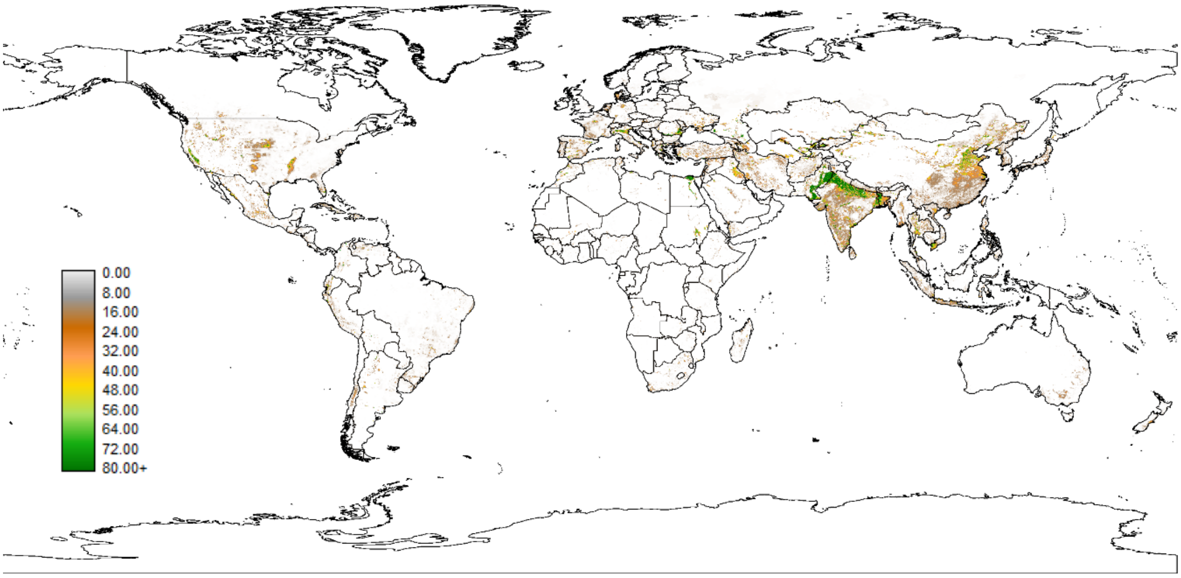
The occurrence of cropland in 2009–2011 based on GLC-Share and calibrated to FAOSTAT statistical data is presented in Figure 8-2 and a map of calibrated shares of cropland equipped for full control irrigation, based on GMIA v5, is shown in Figure 8-3.

Figure 8-2 Share of cropland by 5 arc-minute grid cell (percent)



Source: FAO and IIASA, 2021

Figure 8-3 Share of full control irrigated land by 5 arc-minute grid cell (percent)



Source: FAO and IIASA, 2021

Attribution of crop production statistics to current cropland

Agricultural crop production data are available at national scale from FAO. Sub-national information was collected and compiled by Montfreda *et al.* (2008), Portmann *et al.* (2008, 2010) and FAO's Agro-MAPS: Global spatial database of agricultural land-use statistics, version 2.5. The spatial occurrence of rain-fed and irrigated cropland compatible with aggregate statistical data was established in the previous step. The main objective of the second step is to allocate crop production statistics to the spatial cropland units while meeting statistical accounts and respecting crop suitability and land capabilities reflected in the spatial land resources inventory.

The algorithm can be summarized as follows: The potential suitability of individual crops in the cropland of each grid cell is available from geographically detailed GAEZ assessments undertaken in Module I to Module V for the different input levels and water sources (i.e., rain-fed and irrigated) including estimates of agronomically attainable crop yields.

The crop production statistics and the spatial information available for each country were used to calculate an initial estimate of crop-wise area allocation and production, a so-called "prior". The priors are subsequently revised in an iterative procedure. Each iteration step determines the discrepancy between statistical totals available at the level of spatial units (countries or sub-national units) and the respective totals calculated by summing harvested areas and production over grid cells. The magnitude of these deviations is used to revise the land and crop allocation and to recalculate discrepancies. The process is continued until all accounting constraints are met (Fischer et al., 2006) and the crop distribution and production is consistent with aggregate statistical data of crop harvested area and production, is allocated to the available rain-fed and irrigated cropland, including its capacity to support multi-cropping under respectively rain-fed and irrigated conditions, and is in agreement with ancillary sub-national data, in particular selected crop area distribution data and agro-ecological suitability of crops as estimated in GAEZ v4. A mathematical description of the iterative rebalancing method used for downscaling is given in Appendix 8-1.

Description of Module VI outputs

The downscaling procedures and implementation using the year 2009–2011 agricultural statistics have resulted in the following data sets:

i. A global inventory of shares of rain-fed and irrigated cropland at 30 arc-seconds, based on FAO's GLC-Share and GMIA v5 products. The inventory is consistent at national level with FAO land use statistics (arable land, land under permanent crops, land equipped for full control irrigation) of 2009–2011;

ii. Mapped distribution of harvested area, yield and production at 5 arc-minutes resolution for all major crops in rain-fed cropland, based on year 2009–2011 FAO statistics;

iii. Mapped distribution of harvested area, yield and production at 5 arc-minutes resolution for all major crops in irrigated land, based on year 2009–2011 FAO statistics, and

iv. Estimates of the spatial distribution of total crop production value and the production values of major crop groups (cereals, root crops, oil crops), valued at year 2000 international prices.

The results of spatial attribution of crop statistics for the year 2009–2011 undertaken in Module VI are stored as GIS rasters of 5 arc-minute grid cells, separately by 26 crops/crop groups, by total cropland, rain-fed and irrigated cropland. The raster data were produced for harvested area, production and implied average crop yield (i.e., yield = production/harvested area) (for examples see Figure 8-4 to Figure 8-6 below).

Note, the downscaled production from FAOSTAT statistics covers all recorded crop production activities and the attribution to statistical physical cropland (arable land and land under permanent crops) rain-fed and irrigated land units of the resource inventory captures the entire resource use intensity (multiple cropping and/or fallowing) of crop production and avoids incomplete or double counting of available resources, which may occur if only selected commodities were to be downscaled.

Table 8-1 Crops/crop aggregates included in GAEZ v4 downscaling of area, production and yields

Downscaled crop/crop group	Crop acronym	Unit* of production	Contributing FAOSTAT primary crops	International price ($/ton) for aggregations**
Wheat	WHE	1000 tons	Wheat	155
Rice	RCW	1000 tons	Rice, paddy	200
Maize	MZE	1000 tons	Maize	125
Sorghum	SRG	1000 tons	Sorghum	130
Millet	MLT	1000 tons	Millet	170
Barley	BRL	1000 tons	Barley	115
Other cereals	OCE	1000 tons	Buckwheat; canary seed; fonio; mixed grain; oats; pop corn; quinoa; rye; triticale; cereals, nes	115–500
Potato and sweet potato	RT1	1000 tons	Potatoes, Sweet potatoes	105, 85
Cassava	RT2	1000 tons	Cassava	75
Yams and other roots	RT3	1000 tons	Taro; yautia; yams; roots and tubers, nes	95–120
Sugar beet	SUB	1000 tons	Sugar beet	32
Sugar cane	SUC	1000 tons	Sugar cane	20
Pulses	PLS	mln GK$	Bambara beans; beans, dry; broad beans, dry; chick peas; cow peas, dry; lentils; peas, dry; pigeon peas; pulses, other	235–450
Soybean	SOY	1000 tons	Soybean	250
Rapeseed	RSD	1000 tons	Rapeseed	330
Sunflower	SFL	1000 tons	Sunflower seed	300
Groundnut	GRD	1000 tons	Groundnuts, with shell	436
Oil palm fruit	OLP	1000 tons	Oil palm fruit	75

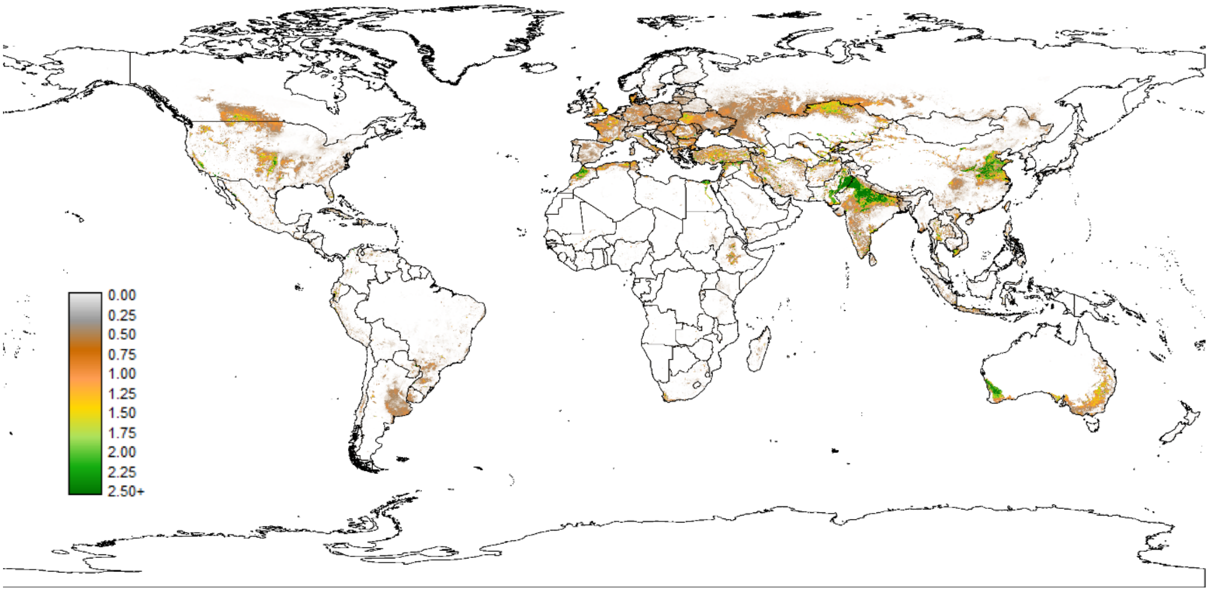
Downscaled crop/crop group	Crop acronym	Unit* of production	Contributing FAOSTAT primary crops	International price ($/ton) for aggregations**
Olives	OLV	1000 tons	Olives	500
Cotton	COT	1000 tons	Seed cotton	525
Banana	BAN	1000 tons	Bananas, plantains	150, 120
Tobacco	TOB	1000 tons	Tobacco, unmanufactured	1500
Vegetables	VEG	mln GK$	All vegetable commodities in FAOSTAT crop production domain ranging from cabbages (358) to vegetables, fresh nes (463)	100–1650
Stimulants	CC2	mln GK$	Cocoa, beans; Coffee, green; Maté; Tea; Tea nes	750, 1000, 1500
Fodder crops	FDD	mln GK$	All commodities in FAOSTAT primary crop production domain ranging from forage and silage, maize (636) to vegetables and roots fodders (655)	25
Crops NES	NES	mln GK$	Includes all other crops from FAOSTAT production domain not covered by 25 crop groups above and excluding coir (813), vegetable tallow (306), oil of stillinga (307), oil of citronella (737), essential oils nes (753) and rubber, natural (836)	100–4000

* *For single crops or fairly homogenous crop groups (other cereals, yams and other roots) the units of production are in 1000 tons of harvested weight (as used in FAOSTAT). For crop groups which include a greater variety of crops (vegetables, stimulants, crops NES) a consistent set of international price weights compiled by FAO (in US dollars of year 2000) were used to sum individual production items to aggregate volumes (volume unit is shown as million GK$). Harvested area of each commodity is expressed in 1000 ha, and yields are tons/ha or 1000 GK$/ha depending on the unit used for total crop production.*

** *The international price weights compiled by FAO (in US dollars of year 2000) were also used to calculate and sum up the value of production and to form high-level commodity aggregations.*

Table 8-1 shows the 26 commodities downscaled from statistical data to spatial rasters at 5 arc-minute resolution in GAEZ v4 and lists the relationship of each downscaled commodity with regard to the items recorded in the FAOSTAT database (http://www.fao.org/faostat/en/#data/QC) from where average 2009–2011 statistical values were extracted from the primary crop production domain as input data for downscaling.

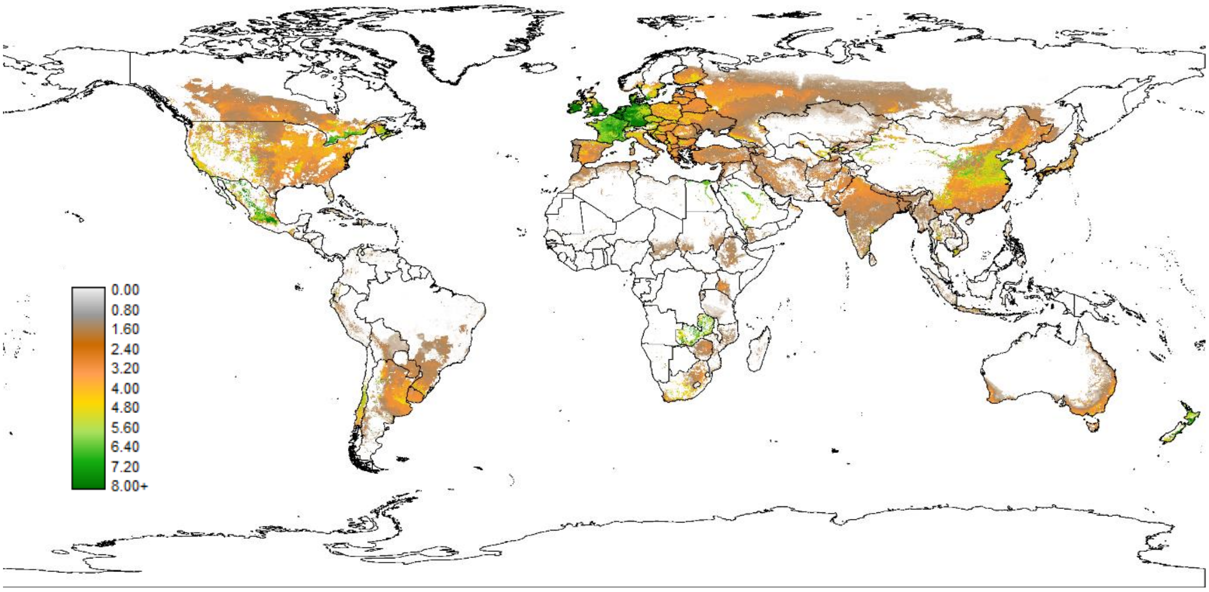
Figure 8-4 Downscaled harvested area of wheat in 2010 (1000 ha)



Source: FAO and IIASA, 2021

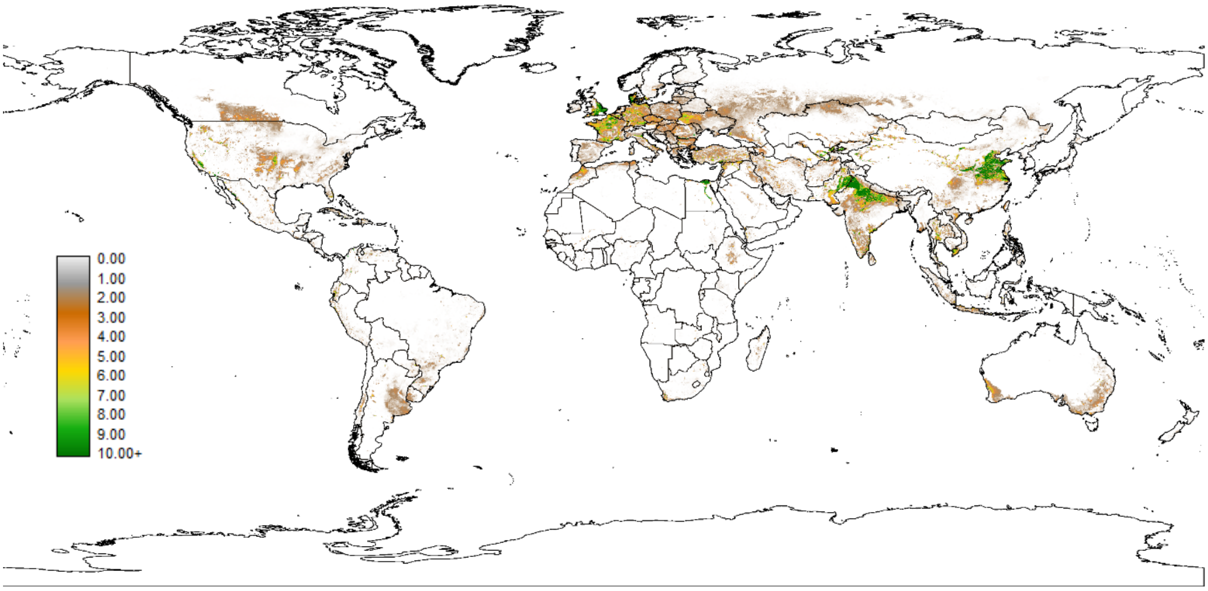
For illustration, maps of downscaled harvested area, yield and production of wheat in 2010 are presented in Figure 8-4, Figure 8-5 and Figure 8-6 respectively. For instance, as is evident in Figure 8-4, the largest concentrations of wheat harvested area can be found in the Indo-Gangetic Plain, in Pakistan and in the North China Plain, whereas wheat yields in 2010 were highest in Europe (see Figure 8-5).

Figure 8-5 Downscaled yield of wheat in 2010 (tons/ha)



Source: FAO and IIASA, 2021

Figure 8-6 Downscaled total production of wheat in 2010 (1000 tons)



Source: FAO and IIASA, 2021

9. Module VII (Yield and production gaps)

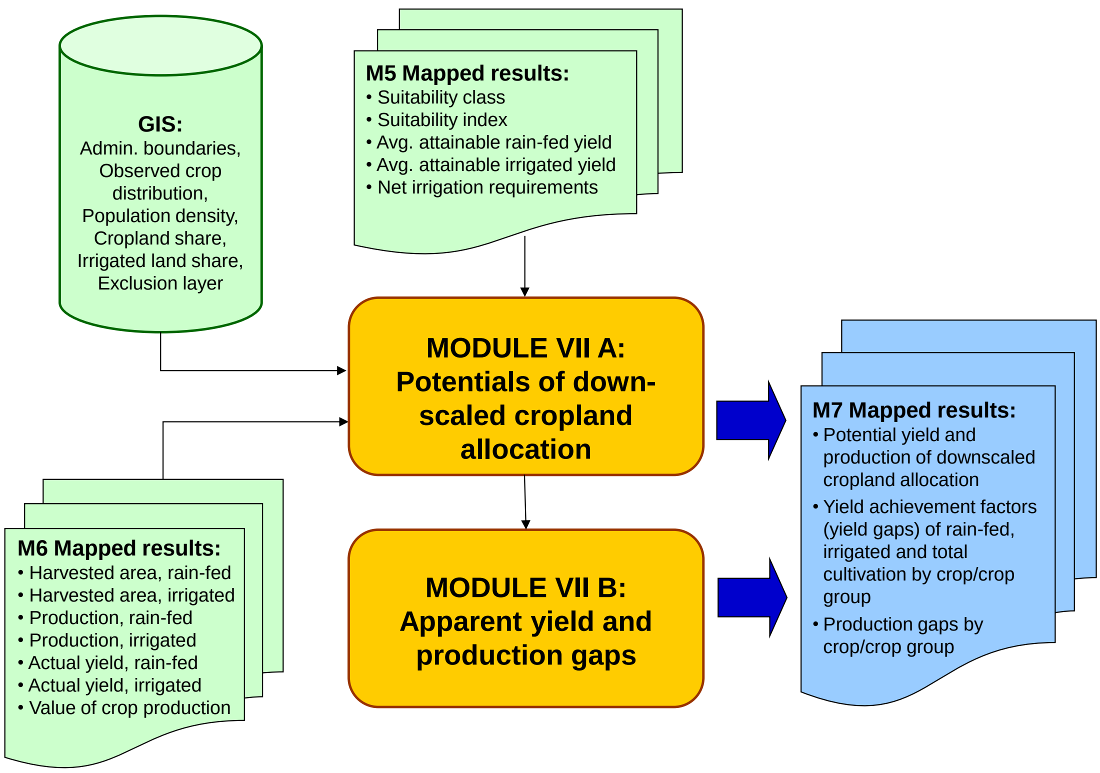
Introduction

The Module VII (Yield and Production Gaps) carries out the final modelling step in GAEZ v4 processing. The quantitative yield gap analysis relies on both the results of crop suitability and potential yield analysis produced in Module V and the downscaling of base year agricultural area and production statistics undertaken in Module VI.

Apparent yield and production gaps have been estimated by comparing at a spatially detailed level of 5 arc-minutes the potential attainable yields and production (as estimated in GAEZ v4) and the harvested areas, actual yields and production obtained by downscaling statistical data for the years 1999–2001 and for 2009–2011 comprising all recorded food, feed and fiber crops (statistical data derived from FAOSTAT, AQUASTAT and selected national sources).

A schematic representation of the information flow in Module VII is presented in Figure 9-1.

Figure 9-1 Information flow in Module VII



Yield and production gaps are estimated by comparing simulated potential and downscaled statistical yield and production of main food, feed and fiber crops.

Yield and production gaps assessment procedures

As indicated in Figure 9-1, there are two main steps involved in Module VII. First, the harvested area allocations produced when downscaling target year statistical production data, in GAEZ v4 respectively for years 1999–2001 and 2009–2011, are combined with estimated potential attainable yields (from Module V) to generate maps of production potential consistent with historical downscaled cropping patterns. In a second step, these maps of production potential are compared with the maps of downscaled actual yield and production to quantify their discrepancies as a measure of apparent yield gaps.

For 22 of the 26 main commodities, comprising a country's total crop production, downscaled crop area, yield and production statistics can be compared with potential crop yield and production results, for both rain-fed and irrigated cultivated land. All 26 commodities are presented in Table 9-1 below.

Table 9-1 Crops/crop aggregates included in GAEZ v4 analysis of yield and production gaps

Downscaled crop/crop group	Crop acronym	Unit of production	LUTs (number) from GAEZ simulations included in the estimation of production potentials*	Conversion factor**
Wheat	WHE	1000 tons	Wheat; winter, spring, sub-tropical, tropical (20)	0.87
Rice	RCW	1000 tons	Rice, paddy; indica, japonica (11)	0.87
Maize	MZE	1000 tons	Maize; tropical lowland, highland, temperate (24)	0.86
Sorghum	SRG	1000 tons	Sorghum; tropical lowland, highland, temperate (18)	0.87
Millet	MLT	1000 tons	Millet; pearl millet, foxtail millet (6)	0.90
Barley	BRL	1000 tons	Barley; winter, spring, sub-tropical, tropical (19)	0.87
Other cereals	OCE	1000 tons	Buckwheat, oats, rye, upland rice(16)	0.87–0.90
Potato and sweet potato	RT1	1000 tons	Potatoes, sweet potatoes (11)	0.20, 0.25
Cassava	RT2	1000 tons	Cassava (2)	0.35
Yams and other roots	RT3	1000 tons	White yam, greater yam, yellow yam, cocoyam (6)	0.35
Sugar beet	SUB	1000 tons	Sugar beet (7)	0.14
Sugar cane	SUC	1000 tons	Sugar cane (1)	0.10
Pulses	PLS	mln GK$	Phaseolous beans, chickpeas, cow peas, dry peas, pigeon peas, gram (35)	-
Soybean	SOY	1000 tons	Soybean (7)	0.90

Rapeseed	RSD	1000 tons	Rapeseed (10)	0.90
Sunflower	SFL	1000 tons	Sunflower seed (6)	0.92
Groundnut	GRD	1000 tons	Groundnuts, shelled (3)	0.65
Oil palm fruit	OLP	1000 tons	Oil palm (1)	0.25
Olives	OLV	1000 tons	Olives (1)	0.22
Cotton	COT	1000 tons	Seed cotton (7)	0.33
Banana	BAN	1000 tons	Bananas, plantains (1)	0.25
Tobacco	TOB	1000 tons	Tobacco, unmanufactured (5)	0.75
Vegetables	VEG	mln GK$	Cabbages, carrots, onions, tomatoes (34)	-
Stimulants	CC2	mln GK$	Cocoa, coffee, tea (7)	-
Fodder crops	FDD	mln GK$	Alfalfa, napier grass, silage maize, pasture legumes, pasture grasses (15)	-
Crops NES	NES	mln GK$		-

** This column lists the crops and number of LUTs simulated in GAEZ v4, which have been used to define the production potential of each downscaled commodity. In each grid-cell the best performing LUT has been selected to represent the production potential of the respective commodity.*
*** This column provides conversion factors that have been applied when comparing yield and production data (provided at fresh/harvest weight) obtained from FAOSTAT and other statistics with GAEZ production potentials (provided as dry weight in most cases, as sugar for sugar beet and sugar cane, and as oil in case of oil palm and olive). The technical conversion coefficients mainly depend on estimated moisture content of harvested products and in a few cases are derived from technical extraction rates, e.g. for sugar crops, oil palm and olive. For some aggregate commodity groups (pulses, vegetables, stimulants, crops NES) comparison with GAEZ results was not undertaken because of substantial commodity differences within the crop group (e.g. pulses, stimulants) and/or insufficient LUTs available to represent a crop group (e.g. vegetables, crops NES).*
**** Tobacco price varies by quality and type of curing; a general figure used in FAOSTAT for unmanufactured tobacco is 1500 GK$. Water content of freshly harvested leafs varies between 85 and 95 % and would contain 10–25% water when cured (Purse glove). For the conversion between FAOSTAT to GAEZ production a factor 0.75 has been assumed.*

Table 9-1 shows the 26 crops/crop groups obtained by downscaling of statistical data into spatial rasters at 5 arc-minute resolution in GAEZ v4. It is important to note that together these 26 crop commodities represent all recorded crop production of each delineated spatial allocation unit (i.e., a country) for which crop statistics were collected. Table 9-1 further shows the available GAEZ LUTs simulated under the historical climate of period 1981–2010, which were used to compile respective commodity-wise production potentials. For instance, GAEZ simulates 20 different wheat LUTs under high input/advanced management assumptions. The algorithm selects in each grid cell the most productive LUT for defining the potential of wheat cultivation in this location.

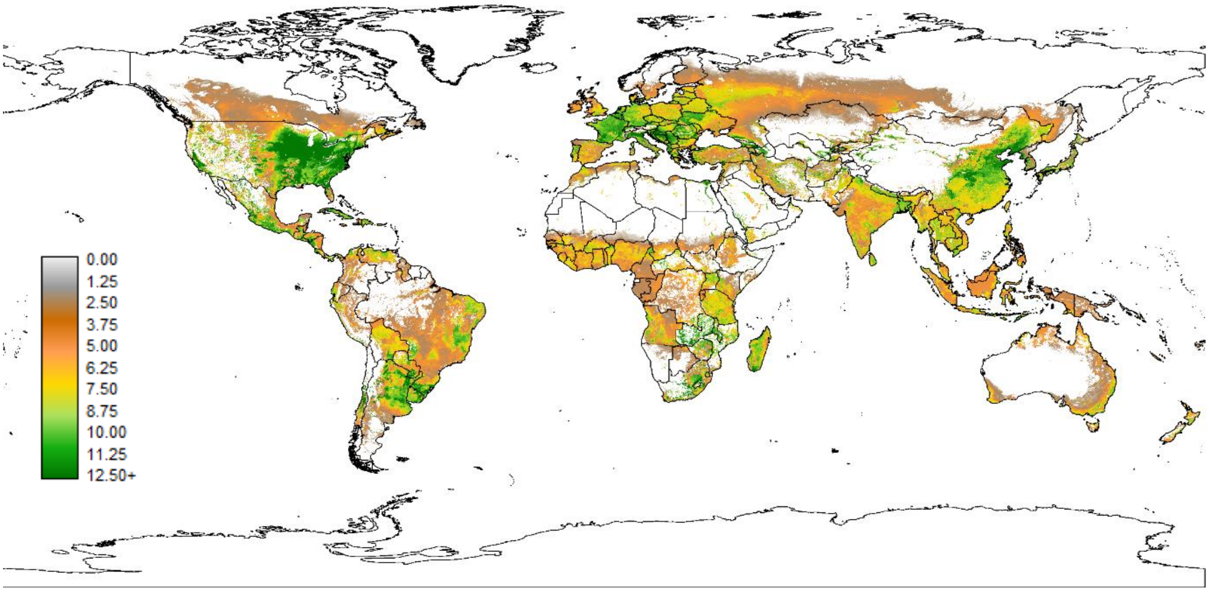
Note that for comparison of FAOSTAT statistical production (usually in harvested/fresh weight) with GAEZ simulated potential production (yield calculated mostly as dry weight of main produce) an appropriate conversion factor must be applied. Technical coefficients used to convert from FAOSTAT to GAEZ crop lists are included in the last column of Table 9-1.

The technical conversion coefficients mainly depend on estimated moisture content of harvested products and in a few cases are derived from technical extraction rates, such as for sugar crops, oil palm and olive. For some aggregate commodity groups (pulses, vegetables, stimulants, crops NES) a comparison with GAEZ results was not undertaken because of substantial commodity differences within the crop group (e.g. pulses, stimulants) and/or insufficient LUTs available to represent a crop group (e.g. vegetables, crops NES).

The comparison of downscaled actual and simulated potential yields and production involves the cultivated land occurring by 5 arc-minute grid cells, separately for rain-fed and irrigated cropland. Comparisons are presented as achievement ratios (actual/potential) for yields and as absolute differences of potential and actual production. The results of yield gap analysis are stored as GIS rasters at 5 arc-minutes resolution, separately for total cropland, irrigated and rain-fed cropland. We illustrate the results obtained in Module VII by the examples shown in Figure 9-2 to Figure 9-4.

Figure 9-2 shows potential attainable cereal yields computed on the basis of GAEZ simulated crop suitability and production (under high input/advanced management assumptions) for an allocation of cereal harvested areas as obtained by downscaling of 2009–2011 crop statistics. Note, this means that the crop potential considered here for the comparison with actual production is subject to cropland use as recorded in the statistical data.

Figure 9-2 Potential attainable yields of downscaled cereal cropping patterns in current cropland

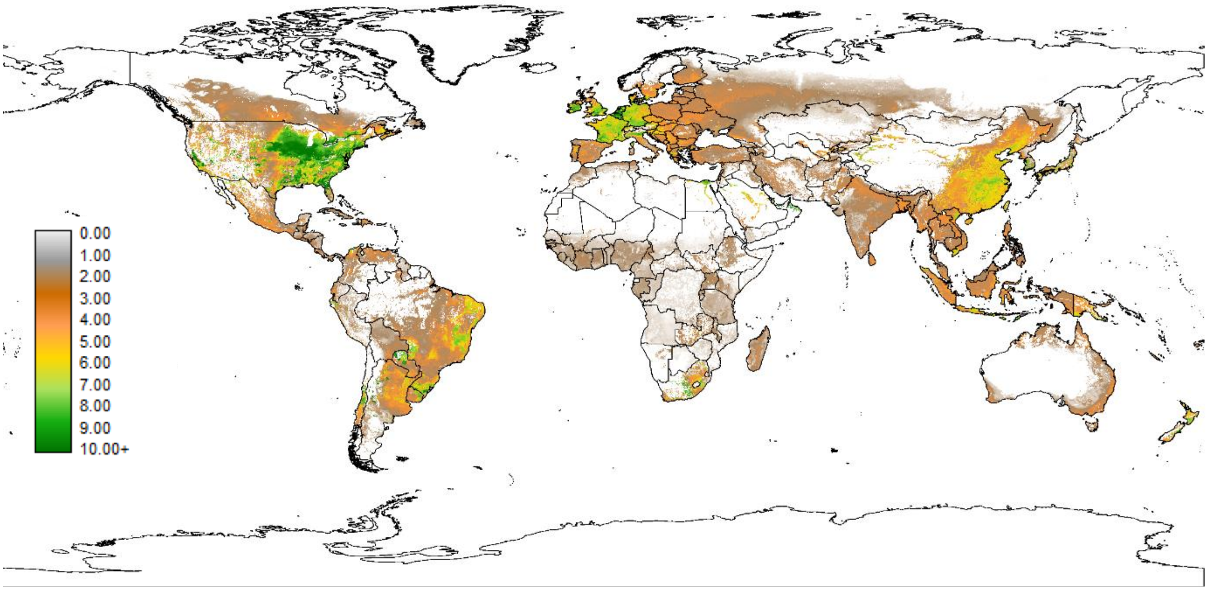


Source: FAO and IIASA, 2021

Figure 9-3 presents a map of actual cereal yields as obtained by downscaling of statistical data of 2009–2011 cereal harvested areas and production in Module VI. The figure shown here represents an aggregation of results based on separate downscaling of all cereal production in terms of wheat, rice, maize, sorghum, millet, barley and other cereals, i.e., the commodities 1–7 in the list of 26 crops/crop groups distinguished in the downscaling.

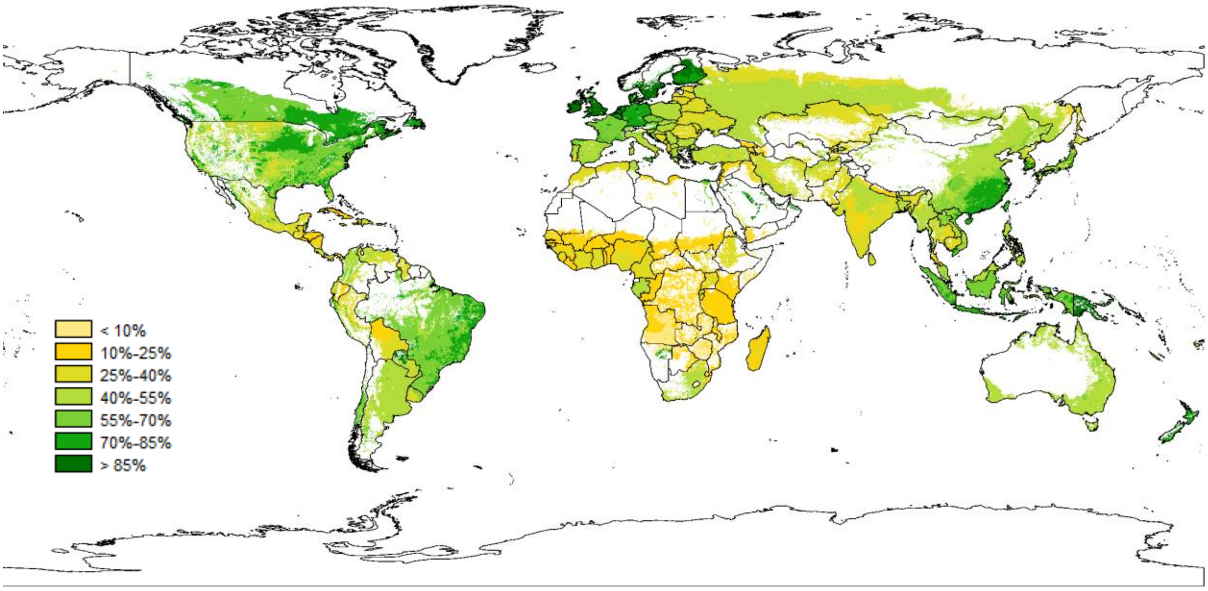
An estimate of apparent yield gaps is then derived by comparing actual to potential yields and production. Figure 9-4 presents calculated ‘yield achievement ratios’ (i.e., ratio of actual/potential production) comparing downscaled actual yields with potentials simulated under high input/advanced management assumptions. Apparent yield gaps are closely related to the calculated yield achievement factors, both summing up to 100 percent. For instance, a yield achievement factor of 75% would imply an apparent yield gap of 25%.

Figure 9-3 Yields of downscaled cereal production in current rain-fed and irrigated cropland, 2009–2011



Source: FAO and IIASA, 2021

Figure 9-4 Yield achievement ratio (100xactual/potential) of cereals in the cropland of 2009–2011



Source: FAO and IIASA, 2021

As can be concluded from Figure 9-4, available data suggests that in the recent past the highest yield achievement ratios were obtained in Europe, North America and parts of China and Brazil. The largest yield gaps clearly occurred in sub-Saharan Africa. Prevailing yield gaps can have many causes, including lack of inputs and poor access to technologies, limitations due to storage, processing and marketing, large climatic variability and other production risks, distorted farmgate prices, to name a few. A global analysis and clustering of widespread yield gap syndromes, based on GAEZ products, can be found in Pradhan *et al.* (2015)

10. Agro-ecological Zones classification

Introduction

The agro-ecological zones (AEZ) methodology provides a framework for establishing a spatial inventory of land resources compiled from global/national environmental data sets and assembled to quantify multiple spatial characteristics required for the assessments of land productivity under location-specific agro-ecological conditions. The land resources inventory includes spatial layers of historical and future climate, soil, terrain, land cover, population density, livestock density, protected areas/areas of high biodiversity value, and administrative boundaries.

On the basis of the available GAEZ v4 land resources information a workable number of AEZ classes was specified for the purpose of targeting users who may need relatively broad-scale tendencies for planning and analysis. AEZ definitions and map classes follow a rigorous methodology and an explicit set of principles. The first principle applied is to make sure the AEZ map classes align with major climate zones, as determined in GAEZ v4, delineated based on historical data of the period 1981–2010. Second, AEZ map classes reflect broad ranges of length of growing period (LGP) boundaries reflecting different agro-environments. Third, agro-ecological zones classes include generalized information regarding prevailing soil/terrain limitations derived from the GAEZ v4 terrain and soil resources inventories.

Factors used for global AEZ classification

The AEZ class layer provides a uniform classification of bio-physical resources relevant to agricultural production systems. The inventory combines spatial layers of thermal and moisture regimes with broad categories of soil/terrain qualities. It also indicates locations of areas with irrigated soils and shows land with severely limiting bio-physical constraints including very cold and very dry (desert) areas as well as areas with very steep terrain or very poor soil/terrain conditions. The basic principles and criteria used for the compilation of the AEZ class layer are listed below.

Thermal climate classes

Based on the twelve thermal climates delineated in GAEZ v4 Module I (see Chapter 3, section 3.3.1), six aggregate categories of major thermal climate (TC) classes, TC1 to TC6, were used in the definition of AEZs in GAEZ v4, namely:

- **TC1**: Tropics, lowland;
- **TC2**: Tropics, highland;
- **TC3**: Subtropics;

- **TC4**: Temperate climate;
- **TC5**: Boreal climate, and
- **TC6**: Arctic climate.

The six climate classes represent broad latitudinal belts based on monthly temperature conditions at sea level (using a uniform lapse rate of 0.55°C/100 m).

Thermal zone classes

Thermal zone (TZ) classes reflect actual temperature conditions (see also Chapter 3, section 3.3.2) and are used to characterize and sub-divide major thermal climate classes into more specific temperature regime classes (TRC). Six thermal zone classes were distinguished:

- **TZ1 Warm:** monthly Ta ≥ 10°C for all months; average annual Ta ≥ 20°C;
- **TZ2 Moderately cool:** monthly Ta ≥ 5°C for all months; monthly Ta ≥ 10°C for 8 or more months;
- **TZ3 Moderate:** monthly Ta ≥ 10°C for 5 or more months; number of days with mean temperature above 20°C (LGP_{t20}) is 75 days or more; accumulated temperature during the period with Ta≥10°C exceeds 3000 (dd);
- **TZ4 Cool**: monthly Ta ≥ 10°C for 4 or more months; average annual Ta ≥ 0°C;
- **TZ5 Cold:** monthly Ta ≥ 10°C for 1 to 3 months; average annual Ta ≥ 0°C, and
- **TZ6 Very cold:** monthly Ta < 10°C for all months and/or average annual Ta < 0°C.

Note, thermal zone classification starts with testing for TZ1 and subsequently, when conditions are not met, testing continues for TZ2, TZ3, TZ4, etc. Testing for TZ3 is done only for grid cells in the temperate thermal climate.

Thermal zone TZ1 occurs in tropical lowland and subtropical thermal climates. There is no frost risk for perennial crops, no hibernation for annual crops and the climate allows foremost the cultivation of crops adapted to warm temperatures. Depending on moisture supply a wide range of crops can be grown. This includes tropical lowland maize and lowland sorghum as well as pearl millet and sugar cane (crop group C4-I) and a wide range of annual and perennial C4 crops, varying from annuals such as indica rice, soybean, groundnut, sweet potato and yam to perennials like oil palm, cocoa, coconut, robusta coffee and rubber (belonging to crop group C3-II).

Thermal zone TZ2 occurs in tropical highlands and in subtropical thermal climates. Heat provision is less than in TZ1 and mean monthly temperature can be less than 10°C for up to 4 months, though mean monthly temperatures stay above 5°C in all months. In tropical highlands, thermal zone TZ2 allows a range of crops to be grown adapted to moderately cool temperatures. These include crops like highland maize and sorghum as well as highland phaseolus bean and arabica coffee. At the margins with tropical lowland also some crops of crop group C3-II can be grown, e.g., tobacco, sunflower, soybean and various vegetables. In the subtropical thermal climate some temperature seasonality occurs and when water is available thermal zone TZ2 can support sequential multi-cropping such as the prominent wheat/rice double cropping system, as for instance practiced in northern India and in parts of eastern China.

Thermal zone TZ3 is considered only in the temperate thermal climate to subdivide the vast temperate region into a moderate and a cool temperature regime class. The moderate zone of the temperate thermal climate provides at least 5 months with monthly temperatures above 10°C and at least 75 days with average daily temperatures above 20°C, conditions which are sufficient to cultivate a thermophilic annual crop like cotton, tobacco or japonica rice with a crop growth cycle length of 5–6 months. The wide range of crops that can be grown in TZ3 include also soybean, groundnut (crop adaptability groups C3-II); maize, sorghum, foxtail millet (crop group C4-II); and wheat, barley, white potato, bean, rapeseed and sunflower (crop group C3-I).

The cool thermal zone TZ4 occurs at higher altitudes in tropics and subtropics and at higher latitudes in the temperate thermal climate. Zone TZ4 cannot accommodate crops adapted to warm temperatures. Cultivation is mostly practiced with C3-I crops, including wheat, barley, potatoes or rapeseed. TZ4 imposes frost risks and therefore frost sensitive perennials like citrus or olive cannot be grown.

The cold thermal zone TZ5 is characterized by only 1 to 3 months with average temperature exceeding 10°C and/or average annual temperature is above 0°C. TZ5 occurs at higher latitudes in the boreal thermal climate or may occur at high altitudes in tropical, subtropical and temperate regions. When creating temperature regime classes, this zone is further subdivided depending on occurrence of permafrost classes (see Table 10–1). Agricultural use of TZ5 outside permafrost zones is limited to pastures and a few cryophilic crops. These crops comprise very short cultivars adapted to germinate and grow at marginal soil temperatures, e.g., specific spring wheat and barley varieties and early white potato.

The very cold thermal zone TZ6 is not suitable for cropping. Mean monthly temperatures are less than 10°C in all months and/or mean annual temperature is below 0°C.

Temperature regime classes

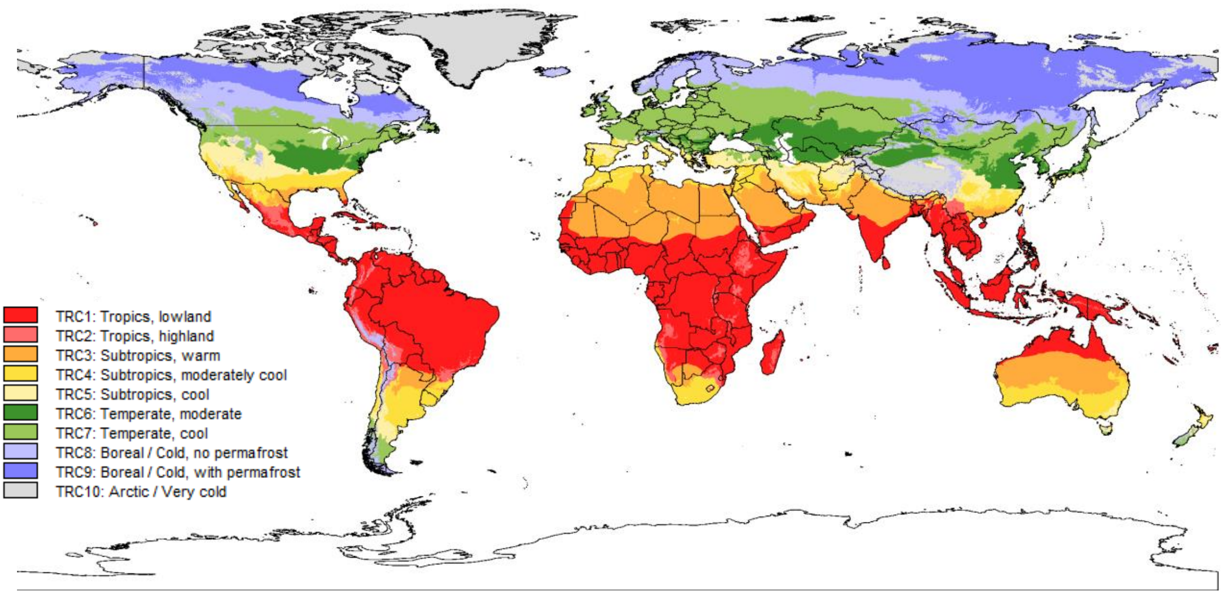
The delineation of ten Temperature Regime Classes (TRC), which are used to define AEZs, combines major thermal climate classes (TC1 to TC6) and thermal zone classes (TZ1 to TZ6) in a systematic way. Note that thermal climates represent latitudinal belts with characteristic patterns of day-length and temperature seasonality, whereas thermal zones characterize actual temperature profile conditions depending on altitude and latitude. Conditions in different TRCs relate to the thermal requirements of different crop adaptability groups. The forming of temperature regime classes TRC1 to TRC10, using classes TC1 to TC6 and TZ1 to TZ6, is summarized in Table 10–1.

Table 10-1 Creation of temperature regime classes

TRC class	Class name	Thermal climate class						Thermal zone class					
		TC1	TC2	TC3	TC4	TC5	TC6	TZ1	TZ2	TZ3	TZ4	TZ5	TZ6
TRC1	Tropics, lowland	×						×					
TRC2	Tropics, highland		×						×		×		
TRC3	Subtropics, warm			×				×					
TRC4	Subtropics, mod. cool			×					×				
TRC5	Subtropics, cool			×							×		
TRC6	Temperate, moderate				×					×			
TRC7	Temperate, cool				×						×		
TRC8	Boreal/Cold, no PFR		×	×	×	×						×	
TRC9	Boreal/Cold, with PFR		×	×	×	×						×	
TRC10	Arctic/Very cold		×	×	×	×	×						×

'With PFR' means occurrence of continuous or discontinuous permafrost classes

Figure 10-1 Temperature regime classes, climate of 1981–2010



Source: FAO and IIASA, 2021

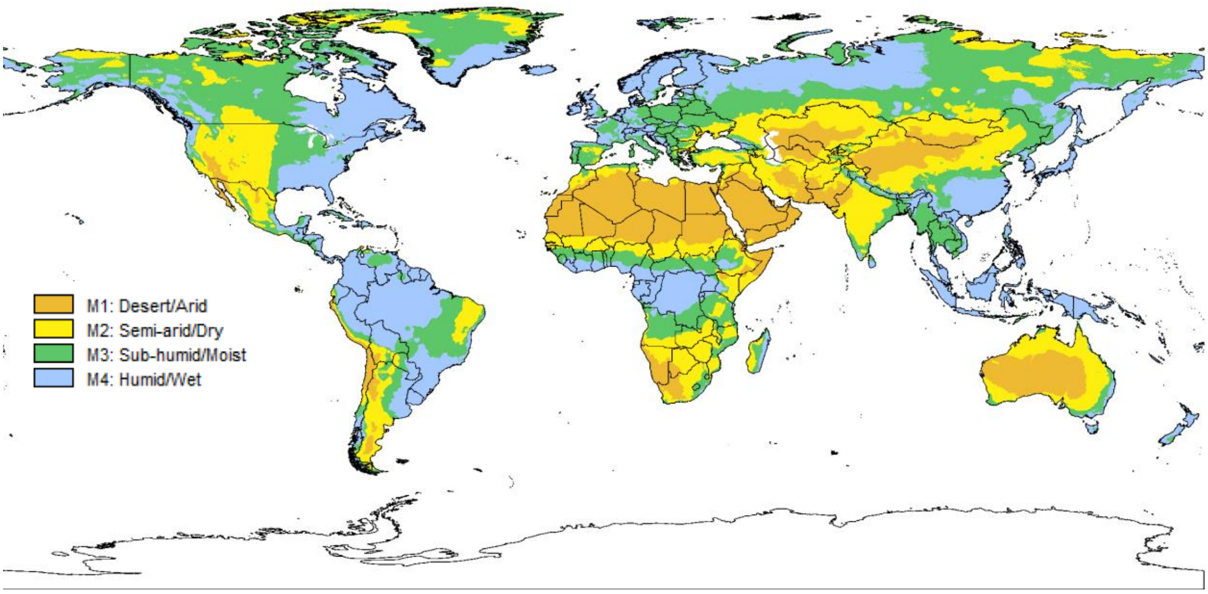
Moisture regime classes

The delineation of four moisture regime classes (Figure 10–2) makes use of the GAEZ v4 agro-climatic inventory and results of the GAEZ v4 daily reference water balance to define broad moisture regime classes following the established AEZ terminology:

- **M1**: delineates desert/arid areas where 0 ≤ LGP* < 60 days;
- **M2**: is used for semi-arid/dry areas with 60 ≤ LGP* < 180;
- **M3**: represents sub-humid/moist areas with 180 ≤ LGP* < 270, and
- **M4**: denotes humid/wet areas where LGP* > 270.

For areas with LGP_{t5} > 330 days the indicator LGP* is set to the average number of annual growing period days. When LGP_{t5} < 330 days, i.e., in areas with seasonal temperature limitations, the LGP* indicator is set as the maximum of LGP days and a function of the annual P/ET0 ratio, using a quadratic regression equation, which was estimated (and applied) in GAEZ v3 and is based on a data set which includes all grid-cells with LGP_{t5} = 365 days. This function, termed equivalent LGP (see section 3.5.2 in Chapter 3), results in 60 days for a ratio P/ET0 ~ 0.15, in 120 days for P/ET0 ~ 0.40, 180 days for P/ET0 ~ 0.65 and 270 days for P/ET0 ~ 1.15.

Figure 10-2 Moisture regime classes, climate of 1981–2010



Source: FAO and IIASA, 2021

Soil/terrain related classes

The delineation of agro-ecological zones in GAEZ v4 distinguishes five classes related to soil quality and terrain conditions. The mapping of classes uses the GAEZ v4 soil/terrain inventory, i.e., the data from HWSD v1.2.1 and a terrain slope distribution inventory by 30 arc-second grid cells, which was derived from original 3 arc-second SRTM data. The following soil/terrain related classes are distinguished:

- **S1**: represents very steep terrain where the sum of percentages of slope classes SLP7 (30–45%) and SLP8 (slope > 45%) exceeds in a grid cell a given target threshold (e.g. 75%) and the sum of slope classes SLP1 to SLP4 (i.e., terrain slopes ≤ 8%) is less than a maximum threshold;
- **S2**: denotes areas with hydromorphic soils, which includes all Gleysols, Histosols, as well as all gleyic and stagnic soil types of FAO'74 and FAO'90 classifications;
- **S3**: comprises grid cells with no or slight soil/terrain limitations;
- **S4**: is for areas with moderate soil/terrain constraints, and
- **S5**: denotes areas with severe and very severe soil/terrain limitations and so-called miscellaneous units of the soil database (e.g. rock outcrops, sand dunes, glaciers, etc.).

For class S1 a minimum threshold of 75% was used for the sum of SLP7 and SLP8 as well as a maximum threshold of 10% for the sum of SLP1 to SLP4. Class S2 was assigned when hydromorhic soils account for at least 67% in a grid cell.

For classes S3 to S5 the severity of soil/terrain limitations is quantified by a soil/terrain suitability index, which is calculated in AEZ as the weighted sum of the component soil/terrain suitability rating factors. It can be obtained by summing area weighted edaphic ratings for all occurring soil/slope class combinations in a grid-cell. The soil unit rating refers to a reference crop (e.g. grain maize) under low input assumptions. The resulting index values range from 0 (entire grid cell is not suitable) to 1 (entire grid cell is rated as very suitable, having no constraints). The algorithm uses two thresholds to subdivide the full suitability index value range into classes S3, S4 and S5. Class boundaries used were [0.667–1.000] for class S3, [0.250–0.667] for class S4, and the remainder, interval [0.000–0.250] for class S5. Note, class S5 includes also all areas evaluated as having continuous or discontinuous permafrost (see Chapter 3, section 3.3.7), i.e., areas with an air frost index *FI* exceeding the threshold of 0.570. Soil/terrain related classes are mapped in Figure 10–3.

Selected special purpose land cover classes

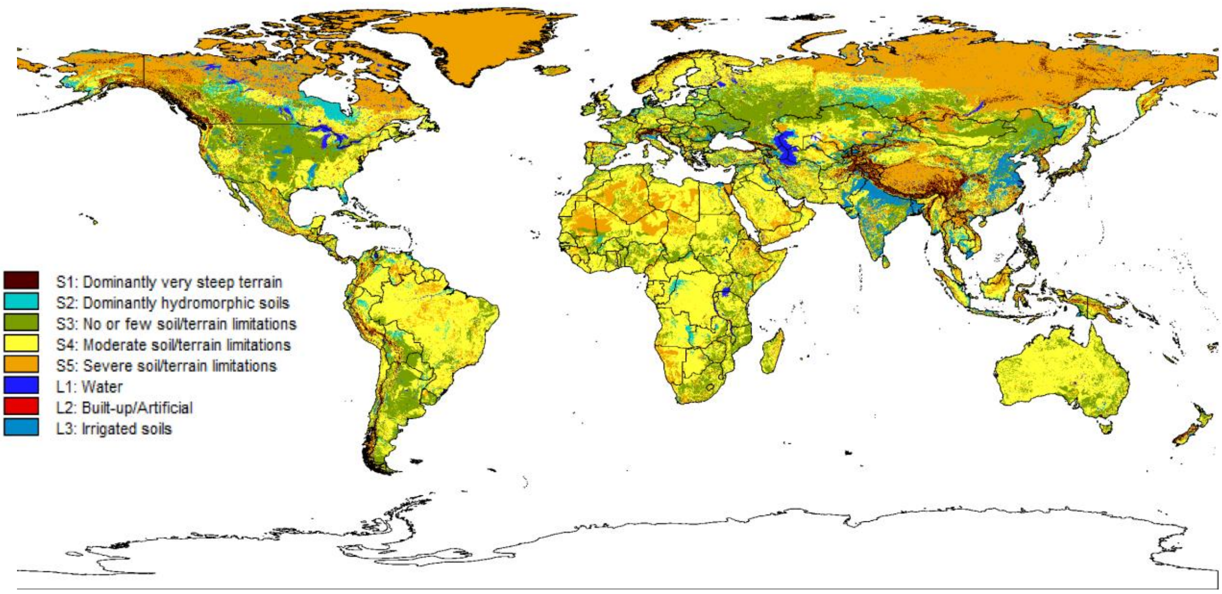
The delineation of agro-ecological zones in GAEZ v4 distinguishes three land cover classes, L1 to L3, listed below. They are related to selected (special purpose) elements of the GAEZ v4 land cover inventory, which was derived from GLC-Share v1.1 and GMIA v5 (for a description see Chapter 2, section 2.3).

For constructing AEZs, three special purpose land cover classes L1 to L3, with very specific properties were extracted and mapped together with soil/terrain related classes, as shown in Figure 10–3:

- **L1**: relates to the dominance of inland water bodies in a grid cell, i.e., where the respective land cover share for water exceeds a specified threshold (e.g. 75% of a 30 arc-second grid cell);
- **L2**: maps areas where artificial surfaces dominate, exceeding a specified threshold (a minimum 75% of a 30 arc-second grid cell was used), and

- **L3**: denotes irrigated areas where the share of irrigated cropland in a grid cell exceeds a specified minimum threshold (e.g., 20% of a 30 arc-second grid cell) or where cropland exceeds a given minimum threshold (e.g. 40% of a 30 arc-second grid cell) and at least half of the cropland in a pixel is equipped for irrigation.

Figure 10-3 Soil/terrain related classes and selected special purpose land cover classes



Source: FAO and IIASA, 2021

Agro-ecological Zones classes in GAEZ v4

The temperature regime classes TRC1-TRC10, moisture regime classes M1-M4, soil/terrain related classes S1-S5, and special purpose land cover classes L1-L3, described above, represent the different dimensions used for AEZ classification. These were combined step by step, following a priority scheme, to form 57 unique AEZ classes, as listed in Table 10–2.

Note, since some special purpose classes are defined by minimum thresholds of occurrence (e.g., water; built-up/artificial surface; irrigated cropland), some of these land cover types, when occurring with low intensity in a grid cell, will not be shown. For instance, water in grid cells where the water share is less than 75% will not be assigned to class AEZ-57 but will be mapped, depending on context, as one class of AEZ-50, AEZ-53 to AEZ-55, or one of AEZ-01 to AEZ-48. Besides the water class (AEZ-57), this qualification applies also to classes AEZ-49 to AEZ-52 and AEZ-56.

The combinations marked in Table 10–1 are listed below by class with some additional explanations:

- **AEZ-01 to AEZ-06**: combinations of TRC1 (tropics, lowland) with M2-M4 and S3-S4;
- **AEZ-07 to AEZ-12**: combinations of TRC2 (tropics, highland) with M2-M4 and S3-S4;

- **AEZ-13 to AEZ-18**: combinations of TRC3 (subtropics, warm) with M2-M4 and S3-S4;
- **AEZ-19 to AEZ-24**: combinations of TRC4 (subtropics, moderately cool) with M2-M4 and S3-S4;
- **AEZ-25 to AEZ-30**: combinations of TRC5 (subtropics, cool) with M2-M4 and S3-S4;
- **AEZ-31 to AEZ-36**: combinations of TRC6 (temperate climate, moderate) with M2-M4 and S3-S4;
- **AEZ-37 to AEZ-42**: combinations of TRC7 (temperate climate, cool) with M2-M4 and S3-S4;
- **AEZ-43 to AEZ-48**: combinations of TRC8 (boreal/cold, no permafrost) with M2-M4 and S3-S4;
- **AEZ-49**: dominantly very steep terrain; all grid cells where soil/terrain related class S1 occurs;
- **AEZ-50**: land with severe soil/terrain limitations; covers all areas of S5 except where set to classes AEZ-49 or AEZ-51 to AEZ-57;
- **AEZ-51**: land with ample irrigated soils; set for pixels where land equipped for irrigation exists and exceeds the specified thresholds for class L3;
- **AEZ-52**: dominantly hydromorphic soils; set for pixels where class S2 occurs, but excluding grid cells which were previously set to classes AEZ-49 or AEZ-51;
- **AEZ-53**: desert/arid; delineates all areas in the arid moisture class M1, except for special purpose land cover classes L1, L2, L3, soil/terrain classes S1 (very steep terrain) and S2 (hydromorphic soils), or thermal regime class TRC10 (i.e., arctic/very cold);
- **AEZ-54**: boreal/cold climate with permafrost; includes all pixels where TRC9 occurs (except for special purpose land cover L1 and L2, or soil/terrain classes S1 and S2, or moisture class M1);
- **AEZ-55**: arctic/very cold climate; includes all pixels where TRC10 occurs (except for special purpose land cover L1 and L2, soil/terrain classes S1 and S2);
- **AEZ-56**: dominantly built-up/artificial surface; is set in all grid cells where L2 occurs, and
- **AEZ-57**: dominantly inland water; is set in all grid cells where L1 occurs.

Table 10-2 Creation of AEZ classes

Agro-ecological Zones class*	Temperature regime class										Moisture class				Soil/terrain class					LC class		
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	1	2	3	4	5	1	2	3
01 TR, lowland; semi-arid, minor s/t lim.	×											×					×					
02 TR, lowland; semi-arid, with s/t lim.	×											×						×				
03 TR, lowland; sub-humid, minor s/t lim.	×												×				×					
04 TR, lowland; sub-humid, with s/t lim.	×												×					×				
05 TR, lowland; humid, minor s/t lim.	×													×			×					
06 TR, lowland; humid, with s/t lim.	×													×				×				
07 TR, highland; semi-arid, minor s/t lim.		×										×					×					
08 TR, highland; semi-arid, with s/t lim.		×										×						×				
09 TR, highland; sub-humid, minor s/t lim.		×											×				×					
10 TR, highland; sub-humid, with s/t lim.		×											×					×				
11 TR, highland; humid, minor s/t lim.		×												×			×					
12 TR, highland; humid, with s/t lim.		×												×				×				
13 STR, warm; semi-arid, minor s/t lim.			×									×					×					
14 STR, warm; semi-arid, with s/t lim.			×									×						×				
15 STR, warm; sub-humid, minor s/t lim.			×										×				×					
16 STR, warm; sub-humid, with s/t lim.			×										×					×				
17 STR, warm; humid, minor s/t lim.			×											×			×					
18 STR, warm; humid, with s/t lim.			×											×				×				
19 STR, mod. cool; semi-arid, minor s/t lim.				×								×					×					
20 STR, mod. cool; semi-arid, with s/t lim.				×								×						×				

Agro-ecological Zones class*	Temperature regime class										Moisture class				Soil/terrain class					LC class		
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	1	2	3	4	5	1	2	3
21 STR, mod. cool; sub-humid, minor s/t lim.				×									×				×					
22 STR, mod. cool; sub-humid, with s/t lim.				×									×					×				
23 STR, mod. cool; humid, minor s/t lim.				×										×			×					
24 STR, mod. cool; humid, with s/t lim.				×										×				×				
25 STR, cool; semi-arid, minor s/t lim.					×							×					×					
26 STR, cool; semi-arid, with s/t lim.					×							×						×				
27 STR, cool; sub-humid, minor s/t lim.					×								×				×					
28 STR, cool; sub-humid, with s/t lim.					×								×					×				
29 STR, cool; humid, minor s/t lim.					×									×			×					
30 STR, cool; humid, with s/t lim.					×									×				×				
31 TE, moderate; dry, minor s/t lim.						×						×					×					
32 TE, moderate; dry, with s/t lim.						×						×						×				
33 TE, moderate; moist, minor s/t lim.						×							×				×					
34 TE, moderate; moist, with s/t lim.						×							×					×				
35 TE, moderate; wet, minor s/t lim.						×								×			×					
36 TE, moderate; wet, with s/t lim.						×								×				×				
37 TE, cool; dry, minor s/t lim.							×					×					×					
38 TE, cool; dry, with s/t lim.							×					×						×				
39 TE, cool; moist, minor s/t lim.							×						×				×					
40 TE, cool; moist, with s/t lim.							×						×					×				
41 TE, cool; wet, minor s/t lim.							×							×			×					
42 TE, cool; wet, with s/t lim.							×							×				×				
43 BO/Cold, no PFR; dry, minor s/t lim.								×				×					×					

Agro-ecological Zones class*	Temperature regime class										Moisture class				Soil/terrain class					LC class		
	1	2	3	4	5	6	7	8	9	10	1	2	3	4	1	2	3	4	5	1	2	3
44 BO/Cold, no PFR; dry, with s/t lim.								×				×						×				
45 BO/Cold, no PFR; moist, minor s/t lim.								×					×				×					
46 BO/Cold, no PFR; moist, with s/t lim.								×					×					×				
47 BO/Cold, no PFR; wet, minor s/t lim.								×						×			×					
48 BO/Cold, no PFR; wet, with s/t lim.								×						×				×				
49 Dominantly very steep terrain															×							
50 Severe soil/terrain limitations																			×			
51 Land with ample irrigated soils																						×
52 Dominantly hydromorphic soils																×						
53 Desert/Arid climate											×											
54 BO/Cold climate, with PFR									×		×	×	×	×								
55 Arctic/Very cold climate										×	×	×	×	×								
56 Dominantly urban/built-up land																				×		
57 Dominantly water																					×	

* *TR: Tropics; STR=Subtropics; TE=Temperate; BO=Boreal; s/t lim.: soil/terrain limitations; PFR=permafrost*

When grid-cell values match the conditions for more than one class, for instance a lake in a desert area, or very steep slopes in a cold climate, it is important that the classes are assigned step by step following a priority scheme to ensure consistency of classification.

The sequence followed to assign AEZ classes begins with checking conditions for special purpose LC classes AEZ-56 and AEZ-57. Then the conditions for classes AEZ-49, AEZ-51 and AEZ-52 are tested and assigned, if matching. Thereafter conditions for classes AEZ-53 and AEZ-54 are tested and assigned, when matching. For instance, a grid cell in a desert area meeting the hydromorphic soils criteria would be assigned to class AEZ-52 (dominantly hydromorphic soils), not to AEZ-53 (desert/arid) which comes later in the priority scheme. The next step is to check for very severe soil/terrain limitations (class AEZ-50). From there onward all combinations of thermal, moisture and soil/terrain conditions are unique and can be assigned to classes AEZ-01 to AEZ-48.

The robust principles of combining thermal and moisture regime classes with soil/terrain and special land cover characteristics can also be applied in regional or national studies. In such cases it is however usually necessary to further refine the various class definitions to reflect in more detail the critical thresholds in each application. Also, it may be necessary to include additional biophysical or socioeconomic characteristics, for instance zones of unimodal versus bimodal rainfall patterns in East Africa, in order to delineate adequate territorial units for analysis and planning.

A next step is to compile for each AEZ class some statistics describing the intensity and distribution of key agricultural indicators. An example for a simplified set of AEZ classes, excluding a sub-division by severity of soil limitations, is presented in Table 10–3.

It shows for each (aggregate) AEZ class the total area, the computed share of cropland, grassland and shrub-covered land, and of tree-covered areas (land cover shares at 30 arc-seconds taken from GAEZ v4 land cover inventory, based on GLC-Share, Latham *et al.* (2014)), the population density (Oak Ridge National Laboratory, 2013) and number of cattle (from GLW2, Robinson *et al.* (2014)), and the mean annual temperature (derived from Harris *et al.* (2014)) averaged over all grid cells in an AEZ class, as well as the total annual precipitation (based on Schneider *et al.* (2011)).

In Table 10–3, the largest extent is found for the Desert/Arid climate zone (AEZ-53), which accounts for 18% of the map total (excluding Antarctica) and covers huge areas in sub-Saharan Africa, central Asia and Australia. The highest population density is found in class AEZ-56 (Dominantly urban/built-up areas), which includes the 30 arc-second grid cells where mapped urban areas exceed a share of 75%.

Of great importance for agricultural activities is class AEZ-51 (Land with ample irrigated soils), which can support high yields and production and where the second highest population density (280 persons per square kilometer) is found. Also, among all classes, it contains the highest share of cropland (62 percent) and records of all classes the largest number of cattle. Contrary to AEZ-51, the lowest population and cattle densities are found in Boreal/Cold (with permafrost) and Arctic/Very cold environments, i.e., AEZ-54 and AEZ-55.

Tree-covered land dominates in humid tropical and subtropical regions as well as in wet temperate and boreal zones whereas grassland and shrub-covered land mostly dominate in semi-arid and dry environments.

Table 10-3 Selected indicators by AEZ Class

Agro-ecological Zones class	TOTAL AREA Mln ha	Land cover % of AEZ zone CROP-LAND	GRASS + SHRUB	TREE-COVER	OTHER COVER	POP 2010 Pers/km²	CATTLE 2010 Head/km²	MEAN TEMP °C	ANN. PRECIP mm
Tropics, lowland; semi-arid	845	13.4	45.0	26.7	14.9	28.5	14.2	25.6	708
Tropics, lowland; sub-humid	868	14.4	38.7	44.4	2.4	37.5	19.5	25.1	1286
Tropics, lowland; humid	1314	10.5	15.9	71.7	1.9	32.3	11.7	25.6	2123
Tropics, highland; semi-arid	56	8.6	57.0	19.2	15.3	34.4	17.1	16.5	558
Tropics, highland; sub-humid	70	15.8	46.6	32.9	4.7	74.3	34.3	17.2	1012
Tropics, highland; humid	56	18.8	28.4	49.2	3.6	111.0	45.3	17.3	1570
Subtropics, warm; semi-arid	187	19.2	32.4	16.4	32.0	52.8	22.0	23.3	601
Subtropics, warm; sub-humid	46	26.9	24.9	39.8	8.4	114.1	50.5	22.6	1169
Subtropics, warm; humid	63	18.3	36.3	39.1	6.3	105.4	39.5	21.6	1656
Subtropics, mod. cool; semi-arid	290	16.0	42.0	11.0	31.0	14.2	5.4	17.4	379
Subtropics, mod. cool; sub-humid	140	31.2	31.5	24.1	13.3	44.8	20.0	16.4	722
Subtropics, mod. cool; humid	207	23.0	27.5	44.8	4.6	64.0	35.5	17.2	1280
Subtropics, cool; semi-arid	260	9.9	58.2	13.7	18.2	14.1	6.5	11.4	360
Subtropics, cool; sub-humid	58	18.8	30.6	40.9	9.7	37.9	12.7	11.2	763
Subtropics, cool; humid	59	15.6	17.4	62.1	4.8	78.6	22.7	13.3	1253
Temperate, moderate; dry	160	20.0	31.3	6.7	42.0	33.8	11.2	9.7	377
Temperate, moderate; moist	105	48.4	23.7	21.3	6.5	78.6	24.1	11.9	882
Temperate, moderate; wet	66	23.4	7.0	62.7	6.8	87.8	17.2	13.4	1222

Agro-ecological Zones class	TOTAL AREA Mln ha	Land cover % of AEZ zone				POP 2010 Pers/km²	CATTLE 2010 Head/km²	MEAN TEMP °C	ANN. PRECIP mm
		CROP-LAND	GRASS + SHRUB	TREE-COVER	OTHER COVER				
Temperate, cool; dry	463	25.0	42.0	10.2	22.8	12.2	5.6	5.0	354
Temperate, cool; moist	474	31.0	16.6	47.6	4.7	36.5	9.7	5.8	626
Temperate, cool; wet	291	12.2	15.2	67.1	5.5	38.9	16.8	6.2	1006
Boreal/Cold, no permafrost; dry	130	5.2	33.0	35.3	26.5	3.6	2.9	0.0	326
Boreal/Cold, no permafrost; moist	257	3.1	20.1	71.4	5.4	2.2	1.1	-0.3	496
Boreal/Cold, no permafrost; wet	320	1.1	20.0	71.7	7.2	2.4	0.6	0.1	713
Dominantly very steep terrain	492	3.0	32.6	43.5	20.8	7.5	8.2	6.7	1034
Severe soil/terrain limitations	879	8.0	28.6	53.2	10.1	24.6	12.7	16.2	1368
Land with ample irrigated soils	523	62.2	17.3	8.3	12.1	280.4	43.5	19.2	868
Dominantly hydromorphic soils	371	12.7	35.3	40.7	11.3	23.5	7.3	9.8	887
Desert/Arid climate	2438	1.1	14.2	1.4	83.3	2.9	1.8	21.7	127
Boreal/Cold, with permafrost	992	0.2	34.4	50.1	15.4	0.2	0.2	-8.4	377
Arctic/Very cold climate	735	0.0	28.8	2.7	68.5	0.2	1.0	-11.7	313
Dominantly urban/built-up land	43	2.9	3.5	1.0	92.6	6158.7	18.2	16.3	977
Dominantly water	188	0.3	1.9	1.0	96.8	1.2	6.9	6.0	584
TOTAL of all classes	**13448**	**11.5**	**26.8**	**32.5**	**29.2**	**50.5**	**10.5**	**13.5**	**788**

The AEZ classes defined by a % threshold of occurrence such as 'Dominantly very steep terrain', 'Dominantly hydromorphic soils', 'Dominantly urban/built-up land' and 'Dominantly water' can also contain some cropland. For instance, a grid cell classified as 'Dominantly water' or 'Dominantly urban/built-up land' can contain up to 25% other land cover classes, including some cropland. 'Dominantly very steep terrain' may include up to 10% flat terrain with cropland.

Climatic requirements of crops have a great influence on their occurrence in different AEZ classes. This is particularly visible in the classes defined along thermal climates and moisture gradients, i.e., AEZ classes AEZ-01 to AEZ-48 represented by the first 24 rows in Table 10–4 and Table 10–5. For instance, Table 10–4 indicates for cereals where the specific harvested area in different zones exceeds or falls short of its global average. For example, the share of wheat harvested area in global cereal harvested area in 2009–2011 was calculated to be nearly 32%. In cool and cold regions the observed share of wheat is much higher than the global average, often more than twice as much. Wheat is hardly present and mostly unsuitable in warm tropical regions. Sorghum and millet on the other hand are most abundant in semi-arid and arid environments of the tropics and subtropics, where they occupy a multiple of their average global shares.

Table 10-4 Distribution of cereal harvested areas in 2010 across AEZ Classes

Agro-ecological Zones class	Cereal Harv. Mln ha	% of total cereal harvested area by zone						
		Wheat	Barley	Maize	Sorghum	Millet	Rice	Other
Tropics, lowland; semi-arid	48.9	1.0	0.1	22.2	32.4	32.8	9.6	1.9
Tropics, lowland; sub-humid	46.7	1.1	0.2	37.8	10.2	6.5	42.4	1.7
Tropics, lowland; humid	36.0	3.7	0.2	50.4	3.2	0.7	41.1	0.7
Tropics, highland; semi-arid	1.7	5.4	4.3	67.9	11.1	5.5	0.6	5.3
Tropics, highland; sub-humid	5.2	15.3	9.1	42.4	9.3	3.1	6.1	14.6
Tropics, highland; humid	4.4	19.7	5.3	47.9	12.2	1.2	4.3	9.5
Subtropics, warm; semi-arid	14.9	31.5	3.2	18.9	10.1	6.7	28.8	0.8
Subtropics, warm; sub-humid	7.4	15.6	0.6	20.7	5.5	3.0	54.2	0.5
Subtropics, warm; humid	6.0	8.9	0.3	32.9	7.3	0.1	50.1	0.3
Subtropics, mod. cool; semi-arid	20.3	63.0	25.4	7.0	1.1	0.0	0.3	3.2
Subtropics, mod. cool; sub-humid	14.0	56.3	22.6	12.5	2.9	0.2	1.0	4.6
Subtropics, mod. cool; humid	18.7	33.4	5.6	35.4	2.5	0.0	21.5	1.7
Subtropics, cool; semi-arid	12.2	64.8	24.1	6.1	1.0	0.0	0.6	3.4
Subtropics, cool; sub-humid	4.5	58.3	25.0	9.4	0.3	0.0	0.6	6.4
Subtropics, cool; humid	3.9	33.1	6.2	38.4	0.5	0.0	19.0	2.8
Temperate, moderate; dry	12.3	49.7	7.5	34.6	0.8	0.4	1.4	5.6
Temperate, moderate; moist	18.7	29.3	2.0	64.5	1.4	0.0	1.2	1.5
Temperate, moderate; wet	5.8	23.5	1.2	59.9	0.4	0.1	14.0	0.8
Temperate, cool; dry	44.0	70.8	13.8	7.9	0.0	0.5	0.2	6.8
Temperate, cool; moist	60.9	46.9	18.6	18.8	0.0	0.3	0.5	14.8
Temperate, cool; wet	14.9	42.1	25.8	20.3	0.1	0.0	0.2	11.4

Boreal/Cold, no permafrost; dry	1.5	76.7	12.1	1.8	0.0	0.0	0.0	9.4
Boreal/Cold, no permafrost; moist	1.8	61.3	24.3	2.1	0.0	0.0	0.0	12.2
Boreal/Cold, no permafrost; wet	0.9	25.5	45.5	0.2	0.0	0.0	0.0	28.8
Dominantly very steep terrain	7.1	21.4	4.9	32.7	2.2	6.7	30.3	1.8
Severe soil/terrain limitations	29.7	17.8	4.7	27.1	9.7	6.1	31.9	2.6
Land with ample irrigated soils	219.1	33.8	2.8	18.7	2.8	2.0	39.1	0.7
Dominantly hydromorphic soils	20.3	33.0	9.1	20.7	3.1	3.1	23.6	7.3
Desert/Arid climate	12.1	15.1	3.4	3.7	35.0	40.0	1.9	0.8
Boreal/Cold, with permafrost	0.0	96.0	4.0	0.0	0.0	0.0	0.0	0.0
Arctic/Very cold climate	0.0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Dominantly urban/built-up land	0.8	28.6	4.3	20.9	1.4	0.7	41.3	2.6
Dominantly water	0.3	21.9	2.9	17.3	2.0	0.9	53.1	1.9
TOTAL of all classes	**694.9**	**31.7**	**7.1**	**23.7**	**5.9**	**4.8**	**23.1**	**3.6**

The AEZ classes defined by a % threshold of occurrence such as 'Dominantly very steep terrain', 'Dominantly hydromorphic soils', 'Dominantly urban/built-up land' and 'Dominantly water' can also contain some cropland. For instance, a grid cell classified as 'Dominantly water' or 'Dominantly urban/built-up land' can contain up to 25% other land cover classes, including some cropland. 'Dominantly very steep terrain' may include up to 10% flat terrain with cropland.

Differences in crop requirements and suitability in different AEZ classes are even more clearly visible for sugar crops (sugar beet and sugar cane) and in the distribution of the harvested areas of root and tuber crops (potato, sweet potato, cassava, yams and cocoyam), as listed in Table 10–5. Sugar beets dominate in cool subtropical and temperate climate zones, whereas sugar cane is the sugar crop of choice in tropical and warm subtropical regions. Concerning roots and tubers, potatoes abound in cool environments, sweet potato and cassava are most important in tropical and warm subtropical zones, and various types of yam are mostly cultivated in humid tropical and warm subtropical regions.

Table 10-5 Distribution of sugar crop and roots & tubers areas in 2010 across AEZ Classes

Agro-ecological Zones class	Sugar crops harvested Mln ha	% sugar harv. area		Root and tubers harvested Mln ha	% of roots & tuber area		
		Sugar beet	Sugar cane		Potato, sweet potato	Cassava	Yams, other roots
Tropics, lowland; semi-arid	1.2	0.0	100.0	6.2	21.7	48.7	29.6
Tropics, lowland; sub-humid	4.0	0.0	100.0	12.7	14.0	54.8	31.2
Tropics, lowland; humid	5.8	0.0	100.0	13.1	11.8	48.0	40.1
Tropics, highland; semi-arid	0.0	0.0	100.0	0.2	41.4	31.5	27.1
Tropics, highland; sub-humid	0.0	0.0	100.0	0.7	60.5	19.8	19.7
Tropics, highland; humid	0.2	0.0	100.0	1.2	71.1	8.9	20.0
Subtropics, warm; semi-arid	0.2	0.8	99.2	0.5	85.3	14.3	0.4
Subtropics, warm; sub-humid	0.1	0.0	100.0	0.1	81.1	13.0	5.9
Subtropics, warm; humid	0.7	0.0	100.0	0.4	53.6	45.3	1.1
Subtropics, mod. cool; semi-arid	0.1	20.5	79.5	0.1	99.1	0.0	0.9
Subtropics, mod. cool; sub-humid	0.1	33.8	66.2	0.2	99.5	0.3	0.2
Subtropics, mod. cool; humid	0.3	2.0	98.0	1.3	97.7	1.5	0.8
Subtropics, cool; semi-arid	0.1	100.0	0.0	0.2	100.0	0.0	0.0
Subtropics, cool; sub-humid	0.0	100.0	0.0	0.2	100.0	0.0	0.0
Subtropics, cool; humid	0.0	100.0	0.0	0.5	99.9	0.0	0.1
Temperate, moderate; dry	0.1	100.0	0.0	0.8	100.0	0.0	0.0
Temperate, moderate; moist	0.1	100.0	0.0	0.5	100.0	0.0	0.0
Temperate, moderate; wet	0.0	100.0	0.0	0.2	100.0	0.0	0.0
Temperate, cool; dry	0.3	100.0	0.0	2.4	100.0	0.0	0.0
Temperate, cool; moist	1.9	100.0	0.0	3.4	100.0	0.0	0.0
Temperate, cool; wet	0.4	100.0	0.0	0.6	100.0	0.0	0.0
Boreal/Cold, no permafrost; dry	0.0	100.0	0.0	0.2	100.0	0.0	0.0
Boreal/Cold, no permafrost; moist	0.0	100.0	0.0	0.1	100.0	0.0	0.0
Boreal/Cold, no permafrost; wet	0.0	100.0	0.0	0.1	100.0	0.0	0.0
Dominantly very steep terrain	0.2	13.3	86.7	1.1	71.4	19.8	8.8
Severe soil/terrain limitations	1.4	7.1	92.9	3.6	43.4	40.9	15.7
Land with ample irrigated soils	10.8	10.6	89.4	7.1	88.7	7.8	3.5

Dominantly hydromorphic soils	0.7	37.8	62.2	1.6	53.6	33.5	12.9
Desert/Arid climate	0.1	14.2	85.8	0.1	68.0	13.1	18.9
Boreal/Cold, with permafrost	0.0	n.a.	n.a.	0.0	n.a.	n.a.	n.a.
Arctic/Very cold climate	0.0	n.a.	n.a.	0.0	n.a.	n.a.	n.a.
Dominantly urban/built-up land	0.0	20.1	79.9	0.0	71.6	14.1	14.4
Dominantly water	0.0	5.8	94.2	0.0	46.2	28.2	25.6
TOTAL of all classes	**28.8**	**15.5**	**84.5**	**59.6**	**45.6**	**33.1**	**21.3**

The AEZ classes defined by a % threshold of occurrence such as 'Dominantly very steep terrain', 'Dominantly hydromorphic soils', 'Dominantly urban/built-up land' and 'Dominantly water' can also contain some cropland. For instance, a grid cell classified as 'Dominantly water' or 'Dominantly urban/built-up land' can contain up to 25% other land cover classes, including some cropland. 'Dominantly very steep terrain' may include up to 10% flat terrain with cropland.

The AEZ analysis in Module I includes a multiple cropping zones classification (see Chapter 3, section 3.5.1). The classification comprises of eight classes that characterize growing conditions according to whether 1, 2 or 3 sequential crops can be cultivated in a year and what combination of cryophilic and thermophilic crops is possible in each class. For instance, the most demanding class regarding year-round heat provision and moisture supply, termed "Zone of triple rice cropping", allows for three wetland rice crops to be grown in sequence. Multiple cropping zones were separately determined for rain-fed conditions (map variable MCR) and for irrigated conditions (map variable MCI), where only heat provision and temperature seasonality are used for differentiation.

Table 10–6 uses an aggregate version of the multiple cropping zones layers to illustrate for cropland in 2010 the relationship between the potential for multiple cropping and the various AEZ classes. Cropland in lowland tropics and warm subtropics has ample heat provision to support three thermophilic crops provided it also receives irrigation or year-round sufficient rainfall. In the respective thermal regime classes (TRC1 and TRC3) water (and inputs) is the main limiting factor for productive use of cropland. Cool temperate and boreal zones allow only one cryophilic crop, regardless of water supply conditions. Much of highland tropics and moderately cool subtropics permits cultivation of two thermophilic crops if water is available. Finally, the moderate temperate class allows for a single thermophilic crop and in part permits double cropping with at least one cryophilic crop. The multiple cropping zones classification can be used to subdivide AEZ classes for refining the agro-ecological analysis at regional or national level.

The spatial distribution of AEZ classes, simplified as listed in Table 10–3 to Table 10–6, is presented in Figure 10–4. The simplified map excludes a further subdivision of climatic zones by 'No or minor soil/terrain limitations' and 'Moderate soil/terrain limitations'. In Figure 10–4 boreal and cold zones are shown in blue colors, temperate climate zones are represented in shades of green, subtropical regions use yellow/orange/light brown, and tropical regions are shown in red shades. Note, this AEZ class map has also been used as one classifier in the compilation of crop summary tables prepared in Module V (see also Appendix 7-2).

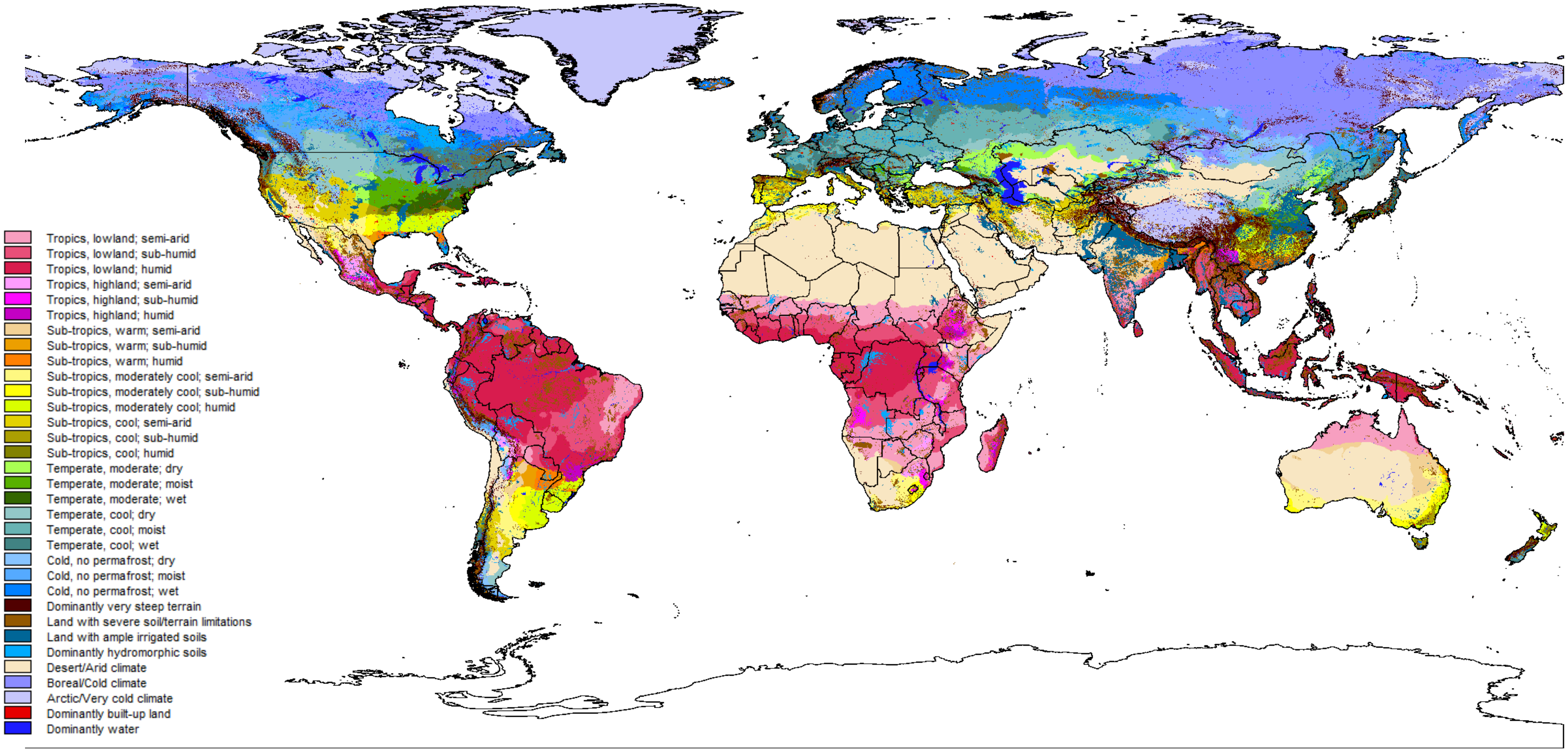
Table 10-6 Distribution of cropland in each AEZ class by rain-fed and irrigated multiple cropping classes

Agro-ecological Zones class	Crop land Mln ha	% area by MCR class and AEZ*				% area by MCI class and AEZ*			
		1 crop A-C	2 crops D-E	2 rice F-G	3 rice H	1 crop A-C	2 crops D-E	2 rice F-G	3 rice H
Tropics, lowland; semi-arid	113.7	99.9	0.1	0.0	0.0	0.0	0.0	0.0	100.0
Tropics, lowland; sub-humid	125.3	24.4	75.3	0.2	0.0	0.0	0.0	0.0	100.0
Tropics, lowland; humid	137.8	0.0	25.0	32.2	42.9	0.0	0.0	0.0	100.0
Tropics, highland; semi-arid	4.8	100.0	0.0	0.0	0.0	3.8	1.4	81.4	13.4
Tropics, highland; sub-humid	11.0	60.1	39.7	0.2	0.0	4.0	12.5	76.4	7.0
Tropics, highland; humid	10.5	4.9	29.9	60.0	5.2	3.1	8.8	77.3	10.8
Subtropics, warm; semi-arid	35.8	99.8	0.2	0.0	0.0	0.0	0.0	0.0	100.0
Subtropics, warm; sub-humid	12.5	49.4	42.0	8.6	0.0	0.0	0.0	0.0	100.0
Subtropics, warm; humid	11.5	0.0	5.2	45.9	48.9	0.0	0.0	0.0	100.0
Subtropics, mod. cool; semi-arid	46.5	99.9	0.1	0.0	0.0	0.0	11.6	85.2	3.2
Subtropics, mod. cool; sub-humid	43.7	68.5	27.1	4.4	0.0	0.3	38.2	59.8	1.8
Subtropics, mod. cool; humid	47.7	3.6	19.6	74.5	2.3	0.6	19.9	76.8	2.7
Subtropics, cool; semi-arid	25.8	100.0	0.0	0.0	0.0	54.6	34.3	11.1	0.0
Subtropics, cool; sub-humid	10.9	89.4	10.5	0.2	0.0	49.1	39.5	11.4	0.0
Subtropics, cool; humid	9.3	27.1	52.5	20.4	0.0	19.1	59.3	21.7	0.0
Temperate, moderate; dry	31.9	100.0	0.0	0.0	0.0	84.6	15.3	0.1	0.0
Temperate, moderate; moist	51.0	69.8	29.5	0.7	0.0	59.6	39.3	1.1	0.0
Temperate, moderate; wet	15.6	24.4	65.1	10.5	0.0	24.3	63.4	12.3	0.0
Temperate, cool; dry	115.8	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Temperate, cool; moist	147.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Temperate, cool; wet	35.5	99.8	0.2	0.0	0.0	98.3	1.7	0.0	0.0
Boreal/Cold, no permafrost; dry	6.7	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Boreal/Cold, no permafrost; moist	7.9	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Boreal/Cold, no permafrost; wet	3.5	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Dominantly very steep terrain	14.8	46.7	23.8	15.5	14.0	31.1	15.8	22.4	30.7

Severe soil/terrain limitations	70.7	53.6	18.4	12.9	15.0	14.6	6.3	12.9	66.2
Land with ample irrigated soils	325.3	74.0	14.1	9.8	2.1	16.7	16.2	16.3	50.8
Dominantly hydromorphic soils	47.1	69.3	15.1	6.1	9.5	59.6	2.6	3.1	34.7
Desert/Arid climate	25.8	100.0	0.0	0.0	0.0	6.1	3.9	10.8	79.3
Boreal/Cold, with permafrost	1.7	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Arctic/Very cold climate	0.2	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Dominantly urban/built-up land	1.3	61.7	18.1	14.6	5.6	28.8	15.8	16.3	39.1
Dominantly water	0.5	50.6	21.4	20.4	7.6	25.0	10.2	18.2	46.6
TOTAL of all classes	**1549.0**	**67.7**	**17.1**	**9.4**	**5.8**	**32.3**	**9.7**	**13.0**	**45.0**

** MCR = multiple cropping class under rain-fed conditions; MCI = multiple cropping class under irrigation conditions. Multiple cropping classes A-H are described in Chapter 3, section 3.5.1. Classes A-C allow up to one sequential crop per year. Classes D and E allow two sequential crops, or one thermophilic crop; under E one crop of the double cropping sequence can be rice, but not both. Zones F and G allow double rice cropping, and only zone H allows for three sequential rice crops per year.*

Figure 10-4 Agro-ecological Zones Classes, climate of 1981–2011



Source: FAO and IIASA, 2021

11. References

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. Crop Evapotranspiration (guidelines for computing crop water requirements), Drainage and Irrigation Paper N 56. Rome, Italy, Food and Agriculture Organization of the United Nations.

BirdLife International. 2017. *World Database of Key Biodiversity Areas* [online]. [Cited 23 October 2017]. www.keybiodiversityareas.org

Brammer, H., Antoine, J., Kassam, A.H. & van Velthuizen, H. 1988. Land Resources Appraisal of Bangladesh for Agricultural Development. Report 3, Land Resources Data Base, Volume II, Soil, Landform and Hydrological Data Base. http://www.fao.org/3/s7223e/s7223e.pdf

CEC. 1985. *Explanatory text and map sheets of the 1: 1.000.000 soil map of the European Communities*. Luxembourg, Directorate-General for Agriculture. Office for official publications of the European Communities.

Doorenbos, J. & Kassam, A.H. 1979. *Yield response to water, Drainage and Irrigation Paper N 33*. Rome, Italy, Food and Agriculture Organization of the United Nations. 203 pp.

Doorenbos, J. & Pruitt, W.O. 1977. *Guidelines for predicting crop water requirements, FAO Irrigation and Drainage Paper N 24*. FAO Irriga edition. Rome, Italy, Food and Agriculture Organization of the United Nations. 154 pp. (also available at http://www.fao.org/3/a-f2430e.Pdf).

EISD/SRI. 1999. *Geo-spatial modeling for Agro-ecological Assessments and Decision Support for Development Planning; Land Suitability Analysis*. Accra, Ghana.

FAO/IIASA. 2000. *Global Agro-Ecological Zones (GAEZ v1.0). CD-ROM Land and Water Media Series*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO/UNDP. 1982. *Assessment of land resources for rain-fed crop production in Mozambique: Agro-climatic and agro-edaphic suitability classification for rain-fed crop production*. Rome, Italy, Food and Agriculture Organization of the United Nations, United Nations Development Programme. (also available at https://library.wur.nl/isric/fulltext/ISRIC_7159.pdf).

FAO/UNEP. 1977. *Assessing Soil Degradation. FAO Soils Bulletin N 34*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1976. *A framework for land evaluation*. FAO Soils edition. Rome, Italy, Food and Agriculture Organization of the United Nations. (also available at http://www.fao.org/3/x5310e/x5310e00.htm).

FAO. 1978. *Report on the Agro-ecological Zones Project, Vol.4 Results for Southeast Asia*. World Soil edition. Rome, Italy, Food and Agriculture Organization of the United Nations,. 74 pp. (also available at http://www.fao.org/3/a-bl893e.pdf).

FAO. 1980. *Land Resources for Populations of the Future: Agro-climatic suitability classification for rain-fed crops: winter barley, upland rice, groundnut, sugar cane, banana/ plantain, and oil palm*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1981. *Report on the agro-ecological zones project (1978–1981), vol. 1: methodology and results for Africa, World soil resources report 48/1*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1984. *Land evaluation for development*. Rome, Italy, Food and Agriculture Organization of the United Nations. (also available at http://www.fao.org/3/U1980E/u1980e00.htm).

FAO. 1985. *Guidelines: Land evaluation for irrigated agriculture - FAO soils bulletin 55*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1990. *Guidelines for Soil Profile Description (3rd edition)*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1993. *Guidelines for land-use planning*. FAO Develo edition. Rome, Italy, Food and Agriculture Organization of the United Nations. (also available at http://www.fao.org/3/t0715e/t0715e00.htm).

FAO. 1995. *Digital Soil Map of the World. Land and Water Digital Media Series # 1*. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 1996. Agro Ecological Zoning Guidelines. Rome, Italy. (also available at http://www.fao.org/3/W2962E/w2962e00.htm#P-2).

FAO. 2005. *UN Land Cover Classification System (LCCS) – Classification concepts and user manual for Software version 2*. Environmen edition. A. Di Gregorio & L.J.M. Jansen, eds. Rome, Italy, Food and Agriculture Organization of the United Nations.

FAO. 2007a. *Land evaluation, Towards a revised framework*. Land and W edition. Rome, Italy, Food and Agriculture Organization of the United Nations (FAO). 124 pp.

FAO. 2007b. The Global Administrative Unit Layers (GAUL), Technical Aspects. GAUL/Doc 01, ESCG. Rome, Italy. (also available at http://www.fao.org/geonetwork).

FAO. 2011. *World map of the major hydrological basins* [online]. https://data.apps.fao.org/map/catalog/static/api/records/7707086d-af3c-41cc-8aa5-323d8609b2d1

FAO. 2015. *The Global Administrative Unit Layers. GAUL Release 2015. List of data and documentation*. Rome, Italy, Food and Agriculture Organization of the United Nations. (also available at https://data.apps.fao.org/map/catalog/srv/eng/catalog.search#/home).

FAO & IIASA. 2012. *Global Agro-Ecological Zones (GAEZ v3.0), Model documentation*. Laxenburg, Austria and Rome, Italy. 196 pp. (also available at http://pure.iiasa.ac.at/id/eprint/13290/1/GAEZ_Model_Documentation.pdf).

FAO & Unesco. undated. *Soil Map of the World 1:5 Million. Volume I - X*. Paris, France, The United Nations Educational, Scientific and Cultural Organization.

FAO & Unesco. 1974. *Soil Map of the World 1:5 Million Volume 1: Legend*. Paris, France, The United Nations Educational, Scientific and Cultural Organization.

FAO, Unesco & ISRIC. 1990. *FAO/Unesco Soil Map of the World (Revised Legend). Reprint from FAO World Soil Resources Report nr 60. ISRIC Technical paper nr 20*. Wageningen, The Netherlands, International Soil Reference and Information Centre.

Fischer, G., van Velthuizen, H., Shah, M. & Nachtergaele, F.O. 2002. *Global Agro-Ecological Assessment for Agriculture in the 21st Century: Methodology and Results. IIASA RR-02-02*. Laxenburg, Austria, International Institute for Applied Systems Analysis.

Fischer, G., Nachtergaele, F.O., Prieler, S., Teixeira, E., Toth, G., van Velthuizen, H., Verelst, L. & Wiberg, D. 2012. *Global Agro-Ecological Zones (Model documentation)*. Laxenburg, Austria, Rome, Italy, International Institute for Applied Systems Analysis, Food and Agriculture Organization of the United Nations. (also available at http://pure.iiasa.ac.at/id/eprint/13290/).

Fischer, G., Tramberend, S., van Velthuizen, H., Bole-Rentel, T. & Reeler, J. 2019. *Sustainable aviation biofuel potential in sub-Saharan Africa. A systems analysis investigation into the current and future potential for biofuel feedstock production. World Wildlife Fund for Nature – South Africa*. Cape Town, South Africa, World Wildlife Fund for Nature – South Africa. 158 pp. (also available at http://pure.iiasa.ac.at/id/eprint/15626/1/Sustainable_Biofuel_Potential_SSAF_FullReport_A4_V1_Pages.pdf).

Geiger, R. 1954. Landolt-B¨ornstein – Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik. *Ch. Klassifikation der Klimate nach W. K¨oppen*, pp. 603–607. Berlin, Springer.

Geiger, R. 1961. *Uberarbeitete Neuausgabe von Geiger, R.: K¨oppen-Geiger/Klima der Erde. (Wandkarte 1:16 Mill.)*. Klett-Perthes, Gotha.

Harris, I., Jones, P.D., Osborn, T.J. & Lister, D.H. 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. *International Journal of Climatology*, 34(3): 623–642. https://doi.org/https://doi.org/10.1002/joc.3711

Hempel, S., Frieler, K., Warszawski, L., Schewe, J. & Piontek, F. 2013. A trend-preserving bias correction – the ISI-MIP approach. *Earth System Dynamics*, 4(2): 219–236. https://doi.org/10.5194/esd-4-219–2013

ISRIC & FAO. 2006. *Harmonized Continental SOTER-derived database (SOTWIS)*. Wageningen, The Netherlands, International Soil Reference and Information Centre.

IUCN. 2019. *Guidelines for using A Global Standard for the Identification of Key Biodiversity Areas. Version 1.1*. KBA Standards and Appeals Committee of the IUCN Species Survival Commission and IUCN World Commission on Protected Areas, ed. Gland, Switzerland, International Union for Conservation of Nature and Natural Resources (IUCN). 148 pp. (also available at https://portals.iucn.org/library/sites/library/files/documents/2019–001.pdf).

Kassam, A.., Van Velthuizen, H., Fischer, G. & Shah, M.M. 1991a. *Agro-ecological Land Resources Assessment for Agricultural Development Planning*. World Soil edition. Rome, Italy, Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis.

Kassam, A.H. 1977. *Net Biomass Production and Yield of Crops with Provisional Results for Tropical Africa*. Rome, Italy, Food and Agriculture Organization of the United Nations, Soil Resources, Management and Conservation Service, Land and Water Development Division. 60 pp.

Kassam, A.H., van Velthuizen, H., Higgins, G.M., Christoforides, A., Voortman, R.L. & Spiers, B. 1983. *Assessment of Land Resources for Crop Production in Mozambique. (6 Volumes)*. Rome, Italy, Food and Agriculture Organization of the United Nations, United Nations Development Programme, Ministry of Agriculture.

Kassam, A.H., van Velthuizen, H., Fischer, G.W. & Shah, M.M. 1991b. Agro-ecological land Resources Assessment for agricultural Development Planning - A case Study of Kenya-Technical Annex 3, Agro-climatic and Agro-edaphic Suitabilities for Barley, Oat, Cowpea, Green Gram and Pigeonpea, World Soil Resources Report 71/3. Rome, Italy, Food and Agriculture Organization of the United Nations, International Institute for Applied Systems Analysis. http://www.fao.org/3/t0741e/T0741E00.htm

Köppen, W. 1900. Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. *Geogr. Zeitschr.*, 6: 593–611, 657–679.

Kowal, J. & Kassam, A.H. 1978. *Agricultural Ecology of Savanna*. Oxford, United Kingdom, Clarendon Press.

Latham, J., Cumani, R., Rosati, I. & Bloise, M. 2014. *Global Land Cover SHARE (GLC-Share) database Beta-Release Version 1.0*. Rome, Italy, Food and Agriculture Organization of the United Nations. 40 pp. (also available at http://www.fao.org/uploads/media/glc-share-doc.pdf).

Lehner, B. & Döll, P. 2004a. Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, 296(1): 1–22. https://doi.org/https://doi.org/10.1016/j.jhydrol.2004.03.028

Lehner, B. & Döll, P. 2004b. Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology*, 296(1): 1–22. https://doi.org/https://doi.org/10.1016/j.jhydrol.2004.03.028

Monfreda, C., Ramankutty, N. & Foley, J.A. 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22(1). https://doi.org/https://doi.org/10.1029/2007GB002947

Monteith, J.L. 1965. Evapotranspiration and the environment. *The State and Movement of Water in Living Organisms. XIXth Symposium. Society for Xp. Biology, Swansea*. pp. 205–234. Paper presented at, 1965, Cambridge, UK.

Monteith, J.L. 1981. Evapotranspiration and surface temperature. *Quarterly Journal Royal Meteorological Society*, 107: 1–27.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P. & Wilbanks, T.J. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463(7282): 747–756. https://doi.org/10.1038/nature08823

Nachtergaele, F.O., van Velthuizen, H., Verelst, L. & Wiberg, D. 2012. *Harmonized World Soil Database (version 1.2)*. Rome, Italy, Food and Agriculture Organization of the United Nations (FAO), International Institute for Applied Systems Analysis (IIASA),ISRIC-World Soil Information, Institute of Soil Science – Chinese Academy of Sciences (ISSCAS), Joint Research Centre of the Europe. 50 pp. (also available at http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/).

Nachtergaele, F.O. 1988. *Methodology for Regional Analysis of Physical Potential for Crop Production. AG:GCP/RAF/230/JPN, Field Document 1, KILIMO, Dar es Salaam. Microfilm*. Rome, Italy, Food and Agriculture Organization of the United Nations.

Nachtergaele, F.O. & Bruggeman, H.. 1986. *Methodology for regional analysis of physical potential for crop production. Annex 2: Climate, soil and topography requirements for major crops in Southeast Asia*. Rome, Italy, Food and Agriculture Organization of the United Nations.

Neye, P.H. & und Greenland, D.J. 1960. *The soil under shifting cultivation. Technical Communication No. 51. Commonwealth Bureau of Soils. Harpenden, 156 S*. (also available at https://onlinelibrary.wiley.com/doi/abs/10.1002/jpln.19610950215).

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M. & Solecki, W. 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change*, 42: 169–180. https://doi.org/https://doi.org/10.1016/j.gloenvcha.2015.01.004

Oak Ridge National Laboratory. 2013. LandScan 2012 Global Population Database. In: *Oak Ridge National Laboratory, UT-Battelle, LLC.* [online]. https://purl.stanford.edu/dd452vk1873

Portmann, F., Siebert, S., Bauer, C. & Döll, P. 2008. *Global data set of monthly growing areas of 26 irrigated crops. Frankfurt Hydrology Paper 06*. Frankfurt am Main, Germany, Institute of Physical Geography, University of Frankfurt.

Portmann, F.T., Siebert, S. & Döll, P. 2010. MIRCA2000—Global monthly irrigated and rain-fed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling. *Global Biogeochemical Cycles*, 24(1). https://doi.org/https://doi.org/10.1029/2008GB003435

Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D.E. & Kropp, J.P. 2015. Closing Yield Gaps: How Sustainable Can We Be? *PLOS ONE*, 10(6): e0129487. (also available at https://doi.org/10.1371/journal.pone.0129487).

Robinson, T.P., Wint, G.R.W., Conchedda, G., Van Boeckel, T.P., Ercoli, V., Palamara, E., Cinardi, G., D'Aietti, L., Hay, S.I. & Gilbert, M. 2014. Mapping the global distribution of livestock. *PloS one*, 9(5): e96084. https://doi.org/10.1371/journal.pone.0096084

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B. & Ziese, M. 2011. GPCC Full Data Reanalysis Version 6.0 at 0.5°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data. https://doi.org/10.5676/DWD_GPCC/FD_M_V6_050

Shi, X., Yu, D., Warner, E.D., Pan, X., Petersen, G.W., Gong, Z.G. & Weindorf, D.C. 2004. *Soil Database of 1:1,000,000 Digital Soil Survey and Reference System of the Chinese Genetic Soil Classification System*. (also available at https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sh2004.4.0129).

Siebert, S., Henrich, V., Frenken, K. & Burke, J. 2013. *Update of the Global Map of Irrigation Areas to version 5*. Rome, Italy, Food and Agriculture Organization of the United Nations. 178 pp. (also available at http://www.fao.org/3/I9261EN/i9261en.pdf).

Smith, M. 1992. *CROPWAT- A computer program for irrigation planning and management*. FAO Irriga edition. Rome, Italy, Food and Agriculture Organization of the United Nations. 126 pp.

Sys, C., van Ranst, E. & Debaveye, J. 1991. *Land Evaluation – Part I, Agricultural Publications No. 7*. Brussels, Belgium, University of Ghent, General Administration for Development Cooperation, International Training Centre for Post-Graduate Soil Scientists (ITC).

Sys, C., van Ranst, E., Debaveye, J. & Beernaert, F. 1993. *Land Evaluation – Parts I, II and III. International Training Centre for Post-Graduate Soil Scientists (ITC), University of Ghent, Agricultural Publications No. 7*. Brussels, Belgium, General Administration for Development Cooperation.

Sys, C. & Riquier, J. 1980. *Ratings of FAO/Unesco soil units for specific crop production*. Rome, Italy, Food and Agriculture Organization of the United Nations.

Taylor, K.E., Stouffer, R.J. & Meehl, G.A. undated. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society*, 93(4): 485–498. https://doi.org/10.1175/BAMS-D-11–00094.1

Uchijima, Z. & Seino, H. 1988. An agroclimatic method of estimating net primary productivity of natural vegetation. *Japan Agricultural ResearchxQuarterly*, 21(4): 244–250. (also available at https://www.jircas.go.jp/sites/default/files/publication/jarq/21–4-244-250_0.pdf).

UNDP/SSTC/FAO/SLA. 1994. *China, Land Resources, Use and Productivity Assesment. Main Report. Technical Report of Project CPR/87/029*. Rome, Italy, Benjing, China, Food and Agriculture Organization of the United Nations, China International Center For Economic And Technical Exchanges, United Nations Development Programme.

UNEP-WCMC & IUCN. 2017. *World Database on Protected Areas (WDPA)* [online]. https://www.iucn.org/theme/protected-areas/our-work/quality-and-effectiveness/world-database-protected-areas-wdpa

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

van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K. & Weyant, J. 2011. A special issue on the RCPs. *Climatic Change*, 109(1): 1. https://doi.org/10.1007/s10584-011–0157-y

Weedon, G.P., Gomes, S., Viterbo, P., Shuttleworth, W.J., Blyth, E., Österle, H., Adam, J.C., Bellouin, N., Boucher, O. & Best, M. 2011. Creation of the WATCH Forcing Data and Its Use to Assess Global and Regional Reference Crop Evaporation over Land during the Twentieth Century. *Journal of Hydrometeorology*, 12(5): 823–848. https://doi.org/10.1175/2011JHM1369.1

Young, A. & Wright, C. 1980. *Rest period requirements of tropical and subtropical soils. Pages 197 – 268. Report on the second FAO/UNFPA expert consultation on land resources for populations of the future*. Rome, Italy, Food and Agriculture Organization of the United Nations.

Zhang, X. & Zhou, G. 1995. A New NPP Model. China Contribution to Global Change Studies. *In* Y.D. and L. Hai., ed. *China Global Change Report No. 2.*, p. Beijing China, Science Press.

12. Appendix 1-1 Recommendations for further GAEZ development

Database updates/improvements

Climate data

AEZ assessments make use of gridded climate data. Many of them are updated on a regular basis. Time series data for the GAEZ v4 historical assessments were obtained from the Climate Research Unit (CRU) at the University of East Anglia, the Global Precipitation Climatology Centre (GPCC), and the EU WATCH Integrated Project.

Climatic Research Unit TS v3.21 (time-series) datasets (Harris *et al.*, 2014) were used in GAEZ v4 for daily mean temperature, diurnal temperature range, cloud cover, vapour pressure, wind speed and wet day frequency. The most recent version of the CRU TS datasets is TS v4.04 released in 2020, which replaces earlier versions and covers the period 1901–2019 (Harris *et al.*, 2020).

For monthly precipitation, GAEZ v4 uses the GPCC Full Data Reanalysis Product Version 6 (Schneider *et al.*, 2011), which contained monthly totals on a regular grid with a spatial resolution of 0.5° x 0.5° latitude by longitude and had temporal coverage from January 1901 until December 2010. GPCC Full Data Monthly Product Version 2020 is the most recent centennial GPCC Full Data Monthly Product providing monthly global land-surface precipitation based on the ~85,000 stations world-wide that feature record durations of 10 years or longer. This product is now available on a regular grid with a spatial resolution of 0.25° x 0.25° latitude by longitude and has a temporal coverage from January 1891 until December 2019 (Schneider *et al.*, 2020). It is the most accurate in situ precipitation reanalysis data set of GPCC and it is used to support regional climate monitoring, model validation, climate variability analysis and water resources assessment studies.

Global sub-daily (3 hours) meteorological forcing data were compiled in WATCH for use with land surface- and hydrological-models (Weedon *et al.*, 2011). The data were derived from the ERA-40 and ERA-Interim reanalysis products and were the basis for GAEZ v4 daily temperature and precipitation data. The ERA-40 and ERA-Interim products included all the key near-surface meteorological variables required in AEZ.

ERA5 is the latest, fifth generation, climate reanalysis produced by the ECMWF. ERA5 has replaced the previous ERA-40 and ERA-Interim reanalyses (i.e., those used as basis for daily temperature and precipitation data in GAEZ v4) and provides hourly data on many atmospheric, land-surface and sea-state parameters together with estimates of uncertainty. ERA5 data are available on the Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S), on regular 0.25° x 0.25° latitude-longitude grids. The ERA5 reanalysis is currently available since 1979 to the present in the form of hourly and monthly time series and, when completed, it will cover the period from 1950 to the present. ERA5 reanalysis will continue to be extended forward in time, with monthly updates being published within three months from real-time. In addition, in 2019 the ERA5-Land dataset has been released: it is a global land-surface dataset at ca. 9 km x 9 km horizontal resolution, available at hourly and monthly time steps from 2001 to present, and consistent with atmospheric data from the ERA5 reanalysis. These recent climate reanalysis data on the CDS represent an unprecedented opportunity for spatialized and high-resolution understanding of climate evolution in recent decades, as well as a support for more robust evaluations for the future, improving bias-correction and spatial downscaling of information from both global and regional climate model projections.

These data products, which are fully consistent with the climate data used in GAEZ v4, will allow in the near future to extend the historical climate analysis in GAEZ up to year 2020. It is recommended to then extend the GAEZ historical climate database and to compile all attributes of an additional historical 30-year base period of 1991–2020.

Climate change projections

Projections of future climate change play a fundamental role in characterizing future societal risks and response options. In GAEZ v4, IPCC Fifth Assessment Report (AR5) climate model outputs for four Representative Concentration Pathways (RCPs) were used to characterize a range of possible future climate distortions included in the agro-climatic resources inventory and crop potential assessments for the 2020's (period 2011–2040), the 2050's (period 2041–2070) and the 2080's (period 2070–2099); see Chapter 2, section 2.1.2.

Since then, the Scenario Model Intercomparison Project (O'Neill *et al.*, 2016) is the primary activity within Phase 6 of the Coupled Model Intercomparison Project (CMIP6) that will provide multi-model climate projections based on alternative scenarios of future emissions and land use changes produced with integrated assessment models. CMIP6 forms an important part of the evidence base in the forthcoming Intergovernmental Panel on Climate Change (IPCC) assessments. First results will be integrated in the IPCC Sixth Assessment Report (AR6), currently due for release in 2022.

The new coordinated experiments under CMIP 6 provide the basis for investigating a number of targeted science and policy questions, including amongst others the effect of a peak and decline in forcing, the consequences of scenarios that limit warming to below 2°C, and the relative contributions to uncertainty from scenarios, climate models, and internal variability. Harmonized, spatially explicit emissions and land use scenarios generated with integrated assessment models have been provided to participating climate modeling groups by late 2016, with the climate model simulations run within the 2017–2018 time frame, and output from the climate model projections made available and analyses performed over the 2018–2020 period.

CMIP6 climate projections differ from those in CMIP5 not only because they are produced with updated versions of climate models, but also because they are driven with SSP-based scenarios produced with updated versions of IAMs and based on updated data on recent emissions trends. Though the climate model simulations with the RCPs in CMIP5 will continue to be a key input to research on climate change, impacts and adaptation for many years (O'Neill *et al.*, 2016), an updated set of GAEZ climate scenarios should be compiled when the CMIP6 analysis is sufficiently complete and model outputs are readily available on CMIP6 data portals.

Global land cover / land use databases

GAEZ v4 makes use of the Global Land Cover-SHARE (GLC-Share), a global land cover database with spatial resolution of 30 arc-seconds (Latham *et al.,* 2014). The GLC-Share and GMIA v5 databases provide key inputs for the downscaling procedures used to spatially allocate actual statistical production of the period 2009–11 and for the interpretation of GAEZ crop suitability analysis results with regard to sustainable agricultural development planning.

It is suggested to extend the downscaling procedure in time by using updated FAOSTAT national statistical data (e.g. harvested area, production and yields of period 2019–2021, when available) and current gridded land cover datasets, e.g., as produced by SEEA-MODIS, containing annual land cover area data for the period 2001–2018, derived from the MODIS Collection and/or SEEA-CCI-LC, containing annual land cover area data for the period 1992–2018, updated to version 2.1 under the European Copernicus program (ESA, 2017).

Update of soil database

GAEZ v4 uses the Harmonized World Soil Database (HWSD v1.2) (Nachtergaele *et al.*, 2012) as source of soil resources data for spatially detailed evaluation of soil qualities and edaphic crop suitability. The HWSD is composed of a global level geographical layer containing reference to more than 16,000 map units linked to an attribute database of some 48,000 soil component records.

Since the publication of HWSD in 2012 several soil information layers compatible with HWSD have become available that could be integrated to significantly enhance the accuracy of this essential input data layer, especially in areas which up to now are covered by FAO's DSMW. Update opportunities concern data products available at:

i. JRC: Circumpolar soil map and updates of soil maps of Africa, Europe, and South America;

ii. IIASA: soil databases in HWSD format developed in national AEZ studies for Turkey, Afghanistan, and Ghana, and

iii. ISRIC: WISE30sec soil attribute database that includes a climatic stratification of 21 000 soil profiles.

Including land degradation information

In order to refine the overall GAEZ assessment, additional environmental information layers could be included in the land resources database. A worthwhile example is land degradation in its multiple aspects, including crucial elements such as soil degradation (soil erosion, -contamination, -sealing, -compaction, -nutrient depletion, -biodiversity), vegetation degradation, and water resources decline in quality and quantity, are not or only partially taken into account. They obviously influence sustainable yield and production capacities and a more thorough treatment of these factors would be desirable.

Methodology improvements and extensions

Verification/calibration of crop/LUT parameterization

IIASA has experience with coupling AEZ models with DSSAT model (Decision Support System for Agrotechnology Transfer) for generating eco-physiological and genetic parameters for use in the AEZ biomass and yield module. The approach systematically calibrates and applies DSSAT crop models at locations where detailed site specific information is available, in order to generate indicators and 'observations' such as yields, crop cycle length, dates of crop development stages, crop evapotranspiration, accumulated temperature sums during the crop growth cycle, irrigation requirements/water deficits, leaf area index and harvest index. These outputs can be used to calibrate or refine existing LUTs and to define new ones. The methodology has been successfully developed and applied in national case studies in China to verify and calibrate LUT parametrizations of wheat, rice, maize, soybean and rapeseed LUTs (Tian *et al.*, 2012; Tian *et al.*, 2014; Fan *et al.*, 2017; Tian *et al.*, 2018; Xu *et al.,* 2019). Expanding this approach would be beneficial for enhanced AEZ applications, notably at national level. For similar purpose, systematically employing experiments with FAO's AquaCrop procedures could also be used to enhance LUT parameterization in AEZ.

Develop a tight link to water resources modelling and water use assessments

Agriculture is the largest user of water. The sector is highly dependent on water resources, accounting for about 70% of total annual water withdrawals. Estimated 40% of the global food crop is derived from irrigated agriculture. Agriculture is in competition with other water users and there exist several examples of over-exploitation of water resources for agricultural uses with dire impacts on the environment.

For land classified as cropland equipped for irrigation, GAEZ v4 has assessed the suitability of crops under irrigated conditions in terms of agronomic requirements and prevailing climate and soil/terrain resources, but has not assessed the actual availability, reliability and quality of irrigation water supply in these areas. Evaluation of future scenarios and planning for irrigation expansion and agricultural investment requires the capability to assess future water conditions. Future global and national assessments would greatly benefit and increase their utility by developing a tight link to water resources modelling and projections of water demand in different sectors.

For instance, IIASA has developed a new large-scale hydrological and water resources model, the Community Water Model (CWatM), which can simulate hydrology both globally and regionally at different resolutions from 30 arc-minutes to 30 arc-seconds at daily time steps (Burek *et al.*, 2020a; Burek *et al.*, 2020b). CWatM is open source in the Python programming environment and has a modular structure. It includes general surface and groundwater hydrological processes but also takes into account human activities, such as water use and reservoir regulation, by calculating water demands, water use, and return flows. Reservoirs and lakes are included in the model scheme. CWatM strives to build a community learning environment which is able to freely use an open-source hydrological model and flexible coupling possibilities to other sectoral models, such as energy and agriculture.

Agro-edaphic evaluation improvement

Recent review of agro-edaphic procedures (see Chapter 6) revealed update potentials with regard to three main themes, namely (i) soil characteristics ratings, (ii) available soil water capacity estimates, and (iii) the refinement of topsoil-subsoil attribute weighting algorithms. A methodology to tackle these opportunities for improvement has been fully developed and could be applied rapidly.

Expanding the number of Land Utilization Types

The number of crops evaluated in GAEZ could be further expanded with LUTs specifically parameterized in the context of national and regional AEZ studies. These additional LUTs could include: basmati rice, cashew, castor bean, hot and sweet chili, cumin, lentil, mango, mustard seed, black pepper, sesame seed, and possible biofuel feedstocks like Solaris tobacco, biomass sorghum, energy cane, carinata, camelina and triticale. Suitability and potential production of some woody species, important for the bioeconomy, such as willow or poplar, have been modelled in subject-specific studies (Fischer *et al.*, 2009; Prieler *et al.*, 2012) and could as well be introduced in the GAEZ analysis.

Strengthen the capabilities in GAEZ to assess alternative ecosystem functions

Land has many important functions. GAEZ outputs emphasize the suitability of land for crop production. The need to plan for more and better food supplies, from less resources and with less environmental impacts, will have to continue with high priority in the next decades. Current GAEZ applies an ‘exclusion’ layer (see Chapter 2, section 2.7.4) to highlight land with a protection status or with recognized biodiversity value. The ‘exclusion’ layer has been compiled from three up-to-date and authoritative international datasets: the World Database of Protected Areas (UNEP-WCMC and IUCN, 2017), the World Database of Key Biodiversity Areas (BirdLife International, 2017), and the Global Lakes and Wetlands Database (Lehner and Döll, 2004). The WDPA and KBA datasets are frequently updated and it is recommended that the GAEZ ‘exclusion’ layer be updated accordingly.

However, GAEZ currently cannot by itself compare the value of a potential crop provisioning service in a location with the value of potential alternative ecosystem services of the land. Multifunctional agriculture is increasingly discussed as a new paradigm for agriculture and rural development. It recognizes different ecosystem services of agricultural production systems including multiple provisioning services (e.g. food, feed, fibre, energy crops), regulating services (e.g. erosion control) and cultural services (e.g. recreation, tourism).

Integration of supplementary modules to quantify trade-offs and synergies among alternative ecosystem services within the GAEZ framework seems possible and desirable. It is recommended to produce an overview of available models and data sources and to develop a strategy for incorporating new modules/develop links to ecosystem valuation approaches that would operate consistently using the spatial data available in the AEZ land resources inventory.

The inclusion of water conservation practices in dry regions

In arid and semi-arid zones, water-conservation management practices are used to cope with marginal and unreliable rainfall. These zones typically receive annual rainfall between 300 and 600 mm and cover an area with total extent of 3.2 billion hectares. Most of these areas occur in western United States, Argentina, northern and southern Africa, in the Sahel zone, Middle East and Central Asia and Australia. Assessment procedures which apply water balance calculations adapted and refined for dry environments have been developed and could readily be implemented.

13. Appendix 3-1 Calculation of reference evapotranspiration

The calculation of reference evapotranspiration (ETo), i.e., the rate of evapotranspiration from a hypothetic reference crop with an assumed crop height of 12 cm, a canopy resistance of 70 ms-1 and an albedo of 0.23 (closely resembling the evapotranspiration from an extensive surface of green grass), is done according to the Penman-Monteith equation (Monteith, 1965, 1981; FAO, 1992b). The calculation procedure uses a standardized set of input parameters, as follows:

- $T_{\max}$ maximum daily temperature (°C)
- $T_{\min}$ minimum daily temperature (°C)
- *RH* mean daily relative humidity (%)
- *U2* wind speed measurement (ms^{-1})
- *SD* bright sunshine hours per day (hours)
- *A* elevation (m)
- *L* latitude (deg)
- *J* Julian date, i.e., number of day in year

The *Penman-Monteith combination equation* can be written in terms of an aerodynamic and a radiation term (FAO, 1992b):

$$ET_o = ET_{ar} + ET_{ra} \tag{1}$$

where the *aerodynamic term* can be approximated by

$$ET_{ar} = \frac{\gamma}{\vartheta + \gamma *} \cdot \frac{900}{T_a + 273} \cdot U2 \cdot (e_a - e_d) \tag{2}$$

and the radiation term by

$$ET_{ra} = \frac{\vartheta}{\vartheta + \gamma *} \cdot (R_n - G) \cdot \frac{1}{\lambda} \tag{3}$$

where variables in (2) and (3) are as follows:

- γ psychrometric constant (kPa $^{o}C^{-1}$)
- γ* modified psychrometric constant (kPa $^{o}C^{-1}$)
- ϑ slope of vapor pressure curve (kPa $^{o}C^{-1}$)
- T_a average daily temperature (°C)
- e_a saturation vapor pressure (kPa)

- e_d vapor pressure at dew point (kPa)
- $(e_a - e_d)$ vapor pressure deficit (kPa)
- $U2$ wind speed measurement (ms^{-1})
- R_n net radiation flux at surface (MJ m^{-2} d^{-1})
- G soil heat flux (MJ m^{-2} d^{-1})
- λ latent heat of vaporization (MJ kg^{-1})

In the calculation procedure for the reference crop we use the following relationships to define terms in (2):

Average daily temperature:

$$T_a = 0.5(T_{\max} + T_{\min}) \tag{4}$$

Latent heat of vaporization:

$$\lambda = 2.501 - 0.002361\,T_a \tag{5}$$

Atmospheric pressure (kPa) at elevation A:

$$P = 101.3\left(\frac{293 - 0.0065\,A}{293}\right)^{5.256} \tag{6}$$

Psychrometric constant:

$$\gamma = 0.0016286 \cdot \frac{P}{\lambda} \tag{7}$$

Aerodynamic resistance:

$$r_a = \frac{208}{U2} \tag{8}$$

Crop canopy resistance:

$$r_c = \frac{R_l}{0.5\,LAI} \tag{9}$$

where under ambient CO_2 concentrations the average daily stomata resistance of a single leaf, R_l (sm-1), is set to R_l = 100, and leaf area index of the reference crop is assumed as

$$LAI = 24 \cdot 0.12 = 2.88$$

Modified psychrometric constant:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \tag{10}$$

Saturation vapor pressure e_a for given temperatures $T_{\min}$ and $T_{\max}$

$$e_{ax} = 0.6108 \exp\left(\frac{17.27\, T_{\max}}{237.3 + T_{\max}}\right) \tag{11}$$

$$e_{an} = 0.6108 \exp\left(\frac{17.27\, T_{\min}}{237.3 + T_{\min}}\right) \tag{12}$$

$$e_a = 0.5\,(e_{ax} + e_{an}) \tag{13}$$

Vapor pressure at dew point, e_d:

$$e_d = \frac{RH}{100} \cdot \frac{0.5}{\left(\frac{1}{e_{ax}} + \frac{1}{e_{an}}\right)} \tag{14}$$

Slope of vapor pressure curve, ϑ, for given temperatures $T_{\max}$ and $T_{\min}$*:*

$$\vartheta_x = \frac{4096\, e_{ax}}{(237.3 + T_{\max})^2} \tag{15}$$

$$\vartheta_n = \frac{4096\, e_{an}}{(237.3 + T_{\min})^2} \tag{16}$$

$$\vartheta = (\vartheta_x + \vartheta_n) \tag{17}$$

Using (4)-(17) all variables in (2) can be calculated from the input parameters. To determine the remaining variables R_n and G used in the radiation term ET_{ra} of equation (3), we proceed with the following calculation steps:

Latitude expressed in rad:

$$\varphi = \frac{L\pi}{180} \tag{18}$$

Solar declination (rad):

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right) \tag{19}$$

Relative distance Earth to Sun:

$$d = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{20}$$

Sunset hour angle (rad):

$$\psi = arc\cos\,(-\tan\varphi \tan\delta) \tag{21}$$

Extraterrestrial radiation (MJ m^{-2} d^{-1}):

$$R_a = 37.586\, d\, (\psi \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\psi) \tag{22}$$

Maximum daylight hours:

$$DL = \frac{24}{\pi}\ \psi \tag{23}$$

Short-wave radiation R_s (MJ m^{-2} d^{-1})

$$R_s = \left(0.25 + 0.5\frac{SD}{DL}\right) R_a \tag{24}$$

For a reference crop with an assumed albedo coefficient $\alpha = 0.23$ *net incoming short-wave radiation* R_{ns} (MJ m^{-2} d^{-1}) is:

$$R_{ns} = 0.77\ R_s \tag{25}$$

Net outgoing long-wave radiation R_{nl} (MJ m^{-2} d^{-1}) is estimated using:

$$R_{nl} = 4.903 \cdot 10^{-9}\left(0.1 + 0.9\frac{SD}{DL}\right)\left(0.34 - 0.139\sqrt{e_d}\right)\frac{\left(273.16 + T_{\max}\right)^4 + \left(273.16 + T_{\min}\right)^4}{2} \tag{26}$$

Using (25) and (26), *net radiation flux* at surface, R_n, becomes

$$R_n = R_{ns} - R_{nl} \tag{27}$$

Finally, *soil heat flux* is approximated using

$$G = 0.14\ (T_{a,n} - T_{a,n-1}) \tag{28}$$

where $T_{a,n}$ and $T_{a,n-1}$ are average monthly temperatures of current and previous month, respectively. With equations (5), (10), (17), (27) and (28) all variables in (3) are defined and can be calculated from the input parameters described at the beginning of this Appendix.

14. Appendix 3-2 Example of Module I output at grid-cell level

The example of grid cell output of agro-climatic analysis shown here is for a grid cell near Ilonga, Tanzania, for rain-fed conditions under reference climate (1981–2010).

Basic characteristics of grid cell

- IROW/ICOL[17]: 1160 (of 2160) 2605 (of 4320)
- ALAT/ALNG: -6.63 (latitude), 37.04 (longitude)
- ALT: 645 m (altitude)
- Admin1 ID: 257 Tanzania
- Admin2 ID: 220 Tanzania
- Soil-MPU ID: 27116
- YEAR: 1981–2010 (reference climate)

Agro-climatic indicators

Table A3-2.1 Monthly climate values

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Rm	128.5	105.8	153.9	157.6	55.4	15.1	7.5	7	9.6	31.5	75	135
Tmx	31	31.4	31	29.4	28.4	27.4	27.1	27.9	29.7	31.1	31.9	31.3
Tmn	20.5	20.5	20.4	19.8	18.7	16.3	15.5	16.3	17.2	18.7	20.1	20.9
Tav	25.8	25.9	25.8	24.6	23.6	21.8	21.3	22.1	23.5	24.9	26	26.1
ETm	123	115	121.4	104.4	102.5	103.1	110.1	120.3	134.1	148.3	137.6	129
ETa	121.9	113.1	115.8	103	101.5	84.6	17.6	7.8	9.6	31.5	74.3	101.1
RH	68	67.2	68.8	73.3	70.7	63.8	60.1	58.3	56.1	57.1	61.4	67
U2	107	103	106	128	145	151	156	159	170	170	152	124
SD	4.6	5	4.6	4	4.2	5.3	5.4	5.3	5.7	5.9	5.6	5
SF	0.4	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4
DL	12.3	12.2	12	11.9	11.7	11.6	11.7	11.8	12	12.2	12.3	12.4
Wx	0	0	0	0	0	0	0	0	0	0	0	0

***Rm**: precipitation (mm); **Tmx**: mean monthly maximum temperature (°C); **Tmn**: mean monthly minimum temperature (°C); **Tav**: mean monthly average temperature (°C); **ETm**: maximum evapotranspiration of reference crop (mm); **ETa**: actual evapotranspitration of*

[17] Number of row/column in 5 arcmin global grid

*reference crop (mm); **Rh**: mean monthly relative humidity (%); **U2**: mean monthly wind run (km/day); **SD**: sunshine duration (hours); **SF**: sunshine fraction (% clear sky); **DL**: day length (hours); **Wx**: excess moisture (mm)*

Temperature profile characteristics

- Thermal climate class: 1 (Tropics, lowland)
- Thermal zone class: 1 (Tropics, warm)
- Mean annual temperature: 24.3 (°C)
- Mean temperature in coldest month: 21.3 (°C)
- Mean temperature in warmest month: 26.1 (°C)
- Thermal regime (#days by class):
  - #days >30, 25–30, 20–25, 15–20 etc.: 0 169 196 0 0 0 0 0 0[18]
  - #days-A >30, 25–30, 20–25, 15–20 etc.: 0 43 99 0 0 0 0 0 0
  - #days-B >30, 25–30, 20–25, 15–20 etc.: 0 126 97 0 0 0 0 0 0
  - #days with temperature >0 >5 >10: 365 365 365[19] (number of days)
- Beginning of period with >0 >5 >10: 1 1 1 (day of year)
- Ending of period with >0 >5 >10: 365 365 365 (day of year)
- Temperature sum of days >0 >5 >10: 8861 8861 8861 (∑°C)
- Average length of days >0 >5 >10: 12.0 12.0 12.0 (hours)

Reference moisture balance

- Annual rainfall: 882 (mm)
- Annual reference evapotranspiration: 1449 (mm)
- Annual precipitation/ET0 ratio: 61 (%)
- Number of growing period days: 235
- Number of growing periods: 1
- No dormancy period
- Thermal regime during LGP1 (#days by class):
  - #days >30, 25–30, 20–25, 15–20 etc.: 0 142 92 0 0 0 0 0 0
  - #days-A >30, 25–30, 20–25, 15–20 etc.: 0 16 0 0 0 0 0 0 0

[18] Number of days in temperature profile segment
[19] Number of days above respectively 0°C, 5°C and 10°C average daily temperature

- #days-B >30, 25–30, 20–25, 15–20 etc.: 0 126 92 0 0 0 0 0 0

- Moisture growing periods:
- LGP #days, #norm, #humid, beg, end: 234 138 98 (days) 318 (14 Oct) 551 (5 Jul)

Daily values of reference soil moisture balance

The following table lists selected input values and output variables from the daily reference soil moisture balance of the FAO reference crop and a reference soil AWC of 150 mm, with the following information provided in individual columns of Table A3-2.2:

Column heading	Description
Day	Julian day number
DoM	Day of month
Tmax	Maximum temperature (°C)
Tavg	Average temperature (°C)
Tmin	Minimum temperature (°C)
Prec	Precipitation (mm)
ET0	Reference evapotranspiration (mm)
ETa	Actual evapotranspiration (mm)
W/ET0	Ratio ETa/ET0 for reference crop
Snow	Snow bucket (mm)
Wsoil	Soil water balance (mm)
Wexc	Excess water lost due to saturation of soil profile (mm)

Table A3-2.2 Example of Module I water balance for a grid cell near Ilonga, Tanzania for period 1981–2010

Day	Mon	DoM	Tmax	Tavg	Tmin	Prec	ET0	ETa	W/ET0	Snow	Wsoil	Wexc
1	1	1	30.7	25.7	20.7	5.3	4	4	1	0	36	0
16	1	16	30.7	25.5	20.4	5.4	3.9	3.9	1	0	48	0
32	2	1	31.5	25.9	20.3	4.9	4.1	4.1	1	0	42	0
47	2	16	31.2	26	20.7	3.9	4.1	4.1	1	0	46	0
60	3	1	33.1	26.6	20	0	4.1	3	0.73	0	31	0
75	3	16	30.2	25.5	20.9	6.1	3.9	3.9	1	0	36	0
91	4	1	29.3	24.9	20.5	6.8	3.5	3.5	1	0	75	0
106	4	16	29.3	24.6	19.9	4.3	3.4	3.4	1	0	120	0
121	5	1	28.1	23.9	19.7	4.1	3.1	3.1	1	0	127	0
136	5	16	28.6	23.8	18.9	2.2	3.3	3.3	1	0	116	0
152	6	1	27.6	22.3	17	1	3.2	3.2	1	0	78	0

167	6	16	27.4	21.8	16.1	0	3.4	2.9	0.85	0	34	0
182	7	1	26.8	21.3	15.8	0.5	3.5	1.3	0.38	0	10	0
197	7	16	27.5	21.3	15.2	0	3.6	0.3	0.07	0	3	0
213	8	1	26.9	21.6	16.3	0.4	3.8	0.5	0.14	0	1	0
228	8	16	27.9	22.1	16.2	0	3.9	0	0	0	0	0
244	9	1	28.6	22.7	16.9	0.8	4.3	0.8	0.19	0	0	0
259	9	16	29.7	23.3	16.9	0.6	4.5	0.6	0.14	0	0	0
274	10	1	31.1	24.5	17.9	0	4.9	0	0	0	0	0
289	10	16	31.5	25	18.6	0	4.9	0	0	0	0	0
305	11	1	31.9	25.8	19.6	5.2	4.8	4.8	1	0	0	0
320	11	16	32.2	26.2	20.3	0	4.6	0	0	0	0	0
335	12	1	32.3	26.3	20.3	0	4.4	0.1	0.01	0	1	0
350	12	16	31.1	25.9	20.8	6.9	4.1	4.1	1	0	14	0
365	12	31	30.7	25.9	21.1	6.9	4	4	1	0	35	0

15. Appendix 4-1 Crops and Land Utilization Types (LUTs)

Suitability and potential yield assessments are available for 11 crop groups (Table A4-1.1), some 53 crops (Table A4-1.2), and were generated for more than 300 crop/LUTs (Table A4-1.3). Results for downscaling of crops/commodities are available for 26 crop/crop groups (Table A4-1.4).

Table A4-1.1 Crop groups

Crop group
Cereals
Roots and tubers
Sugar crops
Pulses
Oil crops
Vegetables
Fruits
Industrial crops
Narcotics and stimulants
Fodder crops
Bioenergy feedstocks

Table A4-1.2 Crops

Common name	*Scientific name*	Crop group
Wheat	*Triticum spp.*	Cereals
Wetland rice	*Oryza sativa*	Cereals
Dryland rice	*Oryza sativa*	Cereals
Maize	*Zea mays*	Cereals
Barley	*Hordeum vulgare*	Cereals
Sorghum	*Sorghum bicolor*	Cereals
Rye	*Secale cereale*	Cereals
Pearl millet	*Pennisetum glaucum*	Cereals
Foxtail millet	*Setaria italica*	Cereals
Oat	*Avena sativa*	Cereals
Buckwheat	*Fagopyrum esculentum*	Cereals

Common name	***Scientific name***	**Crop group**
White potato	*Solanum tuberosum*	Roots and tubers
Sweet potato	*Ipomoea batatas*	Roots and tubers
Cassava	*Manihot esculenta*	Roots and tubers
Yam and Cocoyam	*Dioscorea spp. and Colocasia esculenta*	Roots and tubers
Sugar cane	*Saccharum spp.*	Sugar crops
Sugar beet	*Beta vulgaris L.*	Sugar crops
Phaseolus bean	*Phaseolus vulgaris and Ph. lunatus*	Pulses
Chickpea	*Cicer arietinum*	Pulses
Cowpea	*Vigna unguiculata*	Pulses
Dry pea	*Pisum sativum L.*	Pulses
Gram	*Vigna radiata*	Pulses
Pigeonpea	*Cajanus cajan*	Pulses
Groundnut	*Arachis hypogaea*	Oil crops
Soybean	*Glycine max*	Oil crops
Sunflower	*Helianthus annuus*	Oil crops
Rape	*Brassica napus*	Oil crops
Oil palm	*Elaeis oleifera*	Oil crops
Olive	*Olea europaea*	Oil crops
Cabbage	*Brassica oleracea*	Vegetables
Carrot	*Daucus carota*	Vegetables
Onion	*Allium cepa*	Vegetables
Tomato	*Lycopersicon lycopersicum*	Vegetables
Banana/Plantain	*Musa spp.*	Fruits
Citrus	*Citrus Sinensis*	Fruits
Coconut	*Cocos nucifera*	Fruits
Cotton	*Gossypium hirsutum.*	Industrial crops
Flax	*Linum usitatissimum*	Industrial crops
Para rubber	*Hevea brasiliensis*	Industrial crops
Cacao	*Theobroma cacao*	Narcotics and stimulants
Coffee	*Coffea arabica*	Narcotics and stimulants
Tea	*Camellia Sinenses var. Sinensis*	Narcotics and stimulants
Tobacco	*Nicotiana tobacum*	Narcotics and stimulants
Maize	*Zea mays*	Silage
Alfalfa	*Medicago sativa*	Fodder crops
Napier grass	*Cenchrus purpureus*	Fodder crops
Pasture legume	*various*	Fodder crops

Common name	*Scientific name*	Crop group
Grass	*various*	Fodder crops
Sorghum	*Sorghum bicolor*	Bioenergy feedstock
Jatropha	*Jatropha curcas.*	Bioenergy feedstocks
Miscanthus	*Miscanthus spp*	Bioenergy feedstocks
Switchgrass	*Panicum virgatum*	Bioenergy feedstocks
Reed canary grass	*Phalaris arundinacea*	Bioenergy feedstocks

Table A4-1.3 Crop/LUTs

Crop group	Crop type	Growth cycle	Harvested part
Cereals	Winter wheat	35+105 days	Grain
Cereals	Winter wheat	40+120 days	Grain
Cereals	Winter wheat	45+135 days	Grain
Cereals	Winter wheat	50+150 days	Grain
Cereals	Spring wheat	90 days	Grain
Cereals	Spring wheat	105 days	Grain
Cereals	Spring wheat	120 days	Grain
Cereals	Spring wheat	135 days	Grain
Cereals	Spring wheat	150 days	Grain
Cereals	Wheat (subtropical cultivars)	105 days	Grain
Cereals	Wheat (subtropical cultivars)	120 days	Grain
Cereals	Wheat (subtropical cultivars)	135 days	Grain
Cereals	Wheat (subtropical cultivars)	150 days	Grain
Cereals	Wheat (tropical highland cultivars)	100 days	Grain
Cereals	Wheat (tropical highland cultivars)	115 days	Grain
Cereals	Wheat (tropical highland cultivars)	130 days	Grain
Cereals	Wheat (tropical highland cultivars)	145 days	Grain
Cereals	Wheat (tropical highland cultivars)	160 days	Grain
Cereals	Wheat (tropical highland cultivars)	175 days	Grain
Cereals	Wheat (tropical highland cultivars)	190 days	Grain
Cereals	Japonica wetland rice	105 days	Grain
Cereals	Japonica wetland rice	120 days	Grain
Cereals	Japonica wetland rice	135 days	Grain
Cereals	Japonica wetland rice	150 days	Grain
Cereals	Japonica wetland rice	165 days	Grain
Cereals	Japonica wetland rice	180 days	Grain

Crop group	Crop type	Growth cycle	Harvested part
Cereals	Japonica wetland rice	195 days	Grain
Cereals	Indica wetland rice	105 days	Grain
Cereals	Indica wetland rice	120 days	Grain
Cereals	Indica wetland rice	135 days	Grain
Cereals	Indica wetland rice	150 days	Grain
Cereals	Indica dryland rice	105 days	Grain
Cereals	Indica dryland rice	120 days	Grain
Cereals	Indica dryland rice	135 days	Grain
Cereals	Maize (tropical lowland cultivars)	90 days	Grain
Cereals	Maize (tropical lowland cultivars)	105 days	Grain
Cereals	Maize (tropical lowland cultivars)	120 days	Grain
Cereals	Maize (tropical lowland cultivars)	135 days	Grain
Cereals	Maize(tropical highland cultivars)	120 days	Grain
Cereals	Maize (tropical highland cultivars)	150 days	Grain
Cereals	Maize (tropical highland cultivars)	180 days	Grain
Cereals	Maize (tropical highland cultivars)	210 days	Grain
Cereals	Maize (tropical highland cultivars)	240 days	Grain
Cereals	Maize (tropical highland cultivars)	270 days	Grain
Cereals	Maize (tropical highland cultivars)	300 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	90 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	105 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	120 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	135 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	150 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	165 days	Grain
Cereals	Maize (temperate and subtropical cultivars)	180 days	Grain
Cereals	Winter barley	35+105 days	Grain
Cereals	Winter barley	40+120 days	Grain
Cereals	Winter barley	45+135 days	Grain
Cereals	Winter barley	50+150 days	Grain
Cereals	Spring barley	90 days	Grain
Cereals	Spring barley	105 days	Grain
Cereals	Spring barley	120 days	Grain
Cereals	Spring barley	135 days	Grain
Cereals	Barley (subtropical cultivars)	90 days	Grain

Crop group	Crop type	Growth cycle	Harvested part
Cereals	Barley (subtropical cultivars)	105 days	Grain
Cereals	Barley (subtropical cultivars)	120 days	Grain
Cereals	Barley (subtropical cultivars)	135 days	Grain
Cereals	Barley (tropical highland cultivars)	100 days	Grain
Cereals	Barley (tropical highland cultivars)	115 days	Grain
Cereals	Barley (tropical highland cultivars)	130 days	Grain
Cereals	Barley (tropical highland cultivars)	145 days	Grain
Cereals	Barley (tropical highland cultivars)	160 day	Grain
Cereals	Barley (tropical highland cultivars)	175 days	Grain
Cereals	Barley (tropical highland cultivars)	190 days	Grain
Cereals	Sorghum (tropical lowland cultivars)	90 days	Grain
Cereals	Sorghum (tropical lowland cultivars)	105 days	Grain
Cereals	Sorghum (tropical lowland cultivars)	120 days	Grain
Cereals	Sorghum (tropical lowland cultivars)	135 days	Grain
Cereals	Sorghum (tropical highland cultivars)	120 days	Grain
Cereals	Sorghum (tropical highland cultivars)	150 days	Grain
Cereals	Sorghum (tropical highland cultivars)	180 days	Grain
Cereals	Sorghum (tropical highland cultivars)	210 days	Grain
Cereals	Sorghum(tropical highland cultivars)	240 days	Grain
Cereals	Sorghum (tropical highland cultivars)	270 days	Grain
Cereals	Sorghum (tropical highland cultivars)	300 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	90 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	105 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	120 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	135 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	150 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	165 days	Grain
Cereals	Sorghum (temperate and subtropical cultivars)	180 days	Grain
Cereals	Winter rye	30+90 days	Grain
Cereals	Winter rye	35+105 days	Grain
Cereals	Winter rye	40+120 days	Grain
Cereals	Winter rye	45+135 days	Grain
Cereals	Spring rye	90 days	Grain
Cereals	Spring rye	105 days	Grain
Cereals	Spring rye	120 days	Grain

Crop group	Crop type	Growth cycle	Harvested part
Cereals	Spring rye	135 days	Grain
Cereals	Pearl millet	70 days	Grain
Cereals	Pearl millet	90 days	Grain
Cereals	Foxtail millet	75 days	Grain
Cereals	Foxtail millet	90 days	Grain
Cereals	Foxtail millet	105 days	Grain
Cereals	Foxtail millet	120 days	Grain
Cereals	Spring oat	90 days	Grain
Cereals	Spring oat	105 days	Grain
Cereals	Spring oat	120 days	Grain
Cereals	Buckwheat	75 days	Grain
Cereals	Buckwheat	90 days	Grain
Roots and tubers	White potato	90 days	Tuber
Roots and tubers	White potato	105 days	Tuber
Roots and tubers	White potato	120 days	Tuber
Roots and tubers	White potato	135 days	Tuber
Roots and tubers	White potato	150 days	Tuber
Roots and tubers	White potato	165 days	Tuber
Roots and tubers	White potato	180 days)	Tuber
Roots and tubers	Cassava	210 days	Root
Roots and tubers	Cassava	perennial	Root
Roots and tubers	Sweet potato	120 days	Tuber
Roots and tubers	Sweet potato	135 days	Tuber
Roots and tubers	Sweet potato	150 days	Tuber
Roots and tubers	Sweet potato	165 days	Tuber
Roots and tubers	White yam	195 days	Tuber
Roots and tubers	White yam	225 days	Tuber
Roots and tubers	Greater yam	240 days	Tuber
Roots and tubers	Greater yam	270 days	Tuber
Roots and tubers	Yellow yam	330 days	Tuber
Roots and tubers	Cocoyam	330 days	Tuber
Sugar crops	Sugar cane	330 days	Sugar
Sugar crops	Sugar beet	120 days	Sugar
Sugar crops	Sugar beet	135 days	Sugar
Sugar crops	Sugar beet	150 days	Sugar

Crop group	Crop type	Growth cycle	Harvested part
Sugar crops	Sugar beet	165 days	Sugar
Sugar crops	Sugar beet	180 days	Sugar
Sugar crops	Sugar beet	195 days	Sugar
Sugar crops	Sugar beet	210 days	Sugar
Pulses	Phaseolus bean (tropical lowland cultivars)	90 days	Grain
Pulses	Phaseolus bean (tropical lowland cultivars)	105 days	Grain
Pulses	Phaseolus bean (tropical lowland cultivars)	120 days	Grain
Pulses	Phaseolus bean (tropical lowland cultivars)	135 days	Grain
Pulses	Phaseolus bean (tropical lowland cultivars)	150 days	Grain
Pulses	Phaseolus bean (tropical highland cultivars)	120 days	Grain
Pulses	Phaseolus bean (tropical highland cultivars)	135 days	Grain
Pulses	Phaseolus bean (tropical highland cultivars)	150 days	Grain
Pulses	Phaseolus bean (tropical highland cultivars)	165 days	Grain
Pulses	Phaseolus bean (tropical highland cultivars)	180 days	Grain
Pulses	Phaseolus bean (temperate and subtropical cultivars)	90 days	Grain
Pulses	Phaseolus bean (temperate and subtropical cultivars)	105 days	Grain
Pulses	Phaseolus bean (temperate and subtropical cultivars)	120 days	Grain
Pulses	Phaseolus bean (temperate and subtropical cultivars)	135 days	Grain
Pulses	Phaseolus bean (temperate and subtropical cultivars)	150 days	Grain
Pulses	Chickpea	90 days	Grain
Pulses	Chickpea	105 days	Grain
Pulses	Chickpea	120 days	Grain
Pulses	Chickpea (cold tolerant)	150 days	Grain
Pulses	Chickpea (cold tolerant)	165 days	Grain
Pulses	Chickpea (cold tolerant)	180 days	Grain
Pulses	Cowpea	80 days	Grain
Pulses	Cowpea	100 days	Grain
Pulses	Cowpea	120 days	Grain
Pulses	Dry pea	90 days	Grain
Pulses	Dry pea	105 days	Grain
Pulses	Dry pea	120 days	Grain

Crop group	Crop type	Growth cycle	Harvested part
Pulses	Green gram	60 days	Grain
Pulses	Green gram	80 days	Grain
Pulses	Green gram	100 days	Grain
Pulses	Pigeon pea	135 days	Grain
Pulses	Pigeon pea	150 days	Grain
Pulses	Pigeon pea	165 days	Grain
Pulses	Pigeon pea	180 days	Grain
Pulses	Pigeon pea	195 days	Grain
Oil crops	Groundnut	90 days	Kernel
Oil crops	Groundnut	105 days	Kernel
Oil crops	Groundnut	120 days	Kernel
Oil crops	Soybean (tropical and subtropical cultivars)	105 days	Grain
Oil crops	Soybean (tropical and subtropical cultivars)	120 days	Grain
Oil crops	Soybean (tropical and subtropical cultivars)	135 days	Grain
Oil crops	Soybean (temperate and subtropical cultivars)	105 days	Grain
Oil crops	Soybean (temperate and subtropical cultivars)	120 days	Grain
Oil crops	Soybean (temperate and subtropical cultivars)	135 days	Grain
Oil crops	Soybean (temperate and subtropical cultivars)	150 days	Grain
Oil crops	Sunflower (tropical and subtropical cultivars)	135 days	Seed
Oil crops	Sunflower (tropical and subtropical cultivars)	150 days	Seed
Oil crops	Sunflower (temperate and subtropical cultivars)	105 days	Seed
Oil crops	Sunflower (temperate and subtropical cultivars)	120 days	Seed
Oil crops	Sunflower (temperate and subtropical cultivars)	135 days	Seed
Oil crops	Sunflower (temperate and subtropical cultivars)	150 days	Seed
Oil crops	Winter rape	35+105 days	Seed
Oil crops	Winter rape	40+120 days	Seed
Oil crops	Winter rape	45+135 days	Seed
Oil crops	Winter rape	45+150 days	Seed
Oil crops	Spring rape	105 days	Seed
Oil crops	Spring rape	120 days	Seed
Oil crops	Spring rape	135 days	Seed
Oil crops	Spring rape	150 days	Seed
Oil crops	Rabi rape	135 days	Seed
Oil crops	Rabi rape	150 days	Seed
Oil crops	Oil palm	perennial	Oil

Crop group	Crop type	Growth cycle	Harvested part
Oil crops	Olive	perennial	Oil
Vegetables	Cabbage	90 days	Head
Vegetables	Cabbage	105 days	Head
Vegetables	Cabbage	120 days	Head
Vegetables	Cabbage	135 days	Head
Vegetables	Cabbage	150 days	Head
Vegetables	Cabbage	165 days	Head
Vegetables	Carrot (fresh-early) (temperate and subtropical cultivars)	60 days	Root
Vegetables	Carrot (fresh-early) (temperate and subtropical cultivars)	75 days	Root
Vegetables	Carrot (fresh-early) (temperate and subtropical cultivars)	90 days	Root
Vegetables	Carrot (storage) (temperate and subtropical cultivars)	135 days	Root
Vegetables	Carrot (storage) (temperate and subtropical cultivars)	165 days	Root
Vegetables	Carrot (storage) (temperate and subtropical cultivars)	195 days	Root
Vegetables	Carrot (fresh) (tropical cultivars)	75 days	Root
Vegetables	Carrot (fresh) (tropical cultivars)	90 days	Root
Vegetables	Carrot (fresh) (tropical cultivars)	105 days	Root
Vegetables	Onion (temperate and subtropical cultivars)	120 days	Bulb
Vegetables	Onion (temperate and subtropical cultivars)	135 days	Bulb
Vegetables	Onion (temperate and subtropical cultivars)	150 days	Bulb
Vegetables	Onion (temperate and subtropical cultivars)	165 days	Bulb
Vegetables	Onion (temperate and subtropical cultivars)	180 days	Bulb
Vegetables	Onion (hybernating) (temperate/subtropical cultivars)	45+105 days	Bulb
Vegetables	Onion (hybernating) (temperate/subtropical cultivars)	60+120 days	Bulb
Vegetables	Onion hybernating) (temperate/subtropical cultivars)	75+135 days	Bulb
Vegetables	Onion (tropical cultivars)	90 days	Bulb
Vegetables	Onion (tropical cultivars)	105 days	Bulb
Vegetables	Onion) (tropical cultivars)	120 days	Bulb
Vegetables	Onion (tropical cultivars)	135 days	Bulb

Crop group	Crop type	Growth cycle	Harvested part
Vegetables	Tomato (temperate and subtropical cultivars)	90 days	Fruit
Vegetables	Tomato (temperate and subtropical cultivars)	105 days	Fruit
Vegetables	Tomato (temperate and subtropical cultivars)	120 days	Fruit
Vegetables	Tomato (temperate and subtropical cultivars)	135 days	Fruit
Vegetables	Tomato (tropical and subtropical cultivars)	105 days	Fruit
Vegetables	Tomato (tropical and subtropical cultivars)	120 days	Fruit
Vegetables	Tomato (tropical and subtropical cultivars)	135 days	Fruit
Fruits	Banana/Plantain	perennial	Fruit
Fruits	Citrus (sub-tropics)	perennial	Fruit
Fruits	Citrus (tropics)	perennial	Fruit
Fruits	Coconut 1 (tall)	perennial)	Copra
Fruits	Coconut 2 (hybrid tall)	perennial	Copra
Fruits	Coconut 3 (dwarf)	perennial	Copra
Industrial crops	Cotton (tropical cultivars)	135 days	Fiber
Industrial crops	Cotton (tropical cultivars)	150 days	Fiber
Industrial crops	Cotton (tropical cultivars)	165 days	Fiber
Industrial crops	Cotton (tropical cultivars)	180 days	Fiber
Industrial crops	Cotton (temperate and subtropical cultivars)	135 days	Fiber
Industrial crops	Cotton (temperate and subtropical cultivars)	150 days	Fiber
Industrial crops	Cotton (temperate and subtropical cultivars)	165 days	Fiber
Industrial crops	Flax	90 days	Fiber
Industrial crops	Flax	105 days	Fiber
Industrial crops	Flax	120 days	Fiber
Industrial crop	Para rubber	perennial	Latex
Narcotics and stimulants	Cacao (comun)	perennial	Beans
Narcotics and stimulants	Cacao (hybrid)	perennial	Beans
Narcotics and stimulants	Coffee arabica	perennial	Green beans
Narcotics and stimulants	Coffee robusta	perennial	Green beans
Narcotics and stimulants	Tea china tea (*camelia sinenses*)	perennial	Leaves
Narcotics and stimulants	Tea hybrid (*sinensis and assamica*)	perennial	Leaves

Crop group	Crop type	Growth cycle	Harvested part
Narcotics and stimulants	Tea assam tea (*camelia sinenses var. assamica*)	perennial	Leaves
Narcotics and stimulants	Tobacco (tropical cultivars)	105 days	Leaves
Narcotics and stimulants	Tobacco (tropical cultivars)	120 days	Leaves
Narcotics and stimulants	Tobacco (tropical cultivars)	135 days	Leaves
Narcotics and stimulants	Tobacco (temperate and subtropical cultivars)	150 days	Leaves
Narcotics and stimulants	Tobacco (temperate and subtropical cultivars)	165 day)	Leaves
Fodder crops	Silage maize (temperate and subtropical cultivars)	105 days	AGB
Fodder crops	Silage maize (temperate and subtropical cultivars)	120 days	AGB
Fodder crops	Silage maize (temperate and subtropical cultivars)	135 days	AGB
Fodder crops	Silage maize (temperate and subtropical cultivars)	150 days	AGB
Fodder crops	Silage maize (temperate and subtropical cultivars)	165 days	AGB
Fodder crops	Silage maize (temperate and subtropical cultivars)	180 days	AGB
Fodder crops	Alfalfa (temperate and subtropical cultivars)	perennial	AGB
Fodder crops	Alfalfa (tropical cultivars)	perennial	AGB
Fodder crops	Napier grass	perennial	AGB
Fodder crops	Pasture legumes (C3/I species)	perennial	AGB
Fodder crops	Pasture legumes (C3/II species)	perennial	AGB
Fodder crops	Pasture grasses (C3/I species)	perennial	AGB
Fodder crops	Pasture grasses (C3/II species)	perennial	AGB
Fodder crops	Pasture grasses (C4/II species)	perennial	AGB
Fodder crops	Pasture grasses (C4/l species)	perennial	AGB
Bioenergy feedstocks	Biomass sorghum (tropical lowland cultivars)	90 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical lowland cultivars)	105 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical lowland cultivars)	120 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical lowland cultivars)	135 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	120 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	150 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	180 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	210 days	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	240 days)	AGB
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	270 days	AGB

Crop group	Crop type	Growth cycle	Harvested part
Bioenergy feedstocks	Biomass sorghum (tropical highland cultivars)	300 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	90 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	105 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	120 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	135 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	150 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	165 days	AGB
Bioenergy feedstocks	Biomass sorghum (temperate and subtropical cultivars)	180 days	AGB
Bioenergy feedstocks	Jatropha	perennial	Seed
Bioenergy feedstocks	Miscanthus (C4/I)	perennial	AGB
Bioenergy feedstocks	Miscanthus (C4/II)	perennial	AGB
Bioenergy feedstocks	Switchgrass	perennial	AGB
Bioenergy feedstocks	Reed canary grass	perennial	AGB
Bioenergy feedstocks	Reed canary grass	perennial	AGB

ABG:Above ground biomass

Table A4-1.4 Crops/crop groups distinguished in Module VI/VII

Crop/commodity	Label	Unit production	Unit harvested
Wheat	WHE	1000 tons	1000 ha
Rice	RCW	1000 tons	1000 ha
Maize	MZE	1000 tons	1000 ha
Sorghum	SRG	1000 tons	1000 ha
Millet	MLT	1000 tons	1000 ha
Barley	BRL	1000 tons	1000 ha
Other cereals	OCE	1000 tons	1000 ha
Potato and sweet potato	RT1	1000 tons	1000 ha
Cassava	RT2	1000 tons	1000 ha
Yams and other roots	RT3	1000 tons	1000 ha
Sugar beet	SUB	1000 tons	1000 ha
Sugar cane	SUC	1000 tons	1000 ha

Crop/commodity	Label	Unit production	Unit harvested
Pulses	PLS	mln GK$	1000 ha
Soybean	SOY	1000 tons	1000 ha
Rapeseed	RSD	1000 tons	1000 ha
Sunflower	SFL	1000 tons	1000 ha
Groundnut	GRD	1000 tons	1000 ha
Oil palm fruit	OLP	1000 tons	1000 ha
Olives	OLV	1000 tons	1000 ha
Cotton	COT	1000 tons	1000 ha
Banana	BAN	1000 tons	1000 ha
Tobacco	TOB	1000 tons	1000 ha
Vegetables	VEG	mln GK$	1000 ha
Stimulants	CC2	mln GK$	1000 ha
Fodder crops	FDD	mln GK$	1000 ha
Crops NES	NES	mln GK$	1000 ha

Other cereals include rye, oats, buckwheat, fonio, etc.
Groundnut in shell
Cotton as primary product seed cotton
Tobacco harvest dry leaves
Stimulants include coffee, tea, cacao
Fodder crops: assuming a fodder price of GK$ 25/ton
Crops NES include all crops from FAOSTAT excluding those covered by 1–25 above
GK$ are international price weights calculated by FAO for period 2000.

16. Appendix 4-2 Parameters for calculation of water-limited yields of annual crops

Table A4-2.1 Parameters used for water-limited yield calculation, cereal crops

CROP NAME	Length of crop stage (% of growth cycle)						Water requirements relative to reference evapotranspiration				Yield loss factors						
	d1	d2a	d2b	d3a	d3b	d4	Kc1	Kc3	Kc5	KcT	Ky1	Ky2a	Ky2b	Ky3a	Ky3b	Ky4	KyT
Wheat (winter)	15	30	0	12	23	20	0.40	1.15	0.30	0.85	0.20	0.20	0.20	0.60	0.50	0.20	1.05
Wheat (spring)	15	25	0	13	27	20	0.30	1.10	0.30	0.85	0.20	0.20	0.20	0.65	0.55	0.20	1.15
Rice (japonica)	20	10	10	13	27	20	1.05	1.20	0.90	1.10	1.00	1.00	1.20	2.50	0.40	0.20	2.00
Rice (indica)	15	10	10	15	30	20	1.05	1.20	0.90	1.10	1.00	1.00	1.20	2.50	0.40	0.20	2.00
Rice (dryland)	15	10	10	15	30	20	0.50	1.20	0.60	0.90	0.40	0.50	1.20	2.50	0.40	0.20	1.25
Maize, tropical (grain)	15	30	0	13	27	15	0.30	1.20	0.35	0.85	0.40	0.40	0.40	1.50	0.50	0.20	1.25
Maize, other (grain)	20	30	0	12	23	15	0.30	1.20	0.35	0.85	0.40	0.40	0.40	1.50	0.50	0.20	1.25
Maize (silage)	20	35	0	12	23	10	0.30	1.10	1.00	0.95	0.40	0.40	0.40	0.40	0.40	0.20	1.00
Barley (winter)	15	30	0	12	23	20	0.40	1.15	0.25	0.85	0.20	0.20	0.20	0.60	0.50	0.20	1.05
Barley (spring)	15	25	0	13	27	20	0.30	1.15	0.25	0.85	0.20	0.20	0.20	0.65	0.55	0.20	1.15
Sorghum, tropical	10	25	0	40	0	25	0.30	1.05	0.55	0.80	0.20	0.20	0.20	0.55	0.45	0.20	0.90
Sorghum, other	20	30	0	12	23	15	0.30	1.05	0.55	0.80	0.20	0.20	0.20	0.55	0.45	0.20	0.90
Biomass sorghum	15	35	0	13	27	10	0.30	1.20	1.05	0.95	0.20	0.20	0.20	0.40	0.40	0.20	0.90
Winter rye	15	30	0	12	23	20	0.30	1.15	0.30	0.85	0.20	0.20	0.20	0.60	0.50	0.20	1.05

CROP NAME	Length of crop stage (% of growth cycle)						Water requirements relative to reference evapotranspiration				Yield loss factors						
	d1	d2a	d2b	d3a	d3b	d4	Kc1	Kc3	Kc5	KcT	Ky1	Ky2a	Ky2b	Ky3a	Ky3b	Ky4	KyT
Spring rye	15	25	0	13	27	20	0.30	1.15	0.30	0.85	0.20	0.20	0.20	0.65	0.55	0.20	1.15
Pearl millet	10	25	0	13	27	25	0.30	1.00	0.30	0.80	0.20	0.20	0.20	0.60	0.80	0.20	0.90
Foxtail millet	15	25	0	13	27	20	0.30	1.20	0.35	0.85	0.20	0.20	0.20	0.60	0.80	0.20	1.00
Spring oat	15	25	0	13	27	20	0.30	1.15	0.25	0.85	0.20	0.20	0.20	0.65	0.55	0.20	1.15
Buckwheat	15	25	0	13	27	20	0.30	1.10	0.30	0.85	0.20	0.20	0.20	0.60	0.80	0.20	0.90

The coefficients d1, …, d4 relate to the characteristics of the crop growth cycle, denoting here the relative length (in percent) of four crop development stages, namely, initial stage, early and late vegetative stage, early and late mid-season stage (flowering and reproductive stage), and maturation stage. Parameters $K1^c$, $K3^c$, *and* $K5^c$ *define crop water requirements respectively for the initial stage, the reproductive phase, and the end of the maturation stage. Coefficient* Kc^T *indicates water requirements relative to reference evapotranspiration over the entire growth cycle. Finally, factors* K^y *quantify the expected yield loss in relation to a crop evapotranspiration deficit, by crop stage and for the entire growth cycle, respectively.*

Table A4-2.2 Parameters used for water-limited yield calculation, other annual crops

CROP NAME	Length of crop stage (% of growth cycle)						Water requirements relative to reference evapotranspiration				Yield loss factors						
	d1	d2a	d2b	d3a	d3b	d4	Kc1	Kc3	Kc5	KcT	Ky1	Ky2a	Ky2b	Ky3a	Ky3b	Ky4	KyT
White potato	20	12	13	0	35	20	0.50	1.15	0.75	0.85	0.20	0.45	0.80	0.70	0.70	0.20	1.10
Sweet potato	15	10	10	0	40	25	0.50	1.15	0.65	0.85	0.20	0.45	0.80	0.70	0.70	0.20	1.10
White yam	20	25	0	0	35	20	0.50	1.10	0.95	0.85	0.20	0.45	0.80	0.70	0.70	0.20	1.10
Greater yam	20	30	0	0	30	20	0.50	1.10	0.95	0.85	0.20	0.45	0.80	0.70	0.70	0.20	1.10
Sugar beet	20	25	0	0	35	20	0.35	1.20	0.70	0.85	0.20	0.65	0.65	0.65	0.65	0.50	1.00
Phaseolous bean	20	25	0	15	20	20	0.40	1.15	0.35	0.75	0.20	0.20	0.20	1.10	0.75	0.20	1.15
Chickpea	20	30	0	10	15	20	0.40	1.00	0.35	0.70	0.20	0.20	0.20	1.10	0.75	0.20	1.15
Cowpea	20	30	0	12	18	20	0.40	1.05	0.35	0.75	0.20	0.20	0.20	1.10	0.75	0.20	1.15
Green gram	20	30	0	12	18	20	0.40	1.05	0.35	0.75	0.20	0.20	0.20	1.10	0.75	0.20	1.15
Dry pea	20	30	0	15	20	15	0.40	1.15	0.30	0.80	0.20	0.20	0.20	0.90	0.70	0.20	1.10
Pigeonpea	20	30	0	12	18	20	0.40	1.05	0.35	0.75	0.20	0.20	0.20	1.10	0.75	0.20	1.15
Groundnut	20	30	0	15	15	20	0.40	1.15	0.60	0.80	0.20	0.20	0.20	0.80	0.60	0.20	0.70
Soybean, tropical	10	25	0	23	27	15	0.40	1.15	0.50	0.85	0.20	0.20	0.20	0.80	1.00	0.20	0.85
Soybean, other	10	30	0	23	27	10	0.40	1.15	0.50	0.85	0.20	0.20	0.20	0.80	1.00	0.20	0.85
Sunflower	15	16	14	22	18	15	0.35	1.05	0.35	0.80	0.20	0.25	0.20	1.00	0.80	0.20	0.95
Rape, winter	10	30	0	22	18	20	0.40	1.05	0.35	0.80	0.20	0.20	0.20	0.80	1.00	0.20	0.85
Rape, spring	10	30	0	22	18	20	0.35	1.05	0.35	0.80	0.20	0.20	0.20	0.80	1.00	0.20	0.85
Cotton	15	25	0	33	17	10	0.35	1.15	0.70	0.85	0.20	0.20	0.20	0.50	0.75	0.25	0.85
Flax	15	25	0	23	12	25	0.35	1.10	0.25	0.75	0.20	0.20	0.20	0.80	0.80	0.50	0.95

CROP NAME	Length of crop stage (% of growth cycle)						Water requirements relative to reference evapotranspiration				Yield loss factors						
	d1	d2a	d2b	d3a	d3b	d4	Kc1	Kc3	Kc5	KcT	Ky1	Ky2a	Ky2b	Ky3a	Ky3b	Ky4	KyT
Tobacco	30	15	20	0	17	18	0.35	1.10	0.80	0.90	0.20	0.20	1.00	0.50	0.50	0.50	0.90
Cabbage	25	35	0	0	30	10	0.70	1.05	0.95	0.90	0.20	0.20	0.20	0.45	0.45	0.60	0.95
Tomato	20	25	0	17	18	20	0.60	1.15	0.80	0.85	0.20	0.40	0.40	1.10	0.80	0.40	1.05
Carrot	20	25	0	0	40	15	0.70	1.05	0.95	0.90	0.20	0.40	0.40	0.80	0.80	0.30	1.10
Onion	10	20	0	0	45	25	0.70	1.05	0.75	0.85	0.20	0.45	0.45	0.80	0.80	0.30	1.10

The coefficients d1, …, d4 relate to the characteristics of the crop growth cycle, denoting here the relative length (in percent) of four crop development stages, namely, initial stage, early and late vegetative stage, early and late mid-season stage (flowering and reproductive stage), and maturation stage. Parameters $K1^{c}$, $K3^{c}$, *and* $K5^{c}$ *define crop water requirements respectively for the initial stage, the reproductive phase, and the end of the maturation stage. Coefficient* Kc^{T} *indicates water requirements relative to reference evapotranspiration over the entire growth cycle. Finally, factors* K^{y} *quantify the expected yield loss in relation to a crop evapotranspiration deficit, by crop stage and for the entire growth cycle, respectively.*

17. Appendix 4-3 Temperature profile requirements

As initial step to screen the suitability of grid-cells for the possible presence of individual LUTs, GAEZ tests the match of prevailing thermal profile conditions with the LUT's temperature requirements.

There are several tests applied to evaluate the extent to which thermal and relative humidity conditions during the crop cycle fit the respective LUT requirements: (i) Thermal (latitudinal) climatic conditions; (ii) permafrost conditions; (iii) length of temperature growing period (LGP_{t5}); (iv) length of frost free period (LGP_{t10}); (v) temperature sums ($Tsum_t$); (vi) temperature profiles; (vii) vernalization conditions; (viii) diurnal temperature ranges (for selected tropical perennials); and (ix) relative humidity conditions (especially for selected tropical perennials).

The temperature profile requirements are crop/LUT-specific rules that specify conditions for crop cycle duration in terms of classes of mean daily temperatures. These classes in 5^0C intervals are defined separately for days with increasing or decreasing temperature trends, in terms of two times 9 classes of "temperature ranges" for days with average temperatures <-5^0C, -5-0^0C, …, 25-30^0C, and >30^0C (at 5^0C intervals).

Table A4-3.1 Temperature profile classes

Average temperature (Ta, °C)	**Growth cycle duration class (days)**		
	Total	**Temperature trend**	
		Increasing	**Decreasing**
> 30	L1/N1	L1a/N1a	L1b/N1b
25–30	L2/N2	L2a/N2a	L2b/N2b
20–25	L3/N3	L3a/N3a	L3b/N3b
15–20	L4/N4	L4a/N4a	L4b/N4b
10–15	L5/N5	L5a/N5a	L5b/N5b
5–10	L6/N6	L6a/N6a	L6b/N6b
0–5	L7/N7	L7a/N7a	L7b/N7b
-5–0	L8/N8	L8a/N8a	L8b/N8b
< -5	L9/N9	L9a/N9a	L9b/N9b

Temperature profile requirements of annual crops have been expressed as constraints on the number of growth cycle days of a crop/LUT falling in different 5^0C temperature intervals. The number of days is indicated by total interval durations L1-L9, by L1a-L9a denoting durations of crop cycle days in periods of increasing temperature trends, and L1b-L9b denoting the number of days in periods of decreasing temperature interval durations.

Temperature profile requirements of perennial crops refer to year-round 5^0C temperature intervals. These year-round interval durations are termed N1-N9 for total, N1a-N9a for durations in temperature profile classes with increasing temperature trend, and N1b-N9b with decreasing temperature trend. For perennials the sum of days spent in N1-N9 equals 365.

In addition to temperature profile classes (see Table A4-3.1) the following variables have been used in the description of temperature profile constraints:

- **CY:** (Annuals) Length of growth cycle.
- **CYa:** (Hybernating annuals) Length of pre-dormancy growth cycle.
- **CYb:** (Hybernating annuals) Length of post-dormancy growth cycle.
- **Dormancy**: Period with mean daily temperatures < 5^0C and a maximum length of 200 days. For hibernating crops to be suitable, on all days below 5^0C the mean daily temperatures must stay above a crop type specific minimum tolerated temperature.
- **LGPT00:** Number of days in a year with mean daily temperatures above 0^0C.
- **LGPT05:** Number of days in a year with mean daily temperatures above 5^0C.
- **LGPT10:** Number of days in a year with mean daily temperatures above 10^0C.
- **RHmin:** Minimum mean monthly relative humidity.
- **RHavg:** Average annual relative humidity.
- **DTRavg:** Difference between annual average maximum and minimum temperatures.
- **DTRhigh:** Largest difference of average monthly maximum and minimum temperatures.
- **NDN16**: Number of days with minimum daily temperature < 16°C.
- **WSTRT:** Accumulated precipitation minus soil evaporation for up to 90 days before starting date.
- **TSM10**: For days in LGPT10, accumulated temperature sum $\sum_{j \in LGPT10} \max(0, Ta_j - 10)$.
- **TSM05**: For days in LGPT05, accumulated temperature sum $\sum_{j \in LGPT05} \max(0, Ta_j - 5)$.
- **T trend**: "Upward" indicates that the crop cycle starting date should fall in the part of the year when temperature is generally increasing, i.e., temperature profile classes N1a to N9a. "Downward" refers to days with decreasing temperature trends, i.e., to classes N1b to N9b.

Possible crop calendars of each LUT are tested for the match of crop/LUT temperature profile requirements and prevailing temperature profiles. Evaluation is done separately for rain-fed and irrigated conditions, considering crop cycle starting days within the reference growing period for rain-fed conditions, and within the applicable temperature growing period (LGP_{T05} or LGP_{T10}) for irrigated conditions. Temperature profile conditions in a grid cell are first tested with regard to 'optimum' requirements of crops. When failing, the 'sub-optimum' crop temperature profile requirements are tested. In each case an "optimum", "sub-optimum" or "not suitable" result is established.

Three threshold values are defined for specifying 'optimum', 'sub-optimum' and 'not suitable' constraint levels. At the 'sub-optimum' threshold it is assumed that crop growth and yield are reduced by 25%, whereas no reduction is applied for values exceeding the threshold for 'optimum' conditions. When the calculated constraint value falls in between the 'optimum' and 'sub-optimum' thresholds, a constraint factor is calculated by linear interpolation. When the constraint value lies between 'sub-optimum' and 'not suitable' thresholds, then again a linear function is used to calculate the constraint factor.

The "most limiting" evaluated constraint factor is then used to reduce potential yields. For this yield adjustment a reduction factor fc_1 is calculated over all constraints:

$$fc_1 = \min k \; \{fc_{1k}, k = 1, \dots, K\},$$

which represents the minimum, i.e., the most severe of the individual temperature (and relative humidity) related reduction factors.

Figure A4-3.1 Constraint function of Type A (left) and Type B (right)

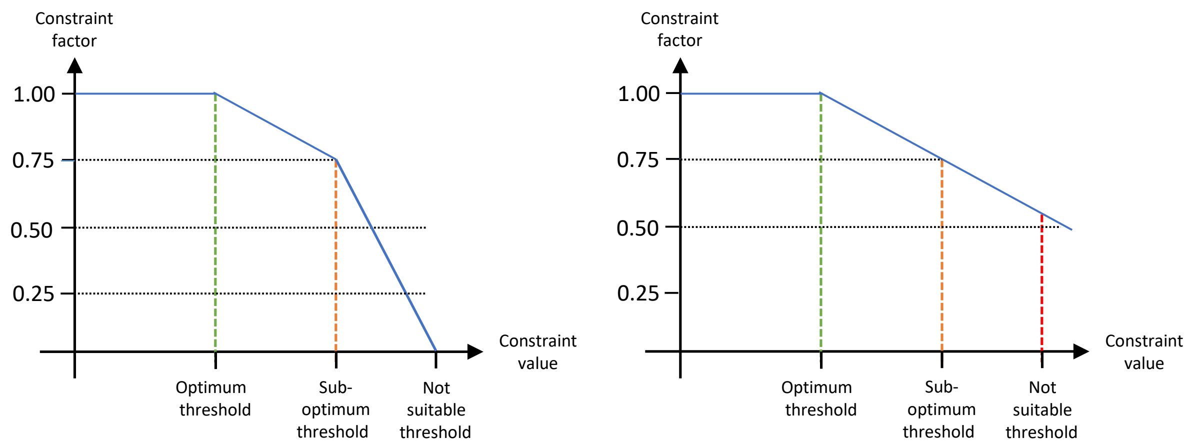


Figure A4-3.1 shows the two types of constraint functions used in Module II to evaluate temperature profile constraints. Constraint functions of Type A, attaining a constraint factor value of 0 at the 'not suitable' threshold, are used for accumulated temperature sums and for constraints related to minimum and average relative humidity levels. Constraints of Type B, extending the line segment defined by 'optimum' and 'sub-optimum' thresholds, are used for all other requirements that limit the number of crop growth cycle days in different temperature profile classes.

Table 4-3.2 presents an example of temperature and humidity profile constraints for LUTs of winter wheat, soybean and coffee arabica. Note, requirements for hibernating crops are specified in terms of pre-dormancy and post-dormancy crop cycle durations (respectively CYa and CYb). Non-hibernating annual crops use a reference growth cycle CY. For perennial crops the specification of profile requirements relates to year-round conditions, i.e., to 365 days.

Table A4-3.2 Example of temperature and humidity profile constraint parameters

Common crop name	Constraint subject	Constraint type	'Optimum' threshold	'Sub-optimum' threshold	'Not suitable' threshold
Winter wheat	L6a	≤	0.500×CYb	0.667×CYb	0.667×CYb
	L6b	≤	0	0	0
	L2a+L2b	≤	0.333×CYb	0.400×CYb	0.333×CYb
	L1a+L1b	≤	0	0	0
	L2b+L3b+L4b+L5b	<	0.500×CYb	0.500×CYb	0.500×CYb
	N3b+N4b+N5b+N6b-(L3b+L4b+L5b)	≥	CYa	CYa	CYa
	Dormancy*				
	Vernalization**				
Soybean, subtropical	L6a+L6b	≤	0	0	0
	L5a+L5b	≤	0.167×CY	0.333×CY	0.333×CY
	L4a+L3a+L3b+L4b	≥	0.167×CY	0.083×CY	0.0416×CY
	L4a+L3a+L2a+L2b+L3b+L4b	≥	0.667×CY	0.500×CY	0.333×CY
	L1a+L1b	≤	0.333×CY	0.500×CY	0.667×CY
	T trend		upward	upward	upward
Coffee arabica	LGP_{T10}	≥	365	305	305
	N9+N8+N7	≤	0	0	0
	N6	≤	0	0.167×365	0.167×365
	N5	≤	0.333×365	0.500×365	0.500×365
	N2	≤	0.333×365	0.500×365	0.667×365
	N1	≤	0	0	0
	RHmin	≤	80%	90%	90%
	RHmin	≥	40%	30%	30%

** A valid dormancy period must be less than 200 days, average daily temperatures are below 5°C, and snow-adjusted values always exceed a crop-specific minimum threshold. For winter wheat the minimum temperature is set to a value between -8°C and -11°C depending on severity of continentality.*
*** For vernalization requirements of winter wheat, winter barley, winter rye and winter rape see Appendix 4-4.*

When the values for 'sub-optimum' and 'not suitable' thresholds are set the same, this means that the constraint function is cut off at the 'sub-optimum' threshold and all constraint values beyond the 'sub-optimum' threshold result in a 'not suitable' evaluation.

When all three thresholds are set to the same value, then the test produces a yes/no decision. When 'optimum' conditions are met, the LUT passes the test; otherwise, the test evaluates to 'not suitable'.

Note, in a situation where the constraint is such that the ‘sub-optimum’ threshold can never be exceeded, then the ‘not suitable’ threshold is set to ‘not applicable’ (‘n.a.’).

Profile constraint parameters for all crops evaluated in this release are provided in a separate Excel document available on the GAEZ v4 platform in the following worksheets:

- Table A4-3.3: Temperature profile constraint parameters for cereal crops
- Table A4-3.4: Temperature profile constraint parameters for root and tuber crops
- Table A4-3.5: Temperature profile constraint parameters for sugar crops
- Table A4-3.6: Temperature profile constraint parameters for pulses
- Table A4-3.7: Temperature profile constraint parameters for annual oil crops
- Table A4-3.8: Temperature and humidity profile constraint parameters for industrial crops
- Table A4-3.9: Temperature and humidity profile constraint parameters for vegetables
- Table A4-3.10: Temperature and humidity profile constraint parameters for perennial fruits and stimulants
- Table A4-3.11: Temperature profile constraint parameters for selected fodder and bioenergy crops

18. Appendix 4-4 Crop vernalization requirements

Some crops require a vernalization period (i.e., days with cold temperatures) for performing specific phenological development phases such as flowering. The production of flowers and grains, which directly influences crop yield, is dependent on the extent and intensity of exposure to periods with cold temperature. This cold temperature requirement is measured in vernalization days (VD, days). In GAEZ, there are four hibernating crops that need to fulfil vernalization requirements in order to produce: winter wheat, winter barley, winter rye and winter rape.

The rate of vernalization (*fvn*, VD/day) for a daily average temperature Ta is calculated for each LUT.

$$fvn(Ta) = \begin{cases} \dfrac{2(Ta - Tv_n)^{\alpha}(T_{opt} - Tv_n)^{2\alpha} - (Ta - Tv_n)^{2\alpha}}{(T_{opt} - Tv_n)^{2\alpha}} & for\, TV_n \le Ta \le Tv_x, else \\ 0 & \end{cases}$$

where:

Tv_n, Tv_{opt}, and Tv_x are the cardinal temperatures for vernalization (minimum, optimum, and maximum)

The coefficient α is calculated as:

$$\alpha = \frac{\ln 2}{\ln(Tv_x - Tv_n) - \ln(Tv_{opt} - Tv_n)}$$

The accumulation of VD occurs during the dormancy period plus up to additional 60 days after dormancy to account for cold temperature during early stages when temperatures increase above 5^0C and vernalization processes continue. The parameters used for *fvn* calculation in GAEZ are shown in Table A4.

Table A4-4.1 Parameterization for the calculation of the rate of vernalization

Crop	Tv_{opt}	Tv_x	Tv_n	VD_0	VD_{100}
Winter wheat	5	15	-1	10	45
Winter barley	4	12	0	8	35
Winter rye	5	15	-2	10	45
Winter rape	3	10	0	8	30

VD_{100} is the number of vernalization days required for achieving full vernalization
VD_0 is the minimum level of VD required in GAEZ for proceeding with yield calculations

The number of vernalization days (VD) is then calculated by accumulating the rate of vernalization (*fvn,* VD/day*)* for the period between the start and the end of the dormancy period plus up to 60 days.

$$VD = \sum fvn(Ta)$$

Yield calculations for a LUT only proceed if VD is greater than VD_0, which implies that some level of vernalization occurred. If VD > $VD_{0,}$ a vernalization factor (*fthz*, fractional) is then calculated as a function of VD:

$$fthz = \frac{VD^5}{VD_{50}^5 + VD^5}$$

where VD_{50} is 50% of the vernalization days required for full vernalization (VD_{100}).

18. Appendix 4-5 Biomass and yield calculation

The AEZ methodology for the calculation of potential net biomass and yields is based on eco-physiological principles, as outlined below:

To calculate the net biomass production (Bn) of a crop, an estimation of the gross biomass production (Bg) and respiration loss (R) is required:

$$B_n = B_g - R \tag{1}$$

The equation relating the rate of net biomass production (bn) to the rate of gross biomass production (bg) and the respiration rate (r) is:

$$b_n = b_g - r \tag{2}$$

The maximum rate of net biomass production (bnm) is reached when the crop fully covers the ground surface. The period of maximum net crop growth, i.e., the point in time when maximum net biomass increments occur, is indicated by the inflection point of the cumulative growth curve. When the first derivative of net biomass growth is plotted against time the resulting graph resembles a normal distribution curve. The model assumes that the average rate of net production (bna) over the entire growth cycle is half the maximum growth rate, i.e., bna = 0.5 bnm. The net biomass production for a crop of N days (Bn) is then:

$$B_n = 0.5\ b_{nm} \times N \tag{3}$$

The maximum rate of gross biomass production (bgm) is related to the maximum net rate of CO_2 exchange of leaves (Pm) which is dependent on temperature, the photosynthesis pathway of the crop, and the level of atmospheric CO_2 concentration.

For a standard crop, i.e., a crop in adaptability group I with Pm = 20 kg ha-1hr-1 and a leaf area index of LAI = 5, the rate of gross biomass production bgm is calculated from the equation:

$$b_{gm} = F \times b_o + (1 - F)\ b_c \tag{4}$$

where:

F = the fraction of the daytime the sky is clouded, $F = (A_c - 0.5\ R_g) / (0.8\ A_c)$, where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal cm^{-2} day^{-1})

$\boldsymbol{b_o}$ = gross dry mater production rate of a standard crop for a given location and time of the year on a completely overcast day, (kg ha^{-1} day^{-1}) (de Wit, 1965)

$\boldsymbol{b_c}$ = gross dry mater production rate of a standard crop for a given location and time of the year on a perfectly clear day, (kg ha^{-1} day^{-1}) (de Wit, 1965)

When P_m is greater than 20 kg ha¹ hr¹, b_{gm} is given by the equation:

$$b_{gm} = F\,(0.8 + 0.01P_m)\,b_o + (1 - F)\,(0.5 + 0.025\,P_m)\,b_c \tag{5}$$

When P_m is less than 20 kg ha¹ hr¹, b_{gm} is calculated according to:

$$b_{gm} = F\,(0.5 + 0.025\,P_m)\,b_o + (1 - F)\,(0.05\,P_m)\,b_c \tag{6}$$

To calculate the maximum rate of net biomass production (bnm), the maximum rate of gross biomass production (bgm) and the rate of respiration (rm) are required. Here, growth respiration is considered a linear function of the rate of gross biomass production (McCree, 1974), and maintenance respiration a linear function of net biomass that has already been accumulated (Bm) When the rate of gross biomass production is bgm, the respiration rate rm is:

$$r_m = k\,b_{gm} + c\,B_m \tag{7}$$

where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and Bm is the net biomass accumulated at the time of maximum rate of net biomass production. For both legume and non legume crops k equals 0.28. However, c is temperature dependent and differs for the two crop groups. At 30^{0}C, factor c30 for a legume crop equals 0.0283 and for a non-legume crop 0.0108. The temperature dependence of ct for both crop groups is modelled with a quadratic function:

$$c_t = c_{30}\,(0.0044 + 0.0019\,T + 0.0010\,T^2). \tag{8}$$

It is assumed that the cumulative net biomass Bm of the crop (i.e., biomass at the inflection point of the cumulative growth curve) equals half the net biomass that would be accumulated at the end of the crop's growth cycle. Therefore, we set Bm = 0.5 Bn, and using (3), Bm for a crop of N days is determined according to:

$$B_m = 0.25\,b_{nm} \times N \tag{9}$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (bnm) or the rate of net dry matter production at full cover for a crop of N days becomes:

$$b_{nm} = 0.72\,b_{gm} / (1 + 0.25\,c_t\,N) \tag{10}$$

Finally, the net biomass production (Bn) for a crop of N days, where 0.5 bnm is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36\,b_{gm} \times L) / (1/N + 0.25\,c_t) \tag{11}$$

where:

$\boldsymbol{b_{gm}}$ = maximum rate of gross biomass production at leaf area index (LAI) of 5

L = growth ratio, equal to the ratio of b_{gm} at actual LAI to b_{gm} at LAI of 5

N = length of normal growth cycle

$\boldsymbol{c_t}$ = maintenance respiration, dependent on both crop and temperature according to equation (8)

Potential yield (Y_p) is estimated from net biomass (B_n) using the equation:

$$Y_p = H_i \, x \, B_n \tag{12}$$

where:

$\boldsymbol{H_i}$ = harvest index, i.e., proportion of the net biomass of a crop that is economically useful

Thus, climate and crop characteristics that apply in the computation of net biomass and yield are: (a) heat and radiation regime over the crop cycle, (b) crop adaptability group to determine applicable rate of photosynthesis Pm, (c) length of growth cycle (from emergence to physiological maturity), (d) length of yield formation period,.(e) leaf area index at maximum growth rate, and (f) harvest index.

Appendix 4-6 Biomass and yield parameters

Table A4-6.1 Biomass and yield parameters used for wheat LUTs

Crop/LUT	Crop/LUT name	Reference growth cycle length	Maximum rate of photosynthes (curve number)	Annula/perennial	Soil water depletion factor group	Legume (1=yes, 0=no)	Tropical lowland	Tropical highland	Subtropics summer rainfall	Subtropics winter rainfall	Subtropics low rainfall	Temperate oceanic	Temperate sub-continental	Temperate continental	Boreal oceanic	Boreal sub-continental	Boreal continental	Arctic	Minimum temperature	Harvest index (high inputs)	Maximum leaf area index (high inputs)	Harvest index (low inputs)	Maximum leaf area index (low inputs)	Yield formation period (percentage of growth cycle)	Ratio of seasonal average rate of net biomass production (b_{na}) and maximum crop growth rate	Lower boundary of accumulated heat units range (dd)	Lower boundary of optimum accumulated heat units (dd)	Upper boundary of optimum accumulated heat units (dd)	Upper boundary of accumulated heat units range (dd)
1	Winter wheat	35+105	2	1	6	0	0	0	1	1	1	1	1	1	0	0	0	0	5	0.50	4.5	0.20	2.5	0.33	0.55	1300	1400	2050	2300
2	Winter wheat	40+120	2	1	6	0	0	0	1	1	1	1	1	1	0	0	0	0	5	0.50	5.0	0.20	2.5	0.33	0.55	1400	1500	2200	2500
3	Winter wheat	45+135	2	1	6	0	0	0	1	1	1	1	1	1	0	0	0	0	5	0.50	5.5	0.20	2.5	0.33	0.55	1500	1600	2350	2700
4	Winter wheat	50+150	2	1	6	0	0	0	1	1	1	1	1	1	0	0	0	0	5	0.50	5.5	0.20	2.5	0.33	0.55	1600	1700	2500	2900
5	Spring wheat	90	1	1	6	0	0	0	1	1	1	1	1	1	1	1	1	0	5	0.45	3.0	0.15	1.8	0.33	0.50	1200	1300	1900	2100
6	Spring wheat	105	1	1	6	0	0	0	1	1	1	1	1	1	1	1	1	0	5	0.45	3.5	0.15	2.0	0.33	0.50	1300	1400	2050	2300
7	Spring wheat	120	1	1	6	0	0	0	1	1	1	1	1	1	1	1	1	0	5	0.45	4.0	0.15	2.3	0.33	0.50	1400	1500	2200	2500
8	Spring wheat	135	1	1	6	0	0	0	1	1	1	1	1	1	1	1	1	0	5	0.45	4.5	0.15	2.5	0.33	0.50	1500	1600	2350	2700
9	Spring wheat	150	1	1	6	0	0	0	1	1	1	1	1	1	1	1	1	0	5	0.45	5.0	0.15	2.5	0.33	0.50	1600	1700	2500	2900
10	Wheat (ST cultivars)	105	1	1	6	0	0	1	1	1	1	1	1	1	0	0	0	0	5	0.50	4.5	0.20	2.5	0.33	0.50	1400	1500	2050	2300
11	Wheat (ST cultivars)	120	1	1	6	0	0	1	1	1	1	1	1	1	0	0	0	0	5	0.50	5.0	0.20	2.5	0.33	0.50	1500	1600	2200	2500
12	Wheat (ST cultivars)	135	1	1	6	0	0	1	1	1	1	1	1	1	0	0	0	0	5	0.50	5.5	0.20	2.5	0.33	0.50	1600	1700	2350	2700
13	Wheat (ST cultivars)	150	1	1	6	0	0	1	1	1	1	1	1	1	0	0	0	0	5	0.50	5.5	0.20	2.5	0.33	0.50	1700	1800	2500	2900
14	Wheat (TRh cultivars)	100	3	1	6	0	1	1	1	1	1	0	0	0	0	0	0	0	5	0.40	3.5	0.15	1.8	0.33	0.50	1250	1350	2200	2550
15	Wheat (TRh cultivars)	115	3	1	6	0	1	1	1	1	1	0	0	0	0	0	0	0	5	0.40	4.0	0.15	2.0	0.33	0.50	1375	1500	2400	2950
16	Wheat (TRh cultivars)	130	3	1	6	0	1	1	1	1	1	0	0	0	0	0	0	0	5	0.40	4.5	0.15	2.3	0.33	0.50	1500	1650	2600	3350
17	Wheat (TRh cultivars)	145	3	1	6	0	1	1	1	1	1	0	0	0	0	0	0	0	5	0.40	4.5	0.15	2.5	0.33	0.50	1625	1800	2800	3750
18	Wheat (TRh cultivars)	160	3	1	6	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0.40	5.0	0.15	2.5	0.33	0.50	1625	1800	2800	3750

19	Wheat (TRh cultivars)	175	3	1	6	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0.40	5.0	0.15	2.5	0.33	0.50	1625	1800	2800	3750
20	Wheat (TRh cultivars)	190	3	1	6	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0.40	5.0	0.15	2.5	0.33	0.50	1625	1800	2800	3750

ST=subtropical; TRh=Tropical highland. The full table A4-6.1.a is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

Table A4-6.2 Maximum rate of photosynthesis (kg ha^{-1} hr^{-1}) by curve number

Curve	Day time temperatures (°C)										
Number	**-5**	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
1	0	0	5	15	20	20	15	5	0	0	0
2	0	0	5	15	25	25	20	10	0	0	0
3	0	0	5	15	25	25	20	15	5	0	0
4	0	0	0	0	15	30	35	35	30	5	0
5	0	0	0	0	15	30	35	35	30	5	0
6	0	0	0	5	15	30	35	35	30	5	0
7	0	0	5	15	20	25	25	25	25	5	0
8	0	0	0	0	5	45	65	65	65	45	5
9	0	0	0	5	45	65	65	65	45	5	0
10	0	0	0	10	20	25	20	10	5	0	0
11	0	0	5	15	20	25	20	10	0	0	0
12	0	0	0	0	15	20	30	30	20	5	0
13	0	0	0	10	20	25	25	10	5	0	0
14	0	0	0	0	15	30	35	35	30	5	0
15	0	0	0	15	45	65	65	50	25	5	0
16	0	0	2.5	10	20	25	25	20	10	5	0
17	0	0	5	15	20	20	15	5	0	0	0
18	0	0	0	2.5	15	35	35	35	30	5	0
19	0	0	2.5	15	37.5	50	50	37.5	25	10	0
20	0	0	0	2.5	30	40	47.5	50	47.5	40	5
21	0	0	0	0	9	18	27	27	18	5	0
22	0	0	0	0	15	30	35	35	30	5	0
23	0	0	5	15	45	65	65	65	45	5	0
24	0	0	0	5	15	45	65	65	65	45	5
25	0	0	5	15	25	30	35	30	25	5	0

19. Appendix 4-7 Example of Module II output at grid-cell level

The example of grid cell output of biomass and yield calculation shown here is for a grid cell near Ilonga, Tanzania, for rain-fed conditions under reference climate (1981–2010), a reference AWC = 200 mm and high input/advanced management assumptions.

Basic characteristics of grid cell

- IROW/ICOL[20]: 1160 (of 2160) 2605 (of 4320)
- ALAT/ALNG: -6.63 (latitude), 37.04 (longitude)
- ALT: 645 m (altitude)
- Admin1 ID: 257 Tanzania
- Admin2 ID: 220 Tanzania
- Soil-MPU ID: 27116
- YEAR: 1981–2010 (reference climate)

Agro-climatic indicators

Table A4-7.1 Monthly climate values

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Rm	128.5	105.8	153.9	157.6	55.4	15.1	7.5	7	9.6	31.5	75	135
Tmx	31	31.4	31	29.4	28.4	27.4	27.1	27.9	29.7	31.1	31.9	31.3
Tmn	20.5	20.5	20.4	19.8	18.7	16.3	15.5	16.3	17.2	18.7	20.1	20.9
Tav	25.8	25.9	25.8	24.6	23.6	21.8	21.3	22.1	23.5	24.9	26	26.1
ETm	123	115	121.4	104.4	102.5	103.1	110.1	120.3	134.1	148.3	137.6	129
ETa	121.9	113.1	115.8	103	101.5	84.6	17.6	7.8	9.6	31.5	74.3	101.1
RH	68	67.2	68.8	73.3	70.7	63.8	60.1	58.3	56.1	57.1	61.4	67
U2	107	103	106	128	145	151	156	159	170	170	152	124
SD	4.6	5	4.6	4	4.2	5.3	5.4	5.3	5.7	5.9	5.6	5
SF	0.4	0.4	0.4	0.3	0.4	0.5	0.5	0.5	0.5	0.5	0.5	0.4
DL	12.3	12.2	12	11.9	11.7	11.6	11.7	11.8	12	12.2	12.3	12.4

***Rm**: precipitation (mm); **Tmx**: mean monthly maximum temperature (°C); **Tmn**: mean monthly minimum temperature (°C); **Tav**: mean monthly average temperature (°C); **ETm**: maximum evapotranspiration of reference crop (mm); **ETa**: actual evapotranspitration of*

[20] Number of row/column in 5 arcmin global grid

reference crop (mm); ***Rh****: mean monthly relative humidity (%);* ***U2****: mean monthly wind run (km/day);* ***SD****: sunshine duration (hours);* ***SF****: sunshine fraction (% clear sky);* ***DL****: day length (hours)*

Moisture profile characteristics

- Annual rainfall: 882 (mm)
- Annual reference evapotranspiration: 1449 (mm)
- Annual Precipitation/ET0 ratio: 61 (%)
- Number of growing period days: 235
- Number of growing periods: 1
- No dormancy period
- Thermal regime during LGP1 (#days by class):
    - #days >30, 25–30, 20–25, 15–20 etc.: 0 142 92 0 0 0 0 0 0
    - #days-A >30, 25–30, 20–25, 15–20 etc.: 0 16 0 0 0 0 0 0 0
    - #days-B >30, 25–30, 20–25, 15–20 etc.: 0 126 92 0 0 0 0 0 0
- Moisture growing periods:
- LGP #days, #norm, #humid, beg, end: 234 138 98 (days) 318 (14 Oct) 551 (5 Jul)

Crop yields

The following table describes the column headings in Table A4-7.2 for crop calendar, yields and yield constraints, with the following information provided in individual columns:

Column heading	Description	Unit
CR	LUT sequence number	
BDy	Begin date of crop cycle (Julian day)	Day of year
EDy	End date of crop cycle (Julian day)	Day of year
CYL	Crop cycle length	Days
fc1	Temperature profile constraint factor (range: 0 – 10000)	Scalar
HI	Harvest index	Scalar
Bn	Total biomass	tons dry weight/ha
By	Harvested biomass	tons dry weight/ha
Ym	Temperature and radiation limited maximum yield	kg dry weight/ha
Ya	Water limited potential agro-climatic yield*	kg dry weight/ha

fc2	Moisture deficit constraint factor (range: 0 – 10000)	Scalar
TS	Temperature sum during growth cycle	∑°C
Weta	Crop actual evapotranspiration (mm)	mm
Wdef	Crop water deficit (mm)	mm
WbSt	Soil moisture balance at the beginning of crop cycle (mm)	mm
WbEd	Soil moisture balance at the end of the crop cycle (mm)	mm
W365	Soil moisture balance at the end of the year (mm)	mm
fky1	Crop stage specific yield loss factor, initial stage (fraction)	Scalar
fky2	Crop stage specific yield loss factor, vegetative stage (fraction)	Scalar
fky3	Crop stage specific yield loss factor, reproductive stage (fraction)	Scalar
fky4	Crop stage specific yield loss factor, maturation stage (fraction)	Scalar
fky0	Yield loss factor for entire growth cycle calculated as weighted product over individual crop stages (fraction)	Scalar
fkyT	Crop stage specific yield loss factor for entire growth cycle (fraction)	Scalar

By = Hi x Bn; Ym = 1000 x By x fc1; Ya = Ym x fc2

** The yields shown in this column do not include the impact of agro-climatic constraints which is evaluated in the next assessment step in Module III.*

Table A4-7.2 Example of Module II output for a grid cell near Ilonga, Tanzania, rain-fed cereals for period 1981–2010 at high inputs

Crop/LUT	CR	BD	CED	CYL	fc1	HI	Bn	By	Ym	Ya	fc2	TS	WbSt	WbEd	KcI	KcM	KcE	fky1	fky2	fky3	fk3	fky4	fkyCS	fkyT
Wheat, Tropical 1	14	92	191	100	0.75	0.40	7.82	3.13	2345	2345	1.00	2311	77	4	0.30	1.07	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wheat, Tropical 2	15	81	195	115	0.75	0.40	9.42	3.77	2825	2824	1.00	2674	45	3	0.26	1.07	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wheat, Tropical 3	16	68	197	130	0.75	0.40	10.83	4.33	3248	3235	1.00	3051	26	3	0.22	1.07	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Wheat, Tropical 4	17	52	196	145	0.75	0.40	11.71	4.68	3512	3511	1.00	3451	43	3	0.38	1.07	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rice, Indica 1	28	63	167	105	0.84	0.52	12.97	6.74	5676	5431	0.96	2540	29	32	0.43	1.16	0.88	0.96	1.00	1.00	1.00	1.00	0.96	0.99
Rice, Indica 2	29	65	184	120	0.87	0.52	14.63	7.61	6612	6245	0.94	2853	31	8	0.39	1.16	0.88	0.95	1.00	1.00	1.00	0.98	0.95	0.94
Rice, Indica 3	30	46	180	135	0.79	0.50	16.45	8.22	6514	6423	0.99	3264	46	11	0.41	1.16	0.88	1.00	1.00	1.00	1.00	0.99	0.99	0.99
Rice, Indica 4	31	46	195	150	0.79	0.48	17.95	8.62	6824	6023	0.88	3583	46	3	0.38	1.16	0.88	1.00	1.00	1.00	1.00	0.95	0.95	0.88
Rice, dryland 1	32	344	83	105	1.00	0.30	11.05	3.31	3314	3310	1.00	2721	3	55	0.42	1.16	0.56	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rice, dryland 2	33	344	98	120	1.00	0.30	13.13	3.94	3938	3938	1.00	3094	3	104	0.38	1.16	0.55	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Rice, dryland 3	34	344	113	135	1.00	0.30	14.95	4.49	4485	4485	1.00	3463	3	131	0.34	1.16	0.55	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, lowland 1	35	344	68	90	1.00	0.45	13.09	5.89	5888	5888	1.00	2336	3	28	0.31	1.15	0.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, lowland 2	36	344	83	105	1.00	0.45	15.97	7.19	7187	7187	1.00	2721	3	55	0.42	1.15	0.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, lowland 3	37	344	98	120	1.00	0.45	17.73	7.98	7977	7977	1.00	3094	3	104	0.38	1.15	0.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, lowland 4	38	344	113	135	1.00	0.45	20.68	9.31	9306	9306	1.00	3463	3	131	0.34	1.14	0.35	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, silage 1	53	62	166	105	1.00	0.60	15.70	9.42	9419	9419	1.00	2544	29	34	0.33	1.05	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, silage 2	54	56	175	120	1.00	0.60	17.65	10.59	10592	10592	1.00	2897	35	16	0.40	1.06	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Maize, silage 3	55	57	191	135	0.99	0.65	19.52	12.69	12590	12514	0.99	3212	34	4	0.36	1.06	0.97	1.00	1.00	1.00	1.00	0.99	0.99	1.00
Barley, Tropical 1	71	91	190	100	0.75	0.40	6.24	2.50	1872	1867	1.00	2314	75	5	0.30	1.12	0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Barley, Tropical 2	72	82	196	115	0.75	0.40	7.21	2.88	2162	2145	0.99	2670	48	3	0.26	1.12	0.25	1.00	1.00	1.00	1.00	0.99	0.99	0.99

Crop/LUT	CR	BD	CED	CYL	fc1	HI	Bn	By	Ym	Ya	fc2	TS	WbSt	WbEd	KcI	KcM	KcE	fky1	fky2	fky3	fk3	fky4	fkyCS	fkyT
Barley, Tropical 3	73	69	198	130	0.75	0.40	8.15	3.26	2445	2409	0.99	3046	28	2	0.22	1.12	0.25	1.00	1.00	1.00	1.00	0.99	0.99	0.99
Barley, Tropical 4	74	55	199	145	0.75	0.40	9.05	3.62	2714	2676	0.99	3436	35	2	0.41	1.12	0.25	1.00	1.00	1.00	1.00	0.99	0.99	0.99
Sorghum, lowland 1	78	344	68	90	1.00	0.35	14.07	4.92	4923	4923	1.00	2336	3	28	0.31	1.00	0.51	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sorghum, lowland 2	79	344	83	105	1.00	0.35	17.09	5.98	5980	5980	1.00	2721	3	55	0.42	1.00	0.49	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sorghum, lowland 3	80	344	98	120	1.00	0.35	19.79	6.93	6925	6925	1.00	3094	3	104	0.38	1.00	0.48	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Sorghum, lowland 4	81	344	113	135	1.00	0.35	21.58	7.55	7553	7553	1.00	3463	3	131	0.34	1.00	0.49	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B-Sorghum, lowland 1	96	344	68	90	1.00	0.70	15.70	10.99	10992	10992	1.00	2336	3	28	0.31	1.14	1.01	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B-Sorghum, lowland 2	97	344	83	105	1.00	0.70	18.57	13.00	13000	13000	1.00	2721	3	55	0.42	1.14	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B-Sorghum, lowland 3	98	344	98	120	1.00	0.70	21.13	14.79	14789	14789	1.00	3094	3	104	0.38	1.14	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B-Sorghum, lowland 4	99	344	113	135	1.00	0.70	23.04	16.13	16129	16129	1.00	3463	3	131	0.34	1.14	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pearl Millet 1	122	14	83	70	1.00	0.25	10.57	2.64	2642	2642	1.00	1815	46	55	0.51	0.95	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Pearl Millet 2	123	344	68	90	1.00	0.25	14.07	3.52	3517	3517	1.00	2336	3	28	0.44	0.95	0.30	1.00	1.00	1.00	1.00	1.00	1.00	1.00

20. Appendix 5-1 Agro-climatic constraints

Table A5-1.1 Agro-climatic constraints for rain-fed conditions when mean annual temperature > 20°C

Common name	Growth cycle	Input level	CT	Wetness indicator LGPagc (days)														
				0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365 -	365 +
Winter wheat	35 + 105	Low	a	100	100	100	50	50	25	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Low	b	0	0	0	0	0	0	0	0	0	25	25	25	25	25	25
Winter wheat	35 + 105	Low	c	25	25	25	25	25	0	0	0	0	0	0	25	25	50	50
Winter wheat	35 + 105	Low	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	Intermediate	a	100	100	100	50	50	25	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Intermediate	b	0	0	0	0	0	0	0	0	0	0	25	25	25	25	25
Winter wheat	35 + 105	Intermediate	c	25	25	25	25	25	0	0	0	0	0	0	25	25	50	50
Winter wheat	35 + 105	Intermediate	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	High	a	100	100	100	50	50	25	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	High	b	0	0	0	0	0	0	0	0	0	0	0	25	25	25	25
Winter wheat	35 + 105	High	c	25	25	25	25	25	0	0	0	0	0	0	0	25	25	50
Winter wheat	35 + 105	High	d	0	0	0	0	0	0	0	0	0	0	10	10	10	30	30

CT = constraint type. The complete Table A5-1.1 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform

Table A5-1.2 Agro-climatic constraints for rain-fed conditions when mean annual temperature < 10°C

Common name	Growth cycle	Input level	CT	Wetness indicator LGPagc (days)														
				0	1–29	30–59	60–89	90–119	0	150–179	180–209	210–239	240–269	0	300–329	330–364	365 -	365 +
Winter wheat	35 + 105	Low	a	100	100	100	30	30	10	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Low	b	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10
Winter wheat	35 + 105	Low	c	10	10	10	10	10	0	0	0	0	0	0	10	10	30	30
Winter wheat	35 + 105	Low	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	Intermediate	a	100	100	100	30	30	10	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Intermediate	b	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10
Winter wheat	35 + 105	Intermediate	c	10	10	10	10	10	0	0	0	0	0	0	10	10	30	30
Winter wheat	35 + 105	Intermediate	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	High	a	100	100	100	30	30	10	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	High	b	0	0	0	0	0	0	0	0	0	0	0	10	10	10	10
Winter wheat	35 + 105	High	c	10	10	10	10	10	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	High	d	0	0	0	0	0	0	0	0	0	0	10	10	10	30	30

CT = constraint type. The complete Table A5-1.2 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

Table A5-1.3 Agro-climatic constraints for irrigated conditions when mean annual temperature > 20°C

Common name	Growth cycle	Input level	CT	Wetness indicator LGPagc (days)														
				0	1–29	30–59	60–89	90–119	0	150–179	180–209	210–239	240–269	0	300–329	330–364	365 -	365 +
Winter wheat	35 + 105	Low	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Low	b	0	0	0	0	0	0	0	0	0	25	25	25	25	25	25
Winter wheat	35 + 105	Low	c	0	0	0	0	0	0	0	0	0	0	0	25	25	50	50
Winter wheat	35 + 105	Low	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	Intermediate	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	Intermediate	b	0	0	0	0	0	0	0	0	0	0	25	25	25	25	25
Winter wheat	35 + 105	Intermediate	c	0	0	0	0	0	0	0	0	0	0	0	25	25	50	50
Winter wheat	35 + 105	Intermediate	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35 + 105	High	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35 + 105	High	b	0	0	0	0	0	0	0	0	0	0	0	25	25	25	25
Winter wheat	35 + 105	High	c	0	0	0	0	0	0	0	0	0	0	0	0	25	25	50
Winter wheat	35 + 105	High	d	0	0	0	0	0	0	0	0	0	0	10	10	10	30	30

CT = constraint type. The complete Table A5-1.3 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

Table A5-1.4 Agro-climatic constraints for irrigated conditions when mean annual temperature < 10°C

Common name	Growth cycle			Input level	CT	Wetness indicator LGPagc (days)														
						0	1–29	30–59	60–89	90–119	0	150–179	180–209	210–239	240–269	0	300–329	330–364	365 -	365 +
Winter wheat	35	+	105	Low	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35	+	105	Low	b	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10
Winter wheat	35	+	105	Low	c	0	0	0	0	0	0	0	0	0	0	0	10	10	30	30
Winter wheat	35	+	105	Low	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35	+	105	Intermediate	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35	+	105	Intermediate	b	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10
Winter wheat	35	+	105	Intermediate	c	0	0	0	0	0	0	0	0	0	0	0	10	10	30	30
Winter wheat	35	+	105	Intermediate	d	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35	+	105	High	a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Winter wheat	35	+	105	High	b	0	0	0	0	0	0	0	0	0	0	0	10	10	10	10
Winter wheat	35	+	105	High	c	0	0	0	0	0	0	0	0	0	0	0	0	10	10	30
Winter wheat	35	+	105	High	d	0	0	0	0	0	0	0	0	0	0	10	10	10	30	30

CT = constraint type. The complete Table A5-1.4 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform

Table A5-1.5 Agro-climatic constraints of early and late frost

Common name	Growth cycle	Input level	CT	Length of frost free period (days)												
				0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–365
Winter wheat	35 + 105	H+I+L	e	100	100	100	100	50	0	0	0	0	0	0	0	0
Winter wheat	40 120	H+I+L	e	100	100	100	125	75	25	-25	0	0	0	0	0	0
Winter wheat	45 135	H+I+L	e	100	100	100	100	100	50	0	0	0	0	0	0	0
Winter wheat	50 150	H+I+L	e	100	100	100	100	125	75	25	0	0	0	0	0	0
Spring wheat	90	H+I+L	e	100	100	100	100	25	0	0	0	0	0	0	0	0
Spring wheat	105	H+I+L	e	100	100	100	138	63	-13	0	0	0	0	0	0	0
Spring wheat	120	H+I+L	e	100	100	100	100	100	25	0	0	0	0	0	0	0
Spring wheat	135	H+I+L	e	100	100	100	100	138	63	-13	0	0	0	0	0	0
Spring wheat	150	H+I+L	e	100	100	100	100	100	100	25	0	0	0	0	0	0
Wheat (subtropical cultivars)	105	H+I+L	e	100	100	100	138	63	-13	0	0	0	0	0	0	0
Wheat (subtropical cultivars)	120	H+I+L	e	100	100	100	100	100	25	0	0	0	0	0	0	0
Wheat (subtropical cultivars)	135	H+I+L	e	100	100	100	100	138	63	-13	0	0	0	0	0	0
Wheat (subtropical cultivars)	150	H+I+L	e	100	100	100	100	100	100	25	0	0	0	0	0	0
Wheat (tropical highland cultivars)	100	H+I+L	e	100	100	100	100	50			0	0	0	0	0	0
Wheat (tropical highland cultivars)	115	H+I+L	e	100	100	100	125	75	25	-25	0	0	0	0	0	0

Common name	Growth cycle	Input level	CT	Length of frost free period (days)												
				0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–365
Wheat (tropical highland cultivars)	130	H+I+L	e	100	100	100	100	100	50	0	0	0	0	0	0	0
Wheat (tropical highland cultivars)	145	H+I+L	e	100	100	100	100	125	75	25	-25	0	0	0	0	0
Wheat (tropical highland cultivars)	160	H+I+L	e	100	100	100	100	100	100	50	0	0	0	0	0	0
Wheat (tropical highland cultivars)	175	H+I+L	e	100	100	100	100	100	125	75	25	-25	0	0	0	0
Wheat (tropical highland cultivars)	190	H+I+L	e	100	100	100	100	100	100	100	50	0	0	0	0	0

CT = constraint type. H+I+L = High, intermediate, low input. The complete Table A5-1.5 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

21. Appendix 6-1 Combinations by crop, input level and water supply

Table A6-1.1 Combinations of crops, input levels and water supply system

Crops/input levels	Water supply systems			
	Rain-fed H, I, L	Irrigation		
		Gravity H, I	Sprinkler H, I	Drip H, I
Wheat	v	corrugation/border	v	-
Wetland rice	v	basin	-	-
Dryland rice	v	-	-	-
Maize	v	furrow	v	-
Barley	v	corrugation/border	v	-
Sorghum	v	furrow	v	-
Rye	v	corrugation/border	v	-
Pearl millet	v	furrow	v	-
Foxtail millet	v	furrow	v	-
Oat	v	corrugation/border	v	-
Buckwheat	v	corrugation/border	v	-
White potato	v	furrow	v	-
Sweet potato	v	furrow	v	-
Cassava	v	-	-	-
Yam, cocoyam	v	-	-	-
Sugar cane	v	basin/furrow	v	-
Sugar beet	v	furrow	v	-
Phaseolus bean	v	furrow	v	v
Chickpea	v	furrow	-	-
Cowpea	v	furrow	-	-
Dry pea	v	furrow	v	-
Gram	v	furrow	-	-
Pigeonpea	v	furrow	-	-
Groundnut	v	furrow	-	-
Soybean	v	furrow	v	-
Sunflower	v	furrow	v	-
Rape	v	furrow	-	-
Oil palm	v	-	-	v

Crops/input levels	Water supply systems			
	Rain-fed H, I, L	Irrigation		
		Gravity H, I	Sprinkler H, I	Drip H, I
Olive	ν	basin/furrow	-	ν
Cabbage	ν	furrow	ν	ν
Carrot	ν	furrow	ν	ν
Onion	ν	furrow	ν	ν
Tomato	ν	furrow	ν	ν
Banana/plantain	ν	basin/furrow	ν	ν
Citrus	ν	basin/furrow	ν	ν
Coconut	ν	furrow	ν	ν
Cacao	ν	furrow	ν	ν
Coffee	ν	furrow	ν	ν
Tea	ν	-	ν	ν
Cotton	ν	furrow	-	-
Flax	ν	furrow	ν	-
Para rubber	ν	-	-	-
Tobacco	ν	furrow	ν	-
Maize (silage)	ν	furrow	ν	-
Alfalfa	ν	corrugation/border	ν	-
Napier grass	ν	-	ν	-
Pasture legume	ν	-	ν	-
Grass	ν	-	ν	-
Sorghum (biomass)	ν	corrugation/border	ν	-
Jatropha	ν	furrow	ν	-
Miscanthus	ν	-	ν	-
Switchgrass	ν	-	ν	-
Reed canary grass	ν	-	ν	-

22. Appendix 6-2 Soil drainage classes

Soil drainage classes are based on Guidelines for estimation of drainage classes based on soil type, texture, soil phase and terrain slope (FAO, 1995). The estimation procedures have been applied to all soil type, texture, soil phase and broad slope classes[21].

Table A6-2.1 Soil drainage characteristics for FAO '74 soil units by slope classes

FAO'90 soil groupings and soil units	Topsoil textural group	Soil drainage characteristics of soil units by slope classes								Soil drainage characteristics of soil units with petrocalcic, petrogypsic, petroferric, duripan and lithic soil phases by slope classes							
		0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	>45%	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	>45%
A	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE
A	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE
A	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE
Af	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE
Af	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE
Af	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE
Ag	coarse	P	P	P	I	I	I	I	I	P	P	P	I	I	I	I	I
Ag	medium	P	P	P	P	I	I	I	I	P	P	P	P	I	I	I	I
Ag	fine	P	P	P	P	P	I	I	I	P	P	P	P	P	I	I	I
Ah	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE
Ah	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE
Ah	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE
Ao	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE
Ao	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE
Ao	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE

The complete Table A6-2.1 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

[21] NB. Fluvisols are characterized by flooding, high groundwater tables and implicitly for poor drainage. This is accounted for in Chapter 6, Section 6.8 Suitability of water-collecting sites. The soil drainage classes presented for Fluvisols refer to soil drainage characteristics only.

Table A6-2.2 Soil drainage characteristics for FAO '90 soil units by slope classes

FAO'90 soil groupings and soil units	Topsoil textural group	Soil drainage characteristics of soil units by slope classes								Soil drainage characteristics of soil units with petroferric, duripan, placic, lithic soil phases by slope classes								Soil drainage characteristics of soil units with anthraquic soil phase by slope classes							
		0–0.5%	0.5–2%	2–5%	5–8%	8–16%	15–30%	30–45%	>45 %	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	>45 %	0–0.5%	0.5–2%	2–5%	5–8%	8–16%	16–30%	30–45%	>45 %
AC	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE	P	P	P	I	I	I	I	I
AC	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE	P	P	P	P	I	I	I	I
AC	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE	P	P	P	P	P	I	I	I
ACf	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE	P	P	P	I	I	I	I	I
ACf	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE	P	P	P	P	I	I	I	I
ACf	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE	P	P	P	P	P	I	I	I
ACg	coarse	P	P	P	I	I	I	I	I	P	P	P	I	I	I	I	I	P	P	P	I	I	I	I	I
ACg	medium	P	P	P	P	I	I	I	I	P	P	P	P	I	I	I	I	P	P	P	P	I	I	I	I
ACg	fine	P	P	P	P	P	I	I	I	P	P	P	P	P	I	I	I	P	P	P	P	P	I	I	I
ACh	coarse	MW	MW	MW	W	W	SE	SE	SE	MW	MW	MW	W	W	SE	SE	SE	P	P	P	I	I	I	I	I
ACh	medium	MW	MW	MW	MW	W	W	SE	SE	I	I	MW	MW	W	W	SE	SE	P	P	P	P	I	I	I	I
ACh	fine	MW	MW	MW	MW	MW	W	W	SE	I	I	I	MW	MW	W	W	SE	P	P	P	P	P	I	I	I
ACp	coarse	P	P	P	I	I	I	I	I	P	P	P	I	I	I	I	I	P	P	P	I	I	I	I	I
ACp	medium	P	P	P	P	I	I	I	I	P	P	P	P	I	I	I	I	P	P	P	P	I	I	I	I
ACp	fine	P	P	P	P	P	I	I	I	P	P	P	P	P	I	I	I	P	P	P	P	P	I	I	I

The complete Table A6-2.2 is provided in the GAEZ Appendix Excel file on the GAEZ v4 platform.

23. Appendix 6-3 Soil requirements for rain-fed crops

Soil requirements are presented for 56 crops under rain-fed and sprinkler irrigation systems, assuming high, intermediate and low levels of inputs and management conditions. Soil requirements ratings are presented separately for Chemical and Physical Soil Characteristics, Soil Textures, Soil Drainage and Soil Phases.

Soil profile

Soil characteristics suitability ratings are empirical coefficients that reflect the effect the value of the soil characteristic has on the yield potential of a specific crop.

- S0 - No constraint (100)
- S1 - Slight constraint (90)
- S2 - Moderate (70)
- S3 - Severe constraint (50)
- S4 - Very severe constraint (30)
- N - Not suitable (10)

Soil texture

Soil texture conditions are influencing various soil qualities (SQ1, SQ2, SQ3 and SQ7). Soil workability ratings differ for high, intermediate and low inputs. Soil texture ratings are compiled for 13 texture classes.

Drainage

Soil drainage ratings are varying by crop and may vary by prevalent soil texture conditions. Assumptions for artificial soil drainage differ by input levels. High level inputs assume full and adequate artificial drainage systems are installed while low and intermediate inputs assume no artificial drainage.

Soil phase

The soil phase ratings have been compiled by input level (high, intermediate and low). The ratings represent constraints implied by the occurrence of soil phases in percentage (100% rating meaning no constraint to 0% rendering a soil totally unsuitable).

The soil phases are organized by soil quality to which they apply and by level of input and management and water supply system. Two rating types have been used: (i) Soil phase rating is applying to 100% of the extent of the soil unit to which the soil phase is attributed and (ii) soil

phase rating is assumed to affect 50% of the soil to which it is attributed while the other 50% is assumed not to be affected.

All parameters are provided in an Excel spreadsheet available on the GAEZ v4 data platform under the following worksheets:

- Table A6-3.1: Chemical and physical soil characteristics ratings
- Table A6-3.2: Soil texture ratings
- Table A6-3.3: Soil drainage ratings
- Table A6-3.4: Soil phase characteristics affecting high input farming
- Table A6-3.5: Soil phase characteristics affecting intermediate input farming
- Table A6.3.6: Soil phase characteristics affecting low input farming

24. Appendix 6-4 Soil requirements for irrigated crops (gravity irrigation)

Soil requirements are presented for 45 crops under gravity irrigation systems, assuming high and intermediate levels of inputs and management conditions. Soil requirements ratings are presented separately for Chemical and Phyisical Soil Characteristics, Soil Textures, Soil Drainage and Soil Phases.

Soil profile

Soil characteristics suitability ratings are empirical coefficients that reflect the effect the value of the soil characteristic has on the yield potential of a specific crop.

- S0 - No constraint (100)
- S1 - Slight constraint (90)
- S2 - Moderate (70)
- S3 - Severe constraint (50)
- S4 - Very severe constraint (30)
- N - Not suitable (10)

Soil texture

Soil texture conditions are influencing various soil qualities (SQ1, SQ2, SQ3 and SQ7). Soil workability ratings differ for high, intermediate and low inputs. Soil texture ratings are compiled for 13 texture classes.

Drainage

Soil drainage ratings are varying by crop and may vary by prevalent soil texture conditions. Assumptions for artificial soil drainage differ by input levels. High level inputs assume full and adequate artificial drainage systems are installed while low and intermediate inputs assume no artificial drainage.

Soil phase

The soil phase ratings have been compiled by input level (high and intermediate). The ratings represent constraints implied by the occurrence of soil phases in percentage (100% rating meaning no constraint to 0% rendering a soil totally unsuitable).

The soil phases are organized by soil quality to which they apply and by level of input and management and water supply system. Two rating types have been used: (i) Soil phase rating is applying to 100% of the extent of the soil unit to which the soil phase is attributed and (ii) soil

phase rating is assumed to affect 50% of the soil to which it is attributed while the other 50% is assumed not to be affected.

All parameters are provided in an Excel file available on the GAEZ v4 data platform under the following worksheets:

- Table A6-4.1: Chemical and physical soil characteristics ratings
- Table A6-4.2: Soil texture ratings
- Table A6-4.3: Soil drainage ratings
- Table A6-4.4: Soil phase characteristics affecting high input farming
- Table A6-4.5: Soil phase characteristics affecting intermediate input farming

25. Appendix 6-5 Soil requirements for Irrigated crops (drip irrigation)

Soil requirements are presented for 15 crops under drip irrigation systems, assuming high, and intermediate levels of inputs and management conditions. Soil requirements ratings are presented separately for Chemical and Physical Soil Characteristics, Soil Textures, Soil Drainage and Soil Phases.

Soil profile

Soil characteristics suitability ratings are empirical coefficients that reflect the effect the value of the soil characteristic has on the yield potential of a specific crop.

- S0 - No constraint (100)
- S1 - Slight constraint (90)
- S2 - Moderate (70)
- S3 - Severe constraint (50)
- S4 - Very severe constraint (30)
- N - Not suitable (10)

Soil texture

Soil texture conditions are influencing various soil qualities (SQ1, SQ2, SQ3 and SQ7). Soil workability ratings differ for high, intermediate and low inputs. Soil texture ratings are compiled for 13 texture classes.

Drainage

Soil drainage ratings are varying by crop and may vary by prevalent soil texture conditions. Assumptions for artificial soil drainage differ by input levels. High level inputs assume full and adequate artificial drainage systems are installed while low and intermediate inputs assume no artificial drainage.

Soil phase

The soil phase ratings have been compiled by input level (high and intermediate). The ratings represent constraints implied by the occurrence of soil phases in percentage (100% rating meaning no constraint to 0% rendering a soil totally unsuitable).

The soil phases are organized by soil quality to which they apply and by level of input and management and water supply system. Two rating types have been used: (i) Soil phase rating is applying to 100% of the extent of the soil unit to which the soil phase is attributed and (ii) soil

phase rating is assumed to affect 50% of the soil to which it is attributed while the other 50% is assumed not to be affected.

All parameters are provided in an Excel file available on the GAEZ v4 data platform under the following worksheets:

- Table A6-5.1: Chemical and physical soil characteristics ratings
- Table A6-5.2: Soil texture ratings
- Table A6-5.3: Soil drainage ratings
- Table A6-5.4: Soil phase characteristics affecting high input farming
- Table A6-5.5: Soil phase characteristics affecting intermediate input farming

26. Appendix 6-6 Soil suitability assessment examples for rain-fed maize

Table A6-6.1 Example soil suitability assessment for rain-fed maize at high level of inputs

TROPICAL LOWLAND MAIZE (120 days) RAIN-FED, HIGH INPUTS/ADVANCED MANAGEMENT																		
HWSD v2.1										**Soil characteristics ratings by soil quality**								
Location	Tanzania, Ilonga																	
Coverage	SOTWIS																	
Soil mapping unit	27116																	
Dominant soil group	AC - Acrisols																	
Soil unit symbol (FAO 90)		ACu	NTu	LXf	LPe						ACu	NTu	LXf	LPe				
Share of soil units in soil mapping unit (%)	SMU %	55	15	15	15													
Reference soil depth (cm)	RSD	100	100	100	30					SQ3, SQ7	100	100	100	10				
Soil phase 1	SPH	No	No	No	No					SQ3, SQ4, SQ5, SQ6, SQ7	100	100	100	100				
Soil phase 2	SPH	No	No	No	No					SQ3, SQ4, SQ5, SQ6, SQ7	100	100	100	100				
Reference drainage class (0–0.5% slope)	DRG	MW	MW	MW	I					SQ4	100	100	100	100				
Gelic soil units	SPR	No	No	No	No					SQ3	100	100	100	100				
Vertic soil units and vertisols	SPR/VSP	No	No	No	No					SQ3, SQ7	100	100	100	100				
Petric soil units	SPR	No	No	No	No					SQ3, SQ7	100	100	100	100				
Soil profile characteristics		**Topsoil**				**Subsoil**					**Topsoil**				**Subsoil**			
Soil unit symbol (FAO 90)		**ACu**	**NTu**	**LXf**	**LPe**	**ACu**	**NTu**	**LXf**	**LPe**		**ACu**	**NTu**	**LXf**	**LPe**	**ACu**	**NTu**	**LXf**	**LPe**
USDA texture classification	SPR/TXT	SL	C	SCL	SL	SCL	Ch	SCL		SQ2	90	100	100	90	100	100	100	

									SQ3	100	100	100	100	100	90	100
									SQ7	100	100	100	100	100	100	100
Gravel content (%)	SPR/GRC	0	1	0	0	0	1	0	SQ3, SQ7	100	100	100	100	100	100	100
pH (H_2O)	pH	6.4	5.3	6.4	5.6	5.0	5.4	6.4	SQ2					50	70	100
CEC (clay) (cmol/kg)	CECclay	21	23	37	192	16	27	47	SQ2					100	100	100
CEC (soil) (cmol/kg)	CECsoil	9	20	15	38	7	20	18	SQ2	100	100	100	100			
Base saturation (%)	BS	79	27	80	56	32	29	82	SQ2	100	70	100	100	70	70	100
Calcium carbonate (% weight)	CCB	0	0	0	0	0	0	0	SQ6	100	100	100	100	100	100	100
Gypsum (% weight)	GYP	0	0	0	0	0	0	0	SQ6	100	100	100	100	100	100	100
Sodicity (ESP) (%)	ESP	1	1	1	1	1	1	2	SQ5	100	100	100	100	100	100	100
Salinity (ECe) (dS/m)	EC	0.1	0.0	0.0	0.0	0.0	0.0	0.0	SQ5	100	100	100	100	100	100	100

Soil quality				
Soil unit symbol (FAO 90)	**ACu**	**NTu**	**LXf**	**LPe**
$SQ2_{topsoil}$	90	70	100	90
$SQ2_{subsoil}$	45	63	100	n.a
$SQ2_{topsoil} = f_{SQ}$ (TXT, BS., CEC_{soil}) and $SQ2_{subsoil} = f_{SQ}$ (TXT, pH, BS, CEC_{clay})				
SQ2 Nutrient retention capacity	61	65	100	90
$SQ3_{topsoil}$	100	100	100	10
$SQ3_{subsoil}$	100	100	90	n.a
SQ3 = τ (RSD) × min [(τ (SPR), τ (SPH), τ (OSD)]				
SQ3 Rooting conditions	100	100	94	10
SQ4 = min[τ(DRG), τ(SPH)]				
SQ4 Oxygen availability	100	100	100	100
$SQ5_{topsoil}$	100	100	100	100
$SQ5_{subsoil}$	100	100	100	
SQ5 = min [τ (ESP) × τ(EC), τ(SPH)]				
SQ5 Presence of salinity and sodicity	100	100	100	100
$SQ6_{topsoil}$	100	100	100	100
$SQ6_{subsoil}$	100	100	100	
$SQ6_{topsoil/subsoil}$ = min[τ(CCB) × τ (GYP), τ(SPH)].				
SQ6 Presence of lime and gypsum	100	100	100	100
$SQ7_{topsoil}$	100	100	100	10
$SQ7_{subsoil}$	100	100	100	
SQ7 = f_{SQ}(τ(RSD), τ(GRC), τ(SPH), τ(TXT), τ(VSP))				

Procedures

HWSD v2.1: Extract for Soil Mapping Unit 27116 (near Ilonga Tanzania) - SOTWIS Coverage.

Soil characteristics ratings by soil quality: For *lowland rain-fed maize - high level inputs and management* (Sources: Annex 6.3 Soil characteristics ratings; Appendix 6.4 Soil texture ratings; Appendix 6.5 Soil drainage ratings, and Appendix 6.6 Soil phase ratings).

Soil quality: The procedures used to derive the soil qualities: (SQ1–7) from various combinations of soil characteristics are described below.

Let $(x_1,\ldots,x_m)$ be a vector of soil characteristics relevant for a particular soil quality SQ and $(\tau(x_1),\ldots,\tau(x_m))$ the vector of respective soil characteristics ratings, $0 \le \tau(x_j) \le 100$.

Further, let j_o denote the soil characteristics with the lowest rating such that: $\tau(x_{jo}) \le \tau(x_j)$, $j = 1,\ldots,m$.

Then we define soil quality SQ as a weighted sum of soil characteristics ratings, as follows:

$$SQ = f_{SQ}(x_1,\ldots,x_m) = \frac{\tau(x_{j_0}) + \frac{1}{m-1}\sum_{j\neq j_0}\tau(x_j)}{2}$$

- **SQ2 Nutrient retention capacity**: $SQ2_{topsoil} = f_{SQ}$ (TXT, BS., CEC_{soil}) and $SQ2_{subsoil} = f_{SQ}$ (TXT, pH, BS, CEC_{clay}).
- **SQ3 Rooting conditions:** SQ3 = τ (RSD) × min [(τ (SPR), τ (SPH), τ (OSD)] for topsoil and subsoil separately.
- **SQ4 Oxygen availability:** SQ4 = min[τ(DRG), τ(SPH)] for topsoil and subsoil combined.
- **SQ5 Presence of salinity and sodicity:** SQ5 = min [τ (ESP)* τ(EC), τ(SPH)] for topsoil and subsoil separately.
- **SQ6 Presence of lime and gypsum:** $SQ6_{topsoil/subsoil}$ = min[τ(CCB) × τ (GYP), τ(SPH)] for topsoil and subsoil separately.
- **SQ7 Workability (field management):** SQ7 = f_{SQ}(τ(RSD), τ(GRC), τ(SPH), τ(TXT), τ(VSP)) for topsoil and subsoil separately.

Combining topsoil and subsoil quality (SQ2, SQ3, SQ5, SQ6 and SQ7): Soil qualities are separately estimated for topsoil (0–30 cm) and subsoil (30–100 cm). In the case of maize, a rooting limit of 85 cm is taken for ACu, NTu, and LXf → subsoil thickness is

SQ7 Workability (field management)	100	100	100	10
Soil suitability rating				
Soil Unit Symbol (FAO 90)	**ACu**	**NTu**	**LXf**	**LPe**
SQ1 Nutrient availability				
SQ2 Nutrient retention capacity	61	65	100	90
SQ3 Rooting conditions	100	100	94	10
SQ4 Oxygen availability	100	100	100	100
SQ5 Presence of salinity and sodicity	100	100	100	100
SQ6 Presence of lime and gypsum	100	100	100	100
SQ7 Workability (field management)	100	100	100	10
SR_{high} = SQ2 × SQ3 × f_{SR}(SQ4, SQ5, SQ6, SQ7)				
Soil suitability rating	61	65	94	5
Occurrences (%) within SMU*	55	15	15	15

55cm and topsoil thickness 30 cm. The ratio topsoil-subsoil rating weights are therefore 35% and 65%. In LPe no subsoil occurs, (top)soil thickness is 30 cm (100%).

Combining soil qualities in soil unit suitability

The procedures used to derive the soil ratings for high levels of input and management from various combinations of soil qualities are as follows: *SR_{high} = SQ2 × SQ3 × f_{SR}(SQ4, SQ5, SQ6, SQ7)*

Let (SQ_1,….,SQ_m) be a vector of soil characteristics relevant for a particular soil rating SR and ($\tau(SQ_1)$,…, $\tau(SQ_m)$) the vector of respective soil quality value, $0 \le \tau(SQ_j) \le 100$.

Further, let j_o denote the soil quality with the lowest value such that: $\tau(SQ_{j_o}) \le \tau(SQ_j)$, j = 1,…,m.

Then we define f_{SR}, as follows:

$$f_{SR}(x_1, \dots, x_m) = \frac{\tau(SQ_{j_0}) + \frac{1}{m-1}\sum_{j \ne j_0} \tau(SQ_j)}{2}$$

*** OSD refers to Obstacle to Roots (ROO), Impermeable layer (IL) and Soil Water Regime limitations (SWR), occurring only in the ESDB coverage of HWSD, are not applicable to the example.*

Table A6-6.2 Example soil suitability assessment for rain-fed maize at low level of inputs

TROPICAL LOWLAND MAIZE (120 days) RAIN-FED, LOW INPUTS/TRADITIONAL MANAGEMENT										
HWSD v2.1						**Soil characteristics ratings by soil quality**				
Location	Tanzania, Ilonga									
Coverage	SOTWIS									
Soil mapping unit	27116									
Dominant soil group	AC - Acrisols									
Soil unit symbol (FAO 90)		ACu	NTu	LXf	LPe		**ACu**	**NTu**	**LXf**	**LPe**
Share of soil units in soil mapping unit (%)	SMU %	55	15	15	15					
Reference soil depth (cm)	RSD	100	100	100	30	SQ3, SQ7	100	100	100	10
Soil phase 1	SPH	No	No	No	No	SQ3, SQ4, SQ5, SQ6, SQ7	100	100	100	100
Soil phase 2	SPH	No	No	No	No	SQ3, SQ4, SQ5, SQ6, SQ7	100	100	100	100
Reference drainage class (0–0.5% slope)	DRG	MW	MW	MW	I	SQ4	100	100	100	90
Gelic soil units	SPR	No	No	No	No	SQ3	100	100	100	100
Vertic soil units and vertisols	SPR/VSP	No	No	No	No	SQ3, SQ7	100	100	100	100
Petric soil units	SPR	No	No	No	No	SQ3, SQ7	100	100	100	100

Soil profile characteristics		**Topsoil**				**Subsoil**					**Topsoil**				**Subsoil**			
Soil unit symbol (FAO 90)		**ACu**	**NTu**	**LXf**	**LPe**	**ACu**	**NTu**	**LXf**	**LPe**		**ACu**	**NTu**	**LXf**	**LPe**	**ACu**	**NTu**	**LXf**	**LPe**
USDA texture classification	SPR/TXT	SL	C	SCL	SL	SCL	Ch	SCL		SQ1	90	100	100	90	100	100	100	
										SQ3	100	100	100	100	100	90	100	
										SQ7	100	100	100	100	100	50	100	
Gravel content (%)	SPR/GRC	0	1	0	0	0	1	0		SQ3, SQ7	100	100	100	100	100	100	100	

Organic carbon (% weight)	OC	1.38	2.45	1.06	1.5	0.41	0.96	0.65	SQ1	100	100	90	100			
pH (H_2O)	pH	6.4	5.3	6.4	5.6	5.0	5.4	6.4	SQ1	100	50	100	70	30	50	100
TEB (cmol/kg)	TEB	7.1	5.4	12.0	21.3	2.2	5.8	14.8	SQ1	90	90	100	100	50	90	100
Calcium carbonate (% weight)	CCB	0	0	0	0	0	0	0	SQ6	100	100	100	100	100	100	100
Gypsum (% weight)	GYP	0	0	0	0	0	0	0	SQ6	100	100	100	100	100	100	100
Sodicity (ESP) (%)	ESP	1	1	1	1	1	1	2	SQ5	100	100	100	100	100	100	100
Salinity (ECe) (dS/m)	EC	0.1	0.0	0.0	0.0	0.0	0.0	0.0	SQ5	100	100	100	100	100	100	100

Soil quality				
Soil unit symbol (FAO 90)	**ACu**	**NTu**	**LXf**	**LPe**
$SQ1_{topsoil}$	87	48	90	68
$SQ1_{subsoil}$	23	48	100	
$SQ1_{topsoil}$ = f_{SQ} (TXT, OC, pH, TEB) and $SQ1_{subsoil}$ = f_{SQ} (TXT, pH, TEB)				
SQ1 Nutrient availability	45	48	97	68
$SQ3_{topsoil}$	100	100	90	10
$SQ3_{subsoil}$	100	90	90	
SQ3 = τ (RSD)*min [(τ (SPR), τ (SPH), τ (OSD)]				
OSD refers to Obstacle to Roots and Impermeable layer**				
SQ3 Rooting conditions	100	94	90	10
SQ4 = min [τ(DRG), τ(SPH)]				
SQ4 Oxygen availability	100	100	100	90
$SQ5_{topsoil}$	100	100	100	100
$SQ5_{subsoil}$	100	100	100	
SQ5 = min [τ (ESP)* τ(EC), τ(SPH)]				
SQ5 Presence of salinity and sodicity	100	100	100	100
$SQ6_{topsoil}$	100	100	100	100
$SQ6_{subsoil}$	100	100	100	
SQ6 = min [τ(CCB)*τ(GYP), τ(SPH)]				
SQ6 Presence of lime and gypsum	100	100	100	100
$SQ7_{topsoil}$	100	100	100	10
$SQ7_{subsoil}$	100	50	100	
SQ7 = f_{SQ} (τ(RSD), τ(GRC), τ(SPH), τ(TXT), τ(VSP))				
SQ7 Workability (field management)	100	100	100	10

Procedures

HWSD v2.1: Extract for Soil Mapping Unit 27116 (near Ilonga Tanzania) - SOTWIS Coverage.

Soil characteristics ratings by soil quality: For *lowland rain-fed maize - low level inputs and management* (Sources: Appendix 6.3 Soil characteristics ratings; Appendix 6.4 Soil texture ratings; Appendix 6.5 Soil drainage ratings, and Appendix 6.6 Soil phase ratings).

Soil quality: The procedures used to derive the soil qualities: (SQ1–7) from various combinations of soil characteristics are described below.

Let (x_1,....,x_m) be a vector of soil characteristics relevant for a particular soil quality SQ and (τ(x_1),..., τ(x_m)) the vector of respective soil characteristics ratings, 0 ≤ τ(x_j) ≤ 100.

Further, let j_o denote the soil characteristics with the lowest rating such that:

τ(x_{jo}) ≤ τ(x_j), j = 1,...,m.

Then we define soil quality SQ as a weighted sum of soil characteristics ratings, as follows:

$$SQ = f_{SQ}(x_1, \dots, x_m) = \frac{\tau(x_{j_0}) + \frac{1}{m-1}\sum_{j \neq j_0} \tau(x_j)}{2}$$

- **SQ1 Nutrient availability**: SQ1t_{opsoil} = f_{SQ} (TXT, OC, pH, TEB and $SQ1_{subsoil}$ = f_{SQ} (TXT, pH, TEB)
- **SQ3 Rooting conditions:** SQ3 = τ (RSD)*min [(τ (SPR), τ (SPH), τ (OSD)] for topsoil and subsoil separately.
- **SQ4 Oxygen availability:** SQ4 = min[τ(DRG), τ(SPH)] for topsoil and subsoil combined.
- **SQ5 Presence of salinity and sodicity:** SQ5 = min [τ (ESP)* τ(EC), τ(SPH)] for topsoil and subsoil separately.
- **SQ6 Presence of lime and gypsum:** $SQ6_{topsoil/subsoil}$ = min[τ(CCB)*τ (GYP), τ(SPH)] for topsoil and subsoil separately.
- **SQ7 Workability (field management):** SQ7 = f_{SQ}(τ(RSD), τ(GRC), τ(SPH), τ(TXT), τ(VSP)) for topsoil and subsoil separately.

Combining topsoil and subsoil quality (SQ2, SQ3, SQ5, SQ6 and SQ7): Soil qualities are separately estimated for topsoil (0–30 cm) and subsoil (30–100 cm). In the case of maize, a rooting limit of 85 cm is taken for ACu, NTu, and LXf → subsoil thickness is 55cm and topsoil

Soil suitability rating				
Soil unit symbol (FAO 90)	**ACu**	**NTu**	**LXf**	**LPe**
SQ1 Nutrient availability	45	48	97	68
SQ2 Nutrient retention capacity	n.a	n.a	n.a	n.a
SQ3 Rooting conditions	100	94	90	10
SQ4 Oxygen availability	100	100	100	90
SQ5 Presence of salinity and sodicity	100	100	100	100
SQ6 Presence of lime and gypsum	100	100	100	100
SQ7 Workability (field management)	100	68	100	10
SR_{low} = SQ1*SQ3*f_{SR}(SQ4, SQ5, SQ6, SQ7)				
Soil suitability rating	45	38	87	4
Occurrences (%) within SMU*	55	15	15	15

thickness 30 cm. The ratio topsoil-subsoil rating weights are therefore 35% and 65%. In LPe no subsoil occurs, (top)soil thickness is 30 cm (100%).

Combining soil qualities in soil unit suitability

The procedures used to derive the soil ratings for low levels of input and management from various combinations of soil qualities are as follows: *SR_{low} = SQ1*SQ3*f_{SR}(SQ4, SQ5, SQ6, SQ7)*

Let (SQ_1,….,SQ_m) be a vector of soil characteristics relevant for a particular soil rating SR and ($\tau(SQ_1)$,…, $\tau(SQ_m)$) the vector of respective soil quality value, $0 \le \tau(SQ_j) \le 100$.

Further, let j_o denote the soil quality with the lowest value such that: $\tau(SQ_{j_o}) \le \tau(SQ_j)$, j = 1,…,m.

Then we define f_{SR}, as follows:

$$f_{SR}(x_1, \dots, x_m) = \frac{\tau(SQ_{j_0}) + \frac{1}{m-1}\sum_{j \neq j_0} \tau(SQ_j)}{2}$$

*** OSD refers to Obstacle to Roots (ROO), Impermeable layer (IL) and Soil Water Regime limitations (SWR), occurring only in the ESDB coverage of HWSD, are not applicable to the example.*

27. Appendix 6-7 Available Soil Water Capacity (AWC) by soil group and by topsoil texture for FAO’90 and FAO’74 soil classifications

Table A6-7.1 Reference Available Soil Water Capacity (FAO’90) by topsoil texture

FAO'90 Soil units and miscellaneous units		AWC by topsoil texture (mm/m)			Reference soil depth (cm)
Symbol	Name	Coarse	Medium	Fine	
FL	FLUVISOLS	250	250	250	100
GL	GLEYSOLS	250	250	250	100
AC	ACRISOLS	146	162	157	100
AL	ALISOLS	146	162	157	100
AN	ANDOSOLS	200	200	200	100
AR	ARENOSOLS	106	180	165	100
ARo	Ferralic Arenosols	95	162	148	100
AT	ANTHROSOLS	200	200	200	100
ATc	Cumulic Anthrosols	250	250	250	100
CH	CHERNOZEMS	106	180	165	100
CHl	Luvic Chernozems	162	180	175	100
CL	CALCISOLS	106	180	165	100
CLl	Luvic Calcisols	162	180	175	100
CM	CAMBISOLS	106	180	165	100
CMo	Ferralic Cambisols	95	162	148	100
FR	FERRALSOLS	146	162	148	100
GR	GREYZEMS	106	180	165	100
GY	GYPSISOLS	106	180	165	100
GYl	Luvic Gypsisols	162	180	175	100
HS	HISTOSOLS	250	250	250	100
KS	KASTANOZEMS	106	180	165	100
KSl	Luvic Kastanozems	162	180	175	100
LP	LEPTOSOLS	106	180	165	30
LV	LUVISOLS	162	180	175	100
LVf	Ferric Luvisols	146	162	157	100
LX	LIXISOLS	146	162	157	100
NT	NITISOLS	146	162	157	100
PD	PODZOLUVISOLS	162	180	175	100

PH	PHAEOZEMS	106	180	165	100
PHl	Luvic Phaeozems	162	180	175	100
PL	PLANOSOLS	152	169	165	100
PT	PLINTHOSOLS	95	162	148	100
PZ	PODZOLS	106	180	165	100
PZf	Ferric Podzols	95	162	148	100
RG	REGOSOLS	106	180	165	100
SC	SOLONCHAKS	106	180	165	100
SN	SOLONETZ	106	180	165	100
VR	VERTISOLS	135	135	135	100
DS	Dunes & shift.sands	106	180	165	100
ST	Salt flats	106	180	165	100
HD	Human disturbed	106	180	165	100
MA	Marsh	250	250	250	100

AWC reference values by FAO'90 soil group and in addition lists values for soil units which deviate from the reference value of the soil group.

Table A6-7.2 Reference Available Soil Water Capacity (FAO'74) by topsoil texture

FAO'74 Soil units and miscellaneous units		AWC by topsoil texture (mm/m)			Reference soil depth (cm)
Symbol	Name	Coarse	Medium	Fine	
J	FLUVISOLS	250	250	250	100
G	GLEYSOLS	250	250	250	100
R	REGOSOLS	106	180	165	100
I	LITHOSOLS	106	180	165	10
Q	ARENOSOLS	106	180	165	100
Qf	Ferralic Arenosols	95	162	148	100
E	RENDZINAS	106	180	165	30
U	RANKERS	106	180	165	30
T	ANDOSOLS	200	200	200	100
V	VERTISOLS	135	135	135	100
Z	SOLONCHAKS	106	180	165	100
S	SOLONETZ	106	180	165	100
Y	YERMOSOLS	106	180	165	100
Yl	Luvic Yermosols	162	180	175	100
X	XEROSOLS	106	180	165	100
Xl	Luvic Xerosols	162	180	175	100
K	KASTANOZEMS	106	180	165	100
Kl	Luvic Kastanozems	162	180	175	100
C	CHERNOZEMS	106	180	165	100
Cl	Luvic Chernozems	162	180	175	100
H	PHAEOZEMS	106	180	165	100
Hl	Luvic Phaeozems	162	180	175	100
M	GREYZEMS	106	180	165	100

B	CAMBISOLS	106	180	165	100
Bf	Ferralic Cambisols	95	162	148	100
L	LUVISOLS	162	180	175	100
Lf	Ferric Luvisols	146	162	157	100
D	PODZOLUVISOLS	162	180	175	100
P	PODZOLS	106	180	165	100
Pf	Ferric Podzols	95	162	148	100
Pp	Placic Podzols	95	162	148	100
W	PLANOSOLS	152	169	165	100
A	ACRISOLS	146	162	157	100
N	NITOSOLS	146	162	157	100
F	FERRALSOLS	146	162	148	100
O	HISTOSOLS	250	250	250	100
DS	DUNES/SHIFTING SANDS	106	180	165	100
ST	SALT FLATS	106	180	165	100
DU	DUNES	106	180	165	100

AWC reference values by FAO'74 soil group and in addition lists values for soil units which deviate from the reference value of the soil group.

28. Appendix 6-8 Terrain slope ratings

Table A6-8.1 Terrain-slope ratings for rain-fed, sprinkler and drip irrigation systems

Crop groups	INPUT LEVEL	Basic rating								Modifier rating (no modifications for terrain slopes < 5%)																								
		FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1	High	S1	S1	S1	S1	S1/S2	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 2		S1	S1	S1	S1	S1/S2	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 3		S1	S1	S1/S2	S2/N	N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1	S2/N	N	N	N
Perennials 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 2		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 3		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 4		S1	S1	S1	S1	S1	S2	N	N	S1	S1	S1	N	N	S1	S1	S1	N	N	S1	S1	S1/S2	N	N	S1	S1	S2	N	N	S1	S1/S2	S2/N	N	N
Perennials 5		S1	S1	S1	S1	S1/S2	N	N	N	S1	S1	S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	N

Crop groups	INPUT LEVEL	FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1	Intermediate	S1	S1	S1	S1	S1	S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 2		S1	S1	S1	S1	S1/S2	S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 3		S1	S1	S1/S2	S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1	S2/N	N	N	N
Perennials 1		S1	S1	S1	S1/S2	S2	S2/N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 2		S1	S1	S1	S1	S1	S1/S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 3		S1	S1	S1	S1	S1	S1/S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 4		S1	S1	S1	S1	S1	S1/S2	S2/N	N	S1	S1	S1	S1/S2	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2/N	N	S1	S1	S2/N	N	N
Perennials 5		S1	S1	S1	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	S2/N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	N

Crop groups	INPUT LEVEL	FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1	Low	S1	S1	S1	S1	S1	S1/S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 2		S1	S1	S1	S1	S1	S1/S2	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 3		S1	S1	S1	S1/S2	S2	S2/N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 1		S1	S1	S1	S1/S2	S2	S2/N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 2		S1	S1	S1	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 3		S1	S1	S1	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 4		S1	S1	S1	S1	S1	S1	S1	S1/N	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1/S2	S1	S1	S1	S1/S2	S2/N	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	S2/N	N
Perennials 5		S1	S1	S1	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	S2/N	N	S1.	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	N

Crop groups

- Annuals 1: wheat, barley, rye, oat
- Annuals 2: dryland rice, maize, sorghum, pearl millet, foxtail millet, buckwheat, white potato, sweet potato, white yam, greater yams, sugar beet, phaseolus bean, chickpea, cowpea, dry pea, gram, pigeon pea, groundnut, soybean, sunflower, rape, cabbage, carrot, onion, tomato, cotton, flax, tobacco
- Annuals 3: wetland rice
- Perennials 1: sugar cane, cassava
- Perennials 2: olive, citrus
- Perennials 3: yellow yam, cocoyam, oil palm, banana/plantain, coconut, cocoa, coffee, jatropha
- Perennials 4: pasture legumes, grasses, tea
- Perennials 5: alfalfa, napier grass, miscanthus, switchgrass, reed canary grass
- Forest: para rubber

Terrain slope rating

- S1: Optimum conditions - No change to agro-climatic suitability which is expressed expressed in VS, S, MS, mS and N classes
- S2: Sub-optimum conditions - Downgrading 100% of extent of agro-climatic suitability class by one class (e,g., VS → S)
- S1/S2: 50% optimum and 50% sub-optimum conditions - Downgrading of 50% of the extent of agro-climatic suitability classes by one class and 50% remains unchanged
- S1/N: 50% optimum and 50% not suitable conditions - Downgrading of 50% of the extent of agro-climatic suitability classes to not suitable and 50% remains unchanged
- S2/N: 50% sub-optimum and 50% not suitable conditions - Downgrading of 50% of the extent of agro-climatic suitability classes by one class and 50% to not suitable (N)
- N: Not suitable conditions - Downgrading 100% of extent of agro-climatic suitability to not suitable (N)

Table A6-8.2 Terrain-slope ratings for gravity irrigation

Crop groups	INPUT LEVEL	Basic rating								Modifier rating (no modifications for terrain slopes < 5%)																								
		FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 2		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 3		S1	S1	S1/S2	S2/N	N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1	S2/N	N	N	N
Perennials 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	N	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 2	High	S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 3		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 4		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1	N	N	S1	S1	S1	N	N	S1	S1.	S1/S2	N	N	S1	S1	S2	N	N	S1	S1/S2	S2/N	N	N
Perennials 5		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	N

Crop groups	INPUT LEVEL	FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Annuals 2		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Annuals 3		S1	S1	S1/S2	S2/N	N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1	S2/N	N	N	S1
Perennials 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Perennials 2	Intermediate	S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Perennials 3		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2/N	N	N	S1	S2	N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Perennials 4		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1	S1/S2	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2/N	N	S1	S1	S2/N	N	S1
Perennials 5		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1/S2	S2/N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	S1
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	S1

Crop groups	INPUT LEVEL	FM class <1300 (%)								FM class 1300–1800 (%)					FM class 1800–2200 (%)					FM class 2200–2500 (%)					FM class 2500–2700 (%)					FM class > 2700 (%)				
		0–0.5	0.5–2	2–5	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45	5–8	8–16	16–30	30–45	>45
Annuals 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 2		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Annuals 3		S1	S1	S1/S2	S2/N	N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 1		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 2	Low	S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 3		S1	S1	S1	S1/S2	S2/N	N	N	N	S1	S1	S1/S2	N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Perennials 4		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	S1/S2	S1	S1	S1	S1/S2	S2/N	S1	S1	S1/S2	S2/N	N	S1	S1	S1/S2	S2/N	N
Perennials 5		S1	S1	S1	S1	S1/S2	S2/N	N	N	S1	S1	S1/S2	S2/N	N	S1	S1/S2	S2	N	N	S1	S2	S2/N	N	N	S1	S2/N	N	N	N	S1/S2	S2/N	N	N	N
Forest		S1	S1	S1	S1	S1	S1	S1/S2	N	S1	S1	S1	S1	S1	S1	S1	S1	S1	N	S1	S1	S1	S1/S2	N	S1	S1	S1/S2	S2	N	S1	S1	S2	S2	N

Crop groups

- Annuals 1: wheat, barley, rye, oat
- Annuals 2: dryland rice, maize, sorghum, pearl millet, foxtail millet, buckwheat, dryland rice, white potato, sweet potato, white yam, greater yams, sugar beet, phaseolus bean, chickpea, cowpea, dry pea, gram, pigeon pea, groundnut, soybean, sunflower, rape, cabbage, carrot, onion, tomato, cotton, flax, tobacco
- Annuals 3: wetland rice
- Perennials 1: sugar cane, cassava
- Perennials 2: olive, citrus
- Perennials 3: yellow yam, cocoyam, oil palm, banana/plantain, coconut, cocoa, coffee, jatropha
- Perennials 4: pasture legumes, grasses, tea
- Perennials 5: alfalfa, napier grass, miscanthus, switchgrass, reed canary grass
- Forest: para rubber

Terrain slope rating

- S1: Optimum conditions - No change to agro-climatic suitability which is expressed expressed in VS, S, MS, mS and N classes
- S2: Sub-optimum conditions - Downgrading 100% of extent of agro-climatic suitability class by one class (e,g., VS → S)
- S1/S2: 50% optimum and 50% sub-optimum conditions - Downgrading of 50% of the extent of agro-climatic suitability classes by one class and 50% remains unchanged
- S1/N: 50% optimum and 50% not suitable conditions - Downgrading of 50% of the extent of agro-climatic suitability classes to not suitable and 50% remains unchanged
- S2/N: 50% sub-optimum and 50% not suitable conditions - Downgrading of 50% of the extent of agro-climatic suitability classes by one class and 50% to not suitable (N)
- N: Not suitable conditions - Downgrading 100% of extent of agro-climatic suitability to not suitable (N)

29. Appendix 6-9 Suitability of water-collecting sites

In water-collecting sites substantially more water can be available to plants as compared to upland situations. Water-collecting sites are difficult to locate in a global study but can be approximately determined for prevalence of specific soil types. Fluvisols[22] and to a lesser extent Gleysols[23] are typically representing the flat terrain of alluvial valleys and other water-collecting sites[24]. The moisture suitability ratings devised for unprotected Fluvisols and Gleysols without artificial drainage are organized in ten groups of crops with comparable growth cycle lengths and similar tolerances to high groundwater levels, waterlogging and flooding. The rating tables are presented below

Short-term dry-land crops (I)

This group includes some short duration crops (wheat, barley, rye, oat, dryland rice, foxtail millet, chickpea, rape, and alfalfa) which are somewhat tolerant to excess moisture. For LGPs less than 30 days it is assumed there is on the average insufficient water to bring these crops to maturation and yield, especially since the contribution from rainfall is also almost non-existent. At LGPs longer than 120 days these crops will grow irrespective additional water. It has been assumed that the Fluvisols are too wet in LGPs over 300 days. Most of these crops are marginal or not suitable in humid areas. Agro-climatic constraints alone will render these long LGPs already marginal to not suitable.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS						33	33	33	33	33	33				
S					33										
MS				33		33	33	33	33	33	33				
mS			33		33										
NS	100	100	67	67	34	34	34	34	34	34	34	100	100	100	100

22: Fluvisols are by definition flooded by rivers. Fluvisols are young soils where sedimentary structures are clearly recognizable in the soil profile.
23: Gleysols are generally not flooded by rivers. However, the soil profiles indicate regular occurrence of high groundwater tables through reduction (gley) features. Low-lying Gleysols may be ponded/water-logged by high groundwater and rainfall during the rainy season.
24: Histosols are partly occurring in water collecting sites as well. When reclaimed, including artificial drainage and after mixing the histic topsoil with underlying mineral materials, Histosols may be turned in very productive soils for intensive forms of arable cropping/horticulture (Driessen and Dudal, 1991). Draining and reclaiming poorly drained Histosols is not recommended because they serve as important habitat for wetland ecosystems and are significant carbon reservoirs. Unreclaimed natural Histosols, due to low bearing capacities of upper histic horizon (bulk density < 0.1 Mg/m3), generally poor drainage conditions and other unfavorable chemical and physical characteristics, are considered unfit to permit its use for arable purposes and therefore rendering possibilities of benefitting from additional water resources in water collecting sites irrelevant.

Short-term dry-land crops (II)

The crops in this group (sorghum, pearl millet, buckwheat, sweet sorghum, cowpea) have either a shorter duration than Group I (pearl millet and cowpea) or tolerance to both drought as well as to excess water (sorghum). Therefore, some parts of the Fluvisols in 1–29 days growing periods some modest yield may be expected (though not in all years). At the wet end of the LGPs these crops are treated similarly to Group I.

Suitability class	Percentage of water-collecting sites suitable per LGP class													
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS					33	33	33	33	33	33	33				
S				33											
MS			33		33	33	33	33	33	33	33				
mS		33		33											
NS	100	67	67	34	34	34	34	34	34	34	34	100	100	100	100

Short-term dry-land crops (III)

The crops in Group III include maize, phaseolus bean, soybean, gram, dry pea, pigeon pea, tobacco and sunflower. They are more sensitive to excess water (especially waterlogging) than Group I and II crops. Therefore, they are not considered to be suitable in areas where LGP exceeds 270 days. Their water requirements are similar or somewhat higher than Group I.

Suitability class	Percentage of water-collecting sites suitable per LGP class													
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS						33	33	33	33						
S					33										
MS				33		33	33	33	33	33					
mS			33		33										
NS	100	100	67	67	34	34	34	34	34	67	100	100	100	100	100

Short-term dry-land crops (IV)

Root crops (white potato, sweet potato, sugar beet) are all sensitive to high groundwater levels and waterlogging. Cotton, flax, groundnut, cabbage, carrot, onion and tomato are also very sensitive to excess moisture. These crops can only be grown on the rarely flooded parts of the Fluvisols, provided they are well drained. Apart from groundnut the growth cycles of the crops in this group are slightly longer than the crops in Group I-III. This makes crops in Group IV slightly more vulnerable.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	**1–29**	**30–59**	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365-**	**365+**
VS															
S															
MS						33	33	33	33						
mS					33	33	33	33	33	33					
NS	100	100	100	100	67	34	34	34	34	67	100	100	100	100	100

Wetland rice (V)

Wetland Rice is difficult to grow under rainfed conditions. Particularly, water management is problematic. Yields obtained from purely rainfed paddy is generally low. 2–3 t/ha is already good. Flood water supply comes in the semiarid areas in an erratic fashion; too little too late or too much too soon. In the sub-humid and humid areas, the flood hazard makes management difficult (submerging and flood damage by flowing water). LGPs less than 150 days have been considered insufficient to obtain yield. Very long LGPs are assumed to be associated with high flood risks (submerging, flowing water, high water levels during maturing and harvest).

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	**1–29**	**30–59**	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365-**	**365+**
VS															
S								33	33	33					
MS							33				33	33	33		
mS						33								33	
NS	100	100	100	100	100	67	67	67	67	67	67	67	67	67	100

Cassava, citrus, coffee, jatropha, yam and cocoyam (VI)

Cassava, citrus, coffee, jatropha, and yam are preferably *not grown* on Fluvisols because of its sensitivity for excessive wetness in the soil. On the higher parts of Fluvisols short duration cassava can be found (e.g., LGP of 180–270 days in Ghana). Since cassava is not really benefiting from extra moisture, the best LGPs are those, where also rainfed cassava would do reasonably well. Towards the wetter end of the LGPs (more than 240–270 days) cassava is not anymore to be considered on Fluvisols.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	**1–29**	**30–59**	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365-**	**365+**
VS															
S															
MS								33	33						
mS							33			33					
NS	100	100	100	100	100	100	67	67	67	67	100	100	100	100	100

Sugar cane, napier grass, miscanthus and switch grass (VII)

Sugar cane, napier grass, miscanthus and switch grass are tolerant to flooding and waterlogging (e.g., see FAO-UNDP, 1988). The water from rainfall and whatever comes from the Fluvisols must meet full crop water requirements for 8 to 9 months. It is assumed that the contribution through additional water from Fluvisols sufficiently extends the growing period starting from LGP 180– 210 days onwards. At harvest presence of excess moisture is less favorable for both yield and management of the crop. There need be a predictable period during which the Fluvisol environment provides at least 2 months of dryer conditions.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	**1–29**	**30–59**	**60–89**	**90–119**	**120–149**	**150–179**	**180–209**	**210–239**	**240–269**	**270–299**	**300–329**	**330–364**	**365-**	**365+**
VS															
S										33	33				
MS									33			33			
mS								33							
NS	100	100	100	100	100	100	100	67	67	67	67	67	100	100	100

Banana/plantain, oil palm, cocoa, para rubber, coconut and tea (VIII)

Banana/plantain, oil palm, cocoa, para rubber, coconut and tea prefer humid conditions. Banana is somewhat tolerant to waterlogging, oil palm somewhat less. High groundwater tables are not tolerated. Both perennials require at least eight months during which full water requirements are met. Fluvisols occurring in LGPs of more than 300 days are assumed to be associated with longer periods with high groundwater levels and are therefore unsuited for oil palm and banana/plantain.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS															
S															
MS								33	33	33					
mS							33				33				
NS	100	100	100	100	100	100	67	67	67	67	67	100	100	100	100

Natural pastures and reed canary grass (IX)

Natural pastures (pasture legumes and grasses) and reed canary grass are well adapted to wet conditions. Normally the species mix is fine-tuned to the environmental conditions. Artificial (sown) pastures might grow unevenly on Fluvisols depending on both local differences of soil fertility and water supply. The total period of water availability on Fluvisols can be considered an adequate measure of the productivity regarding pastures (of course, periods of waterlogging, flooding and inundation are to be subtracted).

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS						33	33	33	67	67	67	33			
S				33	33		33	33	33	33	33		33		
MS			33		33	33		34				33		33	
mS		33		33			34						33	33	33
NS	100	67	67	34	34	34						34	34	34	67

Olives (X)

Olives tolerate neither high groundwater tables nor waterlogging, flooding or inundation. Therefore, olives are not considered for cultivation on Fluvisols.

Suitability class	Percentage of water-collecting sites suitable per LGP class														
	0	1–29	30–59	60–89	90–119	120–149	150–179	180–209	210–239	240–269	270–299	300–329	330–364	365-	365+
VS															
S															
MS															
mS															
NS	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

30. Appendix 6-10 Fallow period requirements

The fallow factors have been established by main crop groups and environmental conditions. The crop groups include cereals, legumes, roots and tubers, and a miscellaneous group consisting of long-term annuals/perennials. The environmental frame consists of individual soil units, thermal regimes and moisture regimes. The thermal regimes are expressed in terms of annual mean temperatures of > 25°C, 20–25°C, 15–20°C and <15°C for tropical climates and temperatures during the hottest month (>20°C or <20°C) for seasonal climates. The moisture regimes are expressed in terms of five broad LGP ranges <60 days, 60–120 days, 120–180 days, 180–270 days, and > 270 days. The fallow factors are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow.

Crop groups

1. Cereals, vegetables, cotton, flax and tobacco, wheat, (wetland rice), dryland rice, maize, barley, sorghum, rye, pearl millet, foxtail millet, oat, buckwheat and cabbage, carrot, onion, tomato as well as cotton, flax and tobacco
2. Legumes + sunflower and rape, phaseolus bean, chickpea, cowpea, dry pea, gram, pigeonpea, groundnut, soybean, and sunflower and rape
3. Roots and Tubers, white potato, sweet patato, cassva, yam and sugar beet
4. Perennials, sugar cane and banana/plantain

Exceptions to the above are:

- For Fluvisols and Gleysols fallow factors are set lower because of their special moisture and fertility conditions.
    - i. For wetland rice on Fluvisols, fallow requirements for all three input levels are set to 10%;
    - ii. For wetland rice on Gleysols, at high and intermediate inputs the fallow requirements are set to 10 % and at low inputs to 20%; and
    - iii. For wetland rice on soils other than Fluvisols and Gleysols, fallow requirements are set as for crop group 1 (cereals).
- Fallow requirements have been assumed to be negligible for the perennial crops oilpalm, olive, citrus, cocoa, tea, coffee, jatropha, coconut, para rubber, miscanthus, switchgrass, reed canary grass and alfalfa. For these perennials, no fallow requirements have been set.

Table A6-10.1 Fallow requirements (%) for low input farming for FAO74 Soil Units

FAO 1974 soil units	**Crop groups**	**Temperature regime**																			
		Tropical climates annual Ta >25^{0}C					**Tropical climates annual Ta 20–25^{0}C**					**Tropical climates: annual Ta 15–20^{0}C** / **Seasonal climates: Ta hottest month > 20^{0}C**					**Tropical climates: annual Ta <15^{0}C** / **Seasonal climates: Ta hottest month <20^{0}C**				
		Length of growing period (days)					**Length of growing period (days)**					**Length of growing period (days)**					**Length of growing period (days)**				
		<60	**60–120**	**120–180**	**180–270**	**<270**	**<60**	**60–120**	**120–180**	**180–270**	**<270**	**<60**	**60–120**	**120–180**	**180–270**	**<270**	**<60**	**60–120**	**120–180**	**180–270**	**<270**
G, Ge, Gc, Gm,Gh	1	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	2	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	3	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	4	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
Gd, Gp, Gx, Rd, Rx, I, Qf,Qa, U, Tv, Xy, Lp, Wd, Ws, Wx, Ap, Fa, Fp, O, Oe, Od, Ox.	1	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	2	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
R, Re, Rc,E , Tm, Th, V, Vp, Vc, K, Kh, Kk, Kl, C, Ch, Ck Cl, Cg, H, Hh, Hc, Hl, Hg, M, Mo, Mg, B, Be, Bh, Bg,Bx, Bk, Bc,, Bv, L, Lo, Lc, Lk, Lv, Lg, Wh, Ah, N, Ne, Nh, Fh	1	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	2	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	3	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	4	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
Q, Ql, Bf.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
Qc.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	80
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	80
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90

FAO 1974 soil units	Crop groups	Temperature regime																			
		Tropical climates annual Ta >25^{0}C					Tropical climates annual Ta 20–25^{0}C					Tropical climates: annual Ta 15–20^{0}C Seasonal climates: Ta hottest month > 20^{0}C					Tropical climates: annual Ta <15^{0}C Seasonal climates: Ta hottest month <20^{0}C				
		Length of growing period (days)					Length of growing period (days)					Length of growing period (days)					Length of growing period (days)				
		<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270
T, To, Bd, Lf,La, Dd, Dg, P, Po, Pl, Pf, Ph,Pg, W, We, Wm A, Ao, Af, Ag, Nd, F, Fo, Fx, Fr, Jd, Jt.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	3	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	4	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
Z, Zo, Zm, Zt, Zg, S, So, Sm, Sg, Y, Yh, Yk, Yy, Yl, Yt	1	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	2	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	3	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	4	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
X, Xh, Xk, Xl.	1	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	2	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	3	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
D, De.	1	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	2	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	3	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	4	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
J, Je, Jc.	1	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	2	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	3	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	4	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30

Ta = mean temperature. Crop groups: 1 = Cereals, 2 = Legumes, 3 = Roots and Tubers, 4= Perennials.

Table A6-10.2 Fallow requirements (%) for low input farming for FAO'90 Soil Units

FAO 1974 soil units	Crop groups	Temperature regime																			
		Tropical climates annual Ta >25^{0}C					Tropical climates annual Ta 20–25^{0}C					Tropical climates: annual Ta 15–20^{0}C					Tropical climates: annual Ta <15^{0}C				
												Seasonal climates: max. Ta > 20^{0}C					Seasonal climates: max. Ta <20^{0}C				
		Length of growing period (days)					Length of growing period (days)					Length of growing period (days)					Length of growing period (days)				
		<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270
FL, Fle, FLc, FLm, FLu, FLs.	1	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	2	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	3	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
	4	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
FLd, FLt, AC, ACh, ACf, Acg, AL, ALh, ALf, ALj, Alg, AN, ANh, ANg, ANi, CMd, FR, FRh, FRx, FRr, Fru, LVf, LVa, LXf, LXa, PDd, PDj, PDg, PL, PLe, PLm, Pli, PT, Pte, PZ,PZh, PZb, PZf, PZc, PZg, PZi, VRd.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	3	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	4	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
GL, GLe, GLk, GLa, GLm, Glu, LXp.	1	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	2	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	3	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
	4	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40	40
GLd, GLt, GLi, ACp, ALp, ANz, ARo, Ara, FRg, FRp, HS, HSl, HSs, HSf, HSt, HSi, LPd, LPu, LPq, PLd, PTd, PTu, PTa, RGd, RGi.	1	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	2	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90

FAO 1974 soil units	Crop groups	Temperature regime																			
		Tropical climates annual Ta >25^{0}C					Tropical climates annual Ta 20–25^{0}C					Tropical climates: annual Ta 15–20^{0}C / Seasonal climates: max. Ta > 20^{0}C					Tropical climates: annual Ta <15^{0}C / Seasonal climates: max. Ta <20^{0}C				
		Length of growing period (days)					Length of growing period (days)					Length of growing period (days)					Length of growing period (days)				
		<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270	<60	60–120	120–180	180–270	<270
ACu, ALu, ANm, ANu, AT, ATa, ATc, ATf, ATu, CH, CHh, CHk, CHl, CHw, CHg, CL, CLh, CLl, CLp, CM, CMe, CMu, CMc, CMx, CMv, CMg, CMi, GR, GRh, GRg, GY, GYh, GYk, GYl, GYp, KS, KSh, KSl, KSk, KSy, LP, LPe, LPk, LPm, Lpi, LV, LVh, LVx, LVk, LVv, LVJ, LVg, LX, LXh, LXj, LXg, NT, NTh, NTr, NTu, PH, PHh, PHc, PHl, PHj, PHg, PLu, RG, RGe, RGc, RGy, RGu, VR, VRe, VRk, VRy.	1	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	2	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	3	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
	4	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	75
AR, ARh, Arl, CMo.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	85
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
ARb, ARc, ARg.	1	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	80
	2	85	80	75	75	85	80	75	70	70	80	80	75	70	70	80	85	80	75	75	80
	3	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
	4	90	85	80	80	90	85	80	75	75	85	85	80	75	75	85	90	85	80	80	90
PD, PDe, PDi.	1	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	2	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	3	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
	4	75	70	65	65	75	70	65	60	60	70	70	65	60	60	70	75	70	65	65	70
SC, SCh, SCm, SCg, SCk, SCn, SCi, SN, SNh,SNm, SNk, Sny, SNj, SNg.	1	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	2	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	3	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80
	4	80	75	70	70	80	75	70	65	65	75	75	70	65	65	75	80	75	70	70	80

Ta = mean temperature. Crop groups: 1 = Cereals, 2 = Legumes, 3 = Roots and Tubers, 4= Perennials.

31. Appendix 7-1 Suitability of major crops under historical climate

As mentioned in Chapter 7 when introducing outputs from Module V (Integration of climatic and edaphic evaluation), the agro-ecological suitability of crops is presented in maps showing results in terms of a few suitability classes. The mapped classes are based on the normalized suitability index *SI*:

$$SI = (90 \text{ x } VS + 70 \text{ x } S + 50 \text{ x } MS + 30 \text{ x } mS + 15 \text{ x } vmS + 0 \text{ x } NS)/0.9$$

where VS, S, …, NS are the area extents in a grid cell assessed as respectively very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS), very marginally suitable (vmS) and not suitable (NS); see class definition in Chapter 7-4.

The index can be calculated for an entire grid cell, as shown in the maps of type SI (for map types produced in Module V see Chapter 7, Table 7-4), and for the share of each grid cell indicated as cropland, map type SC, assuming that crop cultivation in a grid cell would first occupy the available better rated soil/terrain conditions.

In this Appendix we show for historical climate conditions of period 1981–2010 the maps of agro-ecological suitability of major crops under rain-fed conditions and assumed high input/advanced management assumption. For wetland rice, which is very often cultivated under irrigation, maps are shown both for rain-fed conditions and assumed irrigation conditions. Table A7-1.1 provides a ranking of crops by global harvested areas extracted from FAOSTAT for the period 2009–2011.

Table A7-1.1 Major agricultural crops ranked by harvested area in 2009–2011

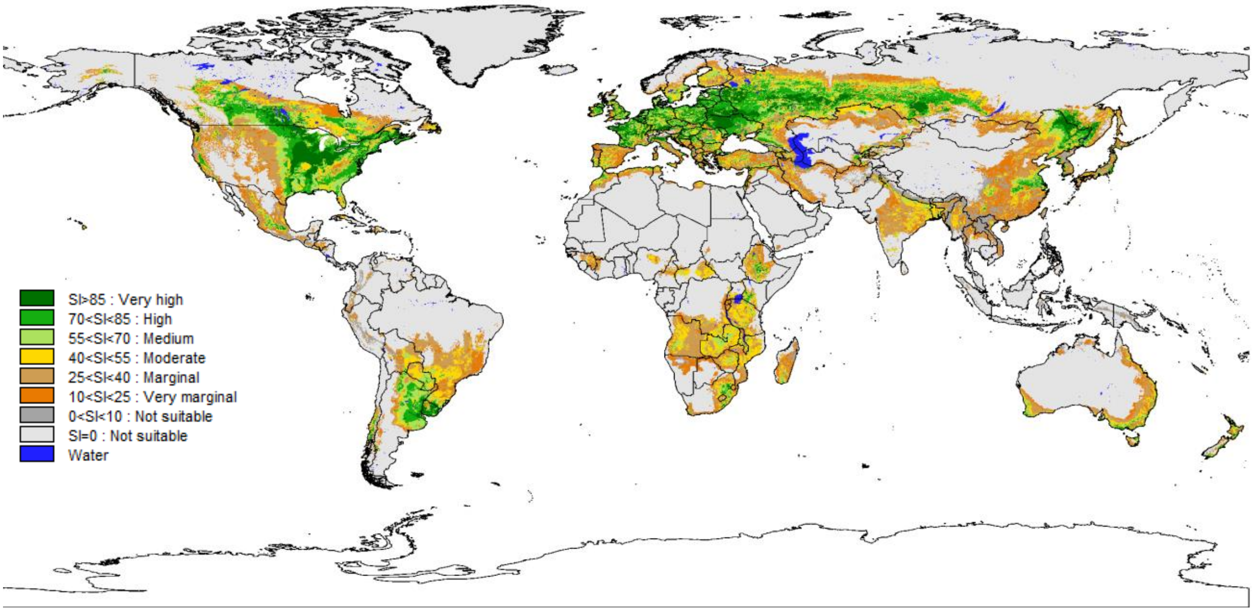
Crop	Harvested area (Mln ha)			Average
	2009	2010	2011	2009–11
Wheat	225.2	215.6	220.3	220.4
Maize	159.4	164.6	171.8	165.3
Rice, paddy	156.7	160.3	161.2	159.4
Soybeans	99.3	102.8	103.8	101.9
Barley	54.6	47.6	48.6	50.3
Sorghum	40.7	42.2	42.2	41.7
Millet	33.9	36.0	34.0	34.6
Rapeseed	31.6	32.1	33.8	32.5
Seed cotton	30.2	31.8	34.5	32.2
Beans, dry	25.7	31.0	30.7	29.1
Groundnuts	24.2	26.1	25.1	25.1

Sunflower seed	24.3	23.1	25.7	24.4
Sugar cane	23.7	23.6	25.5	24.3
Cassava	19.3	19.6	20.5	19.8
Oil palm	16.2	19.5	20.4	18.7
Potatoes	18.6	18.2	18.7	18.5

FAOSTAT, downloaded on 12 January 2021

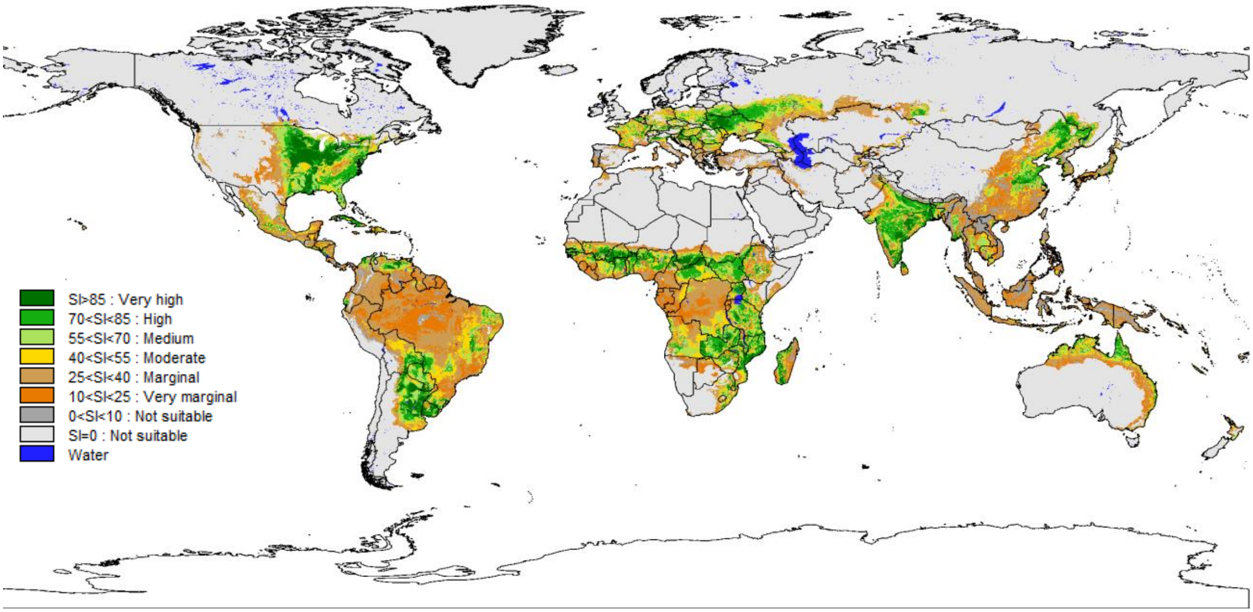
On the following pages maps of crop suitability are shown by rank of importance in cropland use, i.e., starting with wheat, followed by maize, etc., and ending with potatoes. Note, the crops listed in Table A7-1.1 and shown in the Appendix accounted for more than 75% of all harvested areas recorded in FAOSTAT for the period 2009–2011.

Figure A7-1.1 Suitability of rain-fed wheat, high inputs, climate of 1981–2010



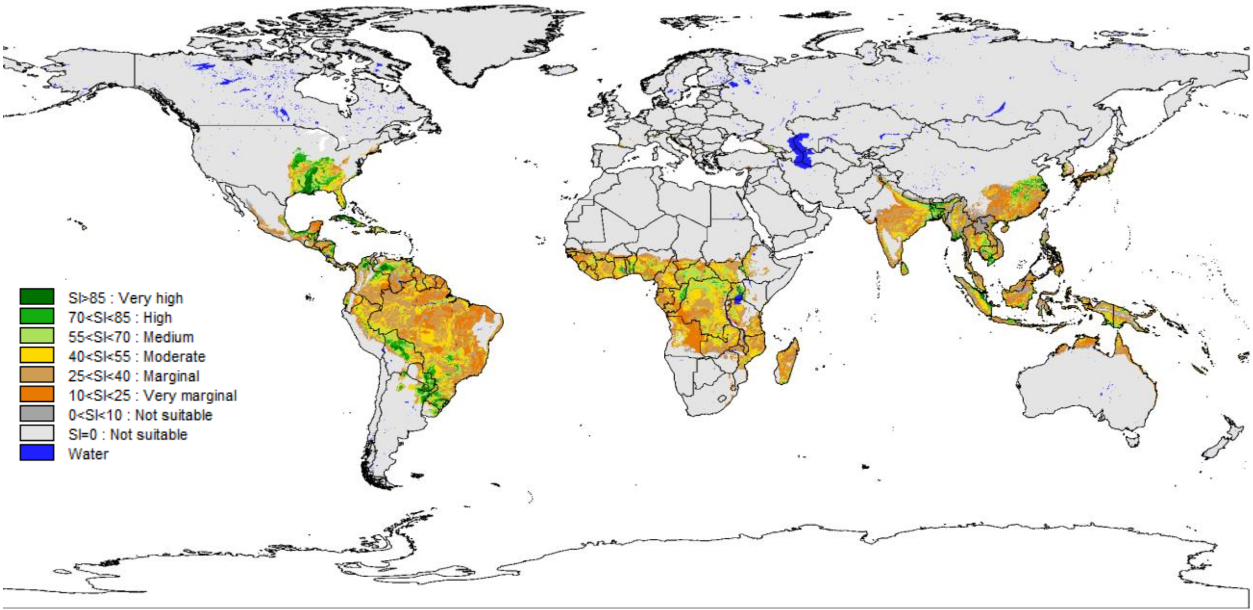
Source: FAO and IIASA, 2021

Figure A7-1.2 Suitability of rain-fed grain maize, high inputs, climate of 1981–2010



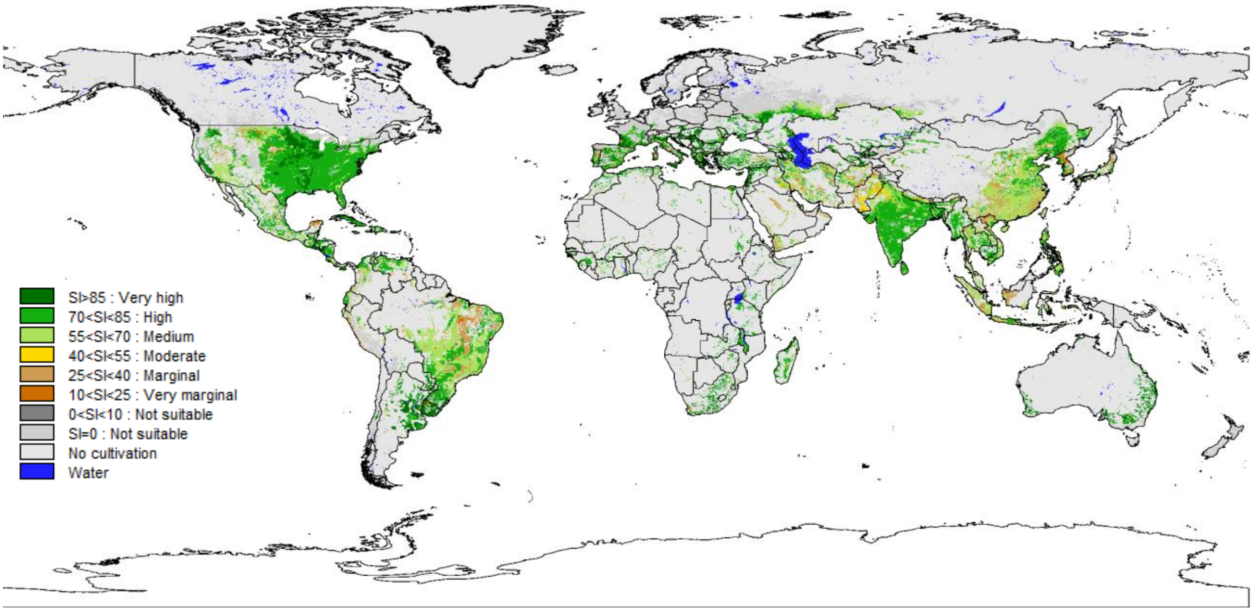
Source: FAO and IIASA, 2021

Figure A7-1.3 Suitability of rain-fed wetland rice, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

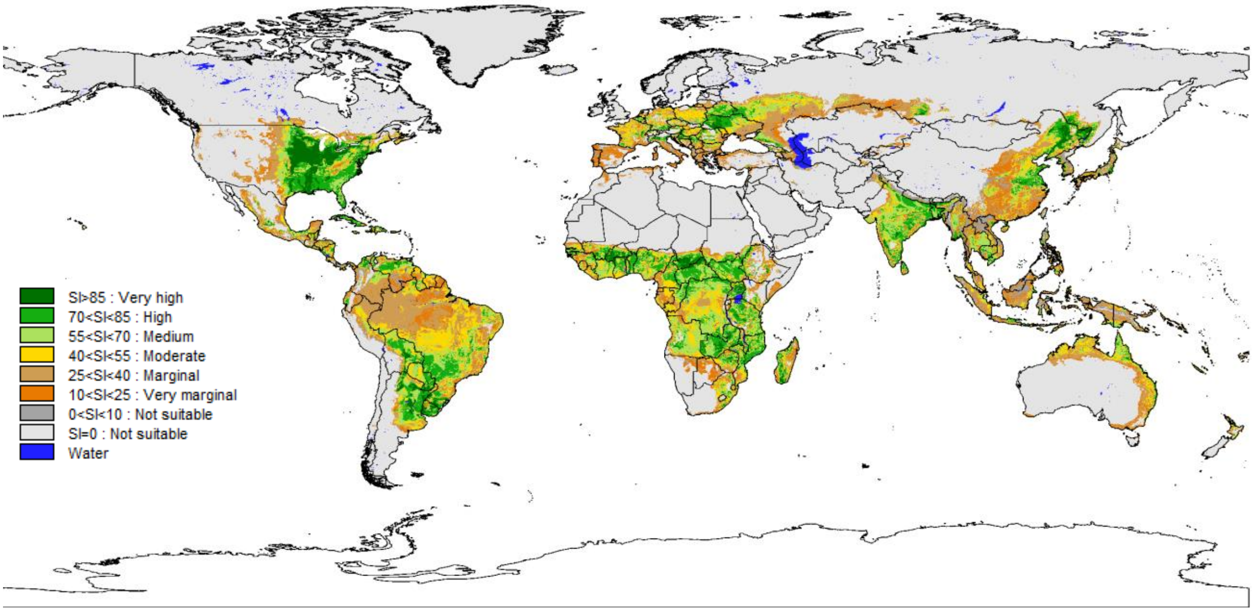
Figure A7-1.4 Suitability of irrigated wetland rice, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

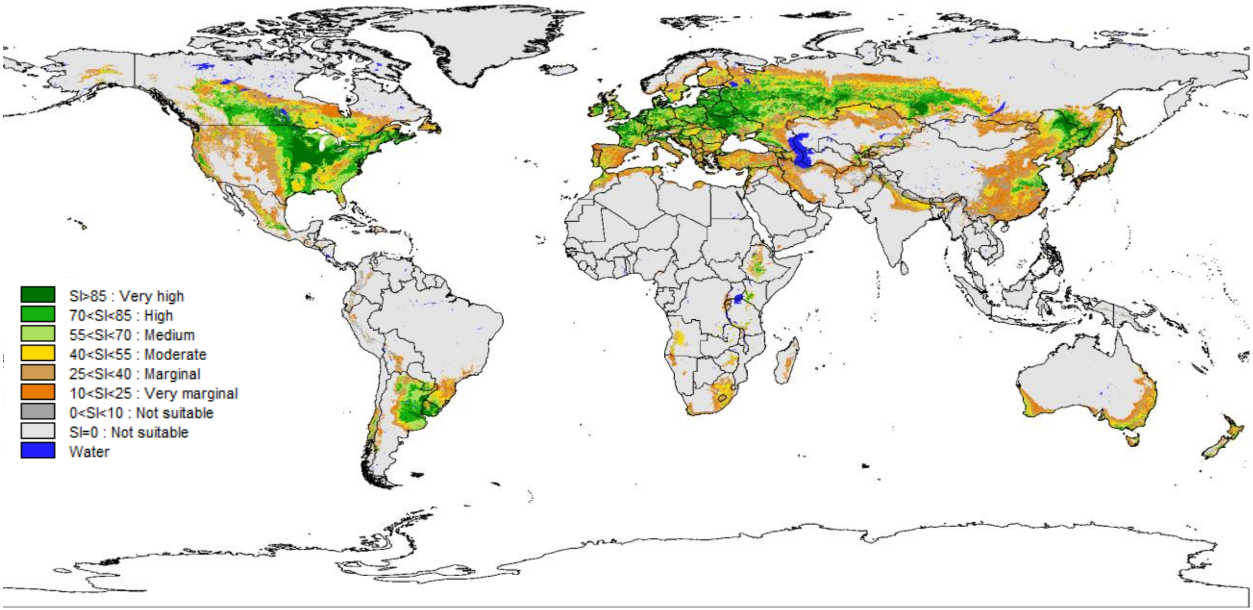
Suitability of wetland rice is shown here for grid cells with a cropland share > 0 and assuming irrigation conditions and a high level of inputs/advanced management. Both wetland rice maps show the results of the most producive rain-fed (Figure A7-1.3) respectively irrigated (Figure A7-1.4) simulated japonica or indica rice LUT.

Figure A7-1.5 Suitability of rain-fed soybeans, high inputs, climate of 1981–2010



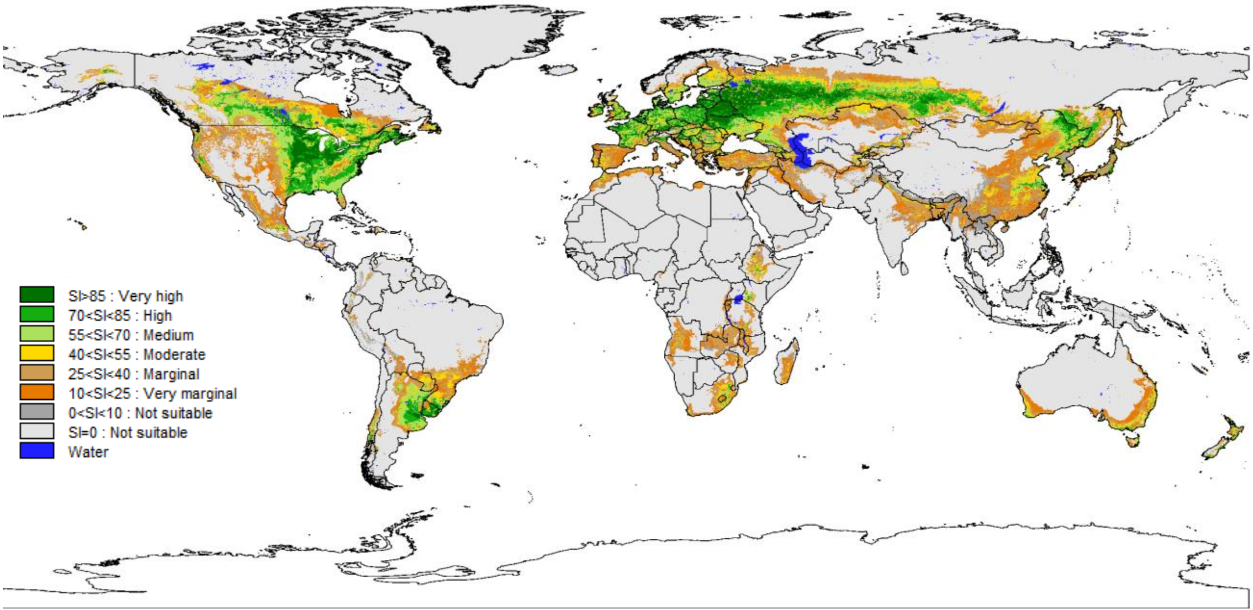
Source: FAO and IIASA, 2021

Figure A7-1.6 Suitability of rain-fed barley, high inputs, climate of 1981–2010



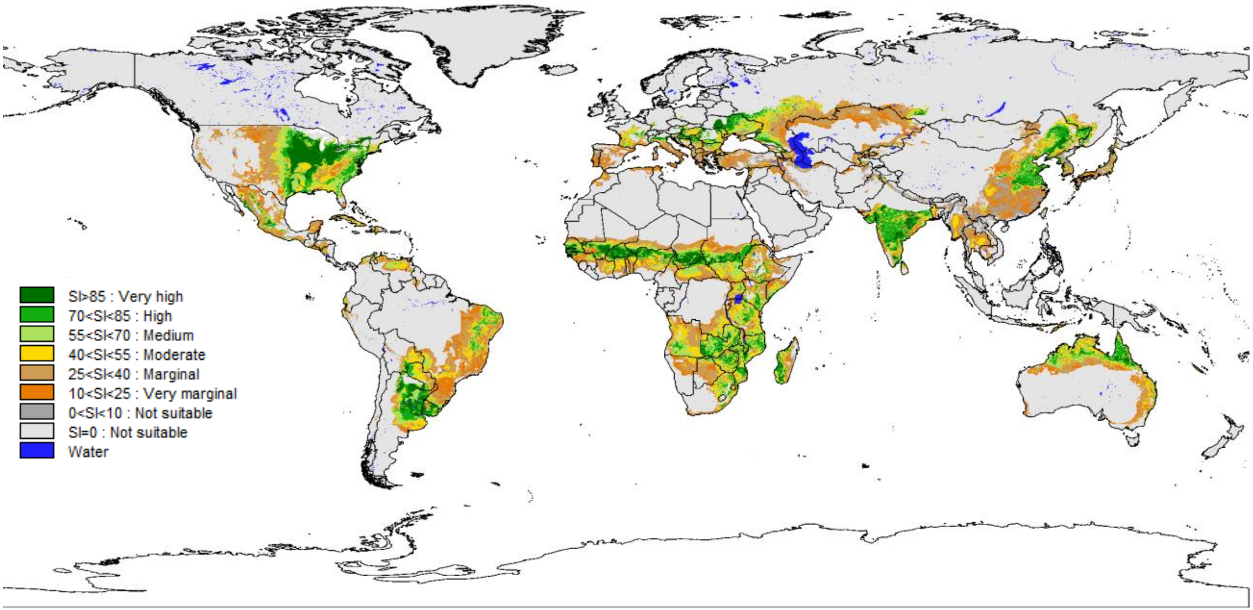
Source: FAO and IIASA, 2021

Figure A7-1.7 Suitability of rain-fed sorghum, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

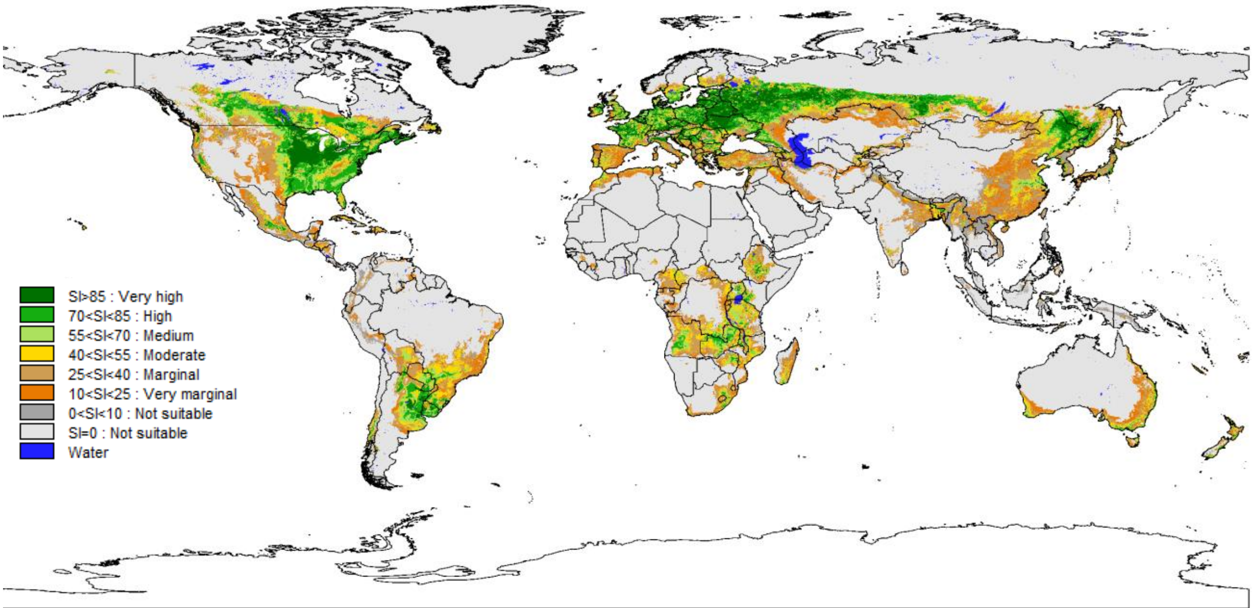
Figure A7-1.8 Suitability of rain-fed millet, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

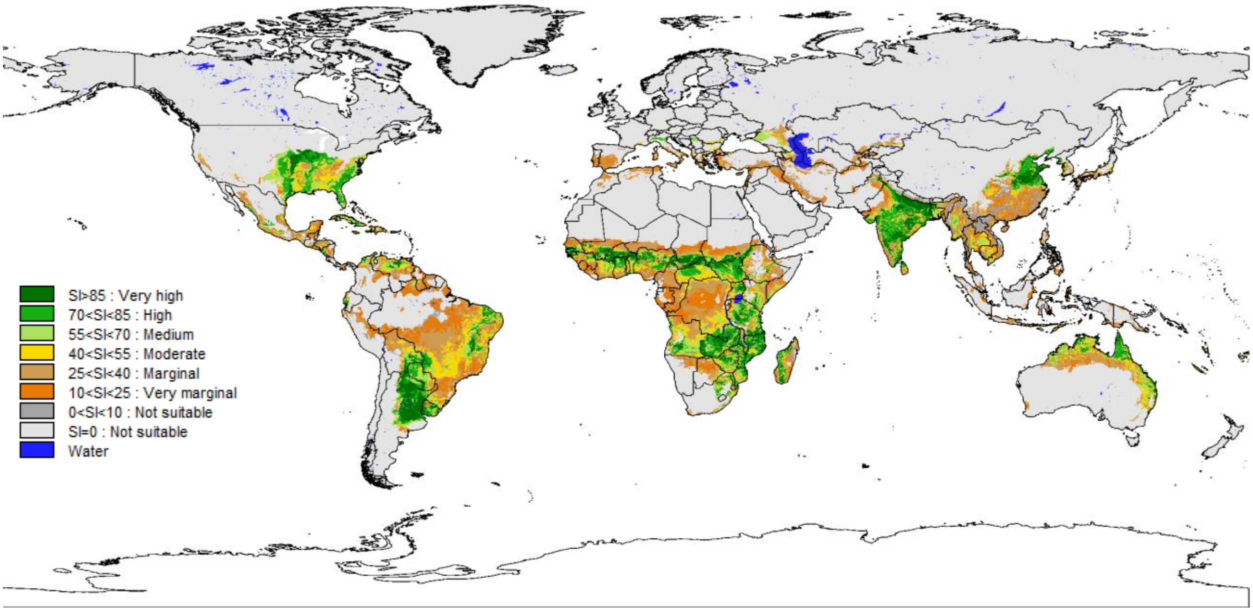
The suitability map shows the simulation results of the most productive rain-fed pearl millet (mostly in tropics) and foxtail millet (mainly in sub-tropics and moderate temperate climate) LUTs.

Figure A7-1.9 Suitability of rain-fed rapeseed, high inputs, climate of 1981–2010



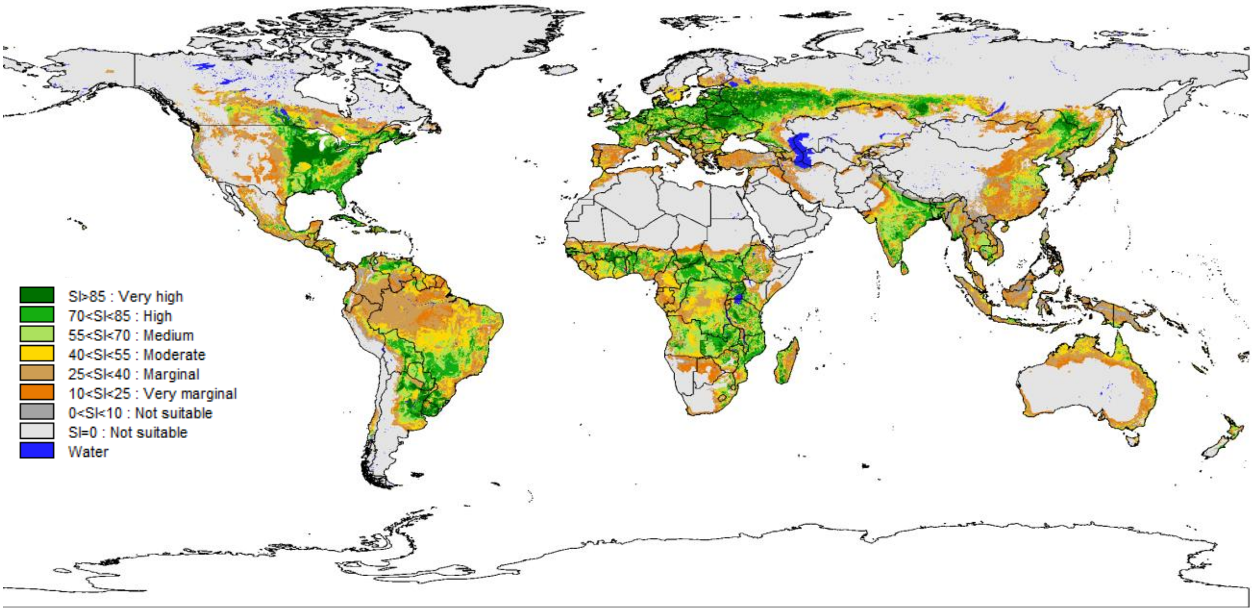
Source: FAO and IIASA, 2021

Figure A7-1.10 Suitability of rain-fed cotton, high inputs, climate of 1981–2010



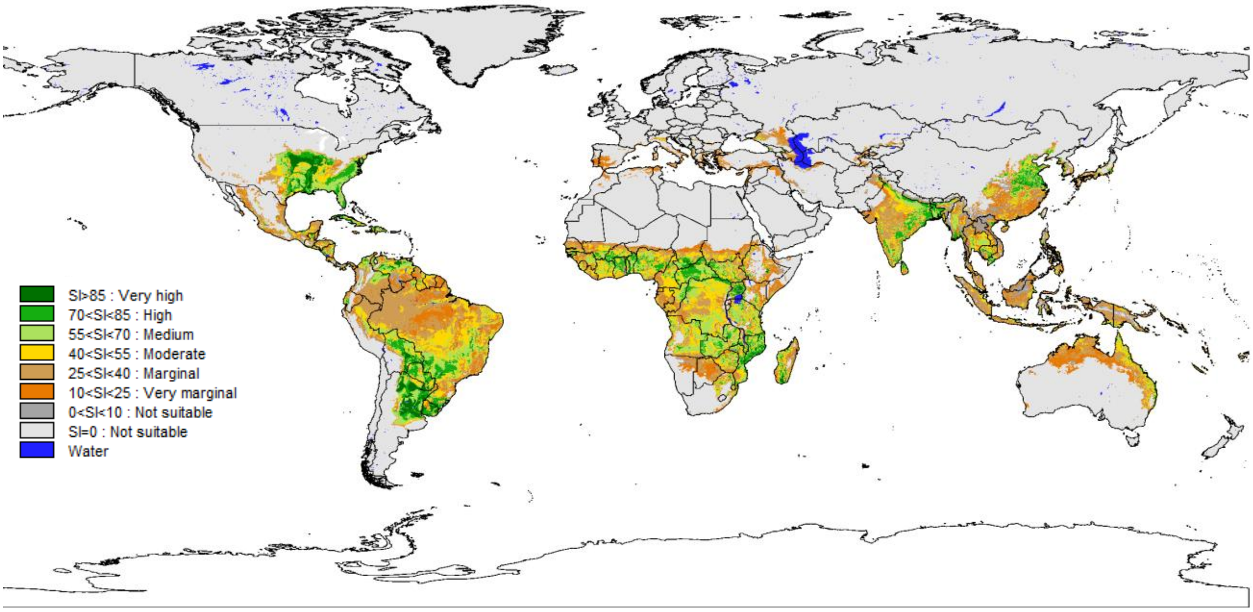
Source: FAO and IIASA, 2021

Figure A7-1.11 Suitability of rain-fed phaseolous beans, high inputs, climate of 1981–2010



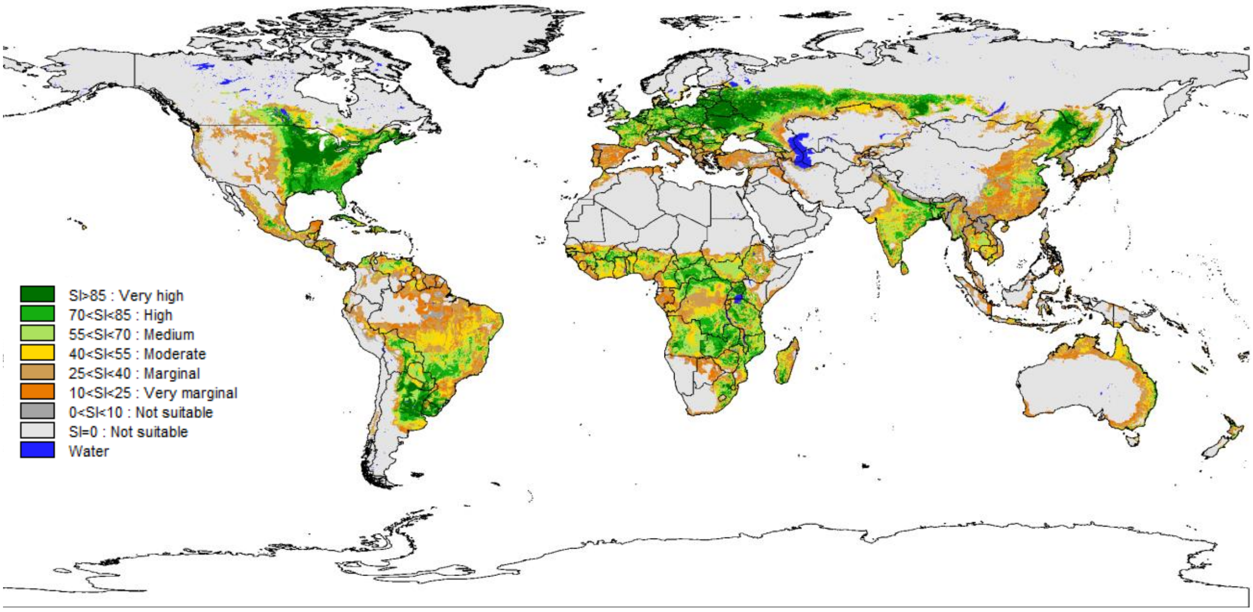
Source: FAO and IIASA, 2021

Figure A7-1.12 Suitability of rain-fed groundnuts, high inputs, climate of 1981–2010



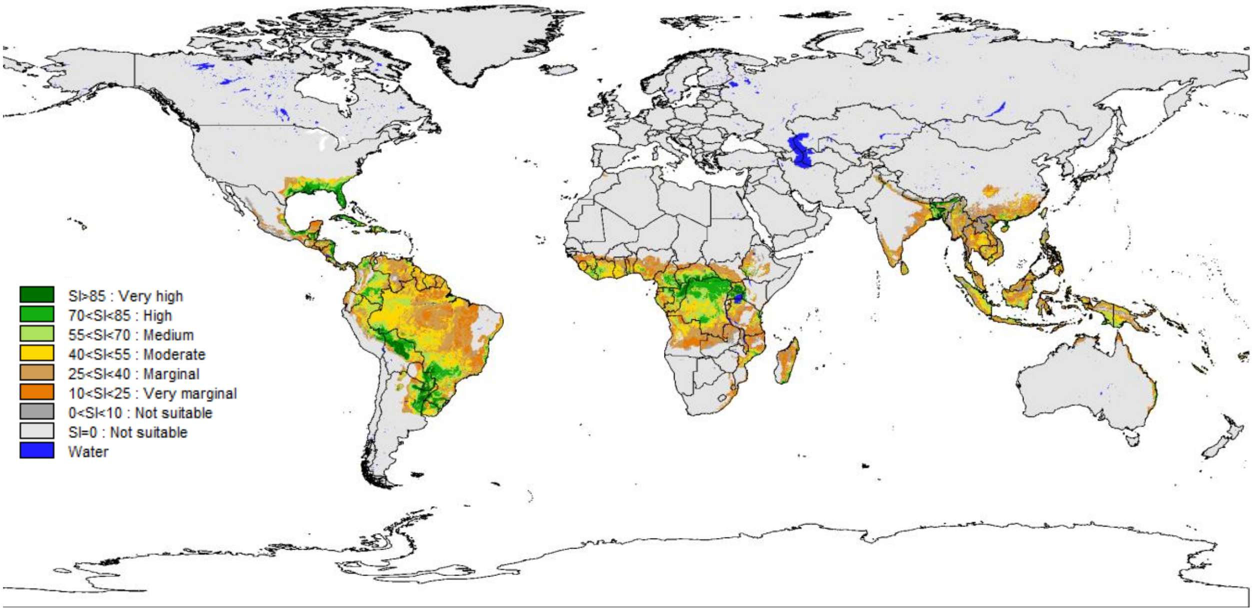
Source: FAO and IIASA, 2021

Figure A7-1.13 Suitability of rain-fed sunflower, high inputs, climate of 1981–2010



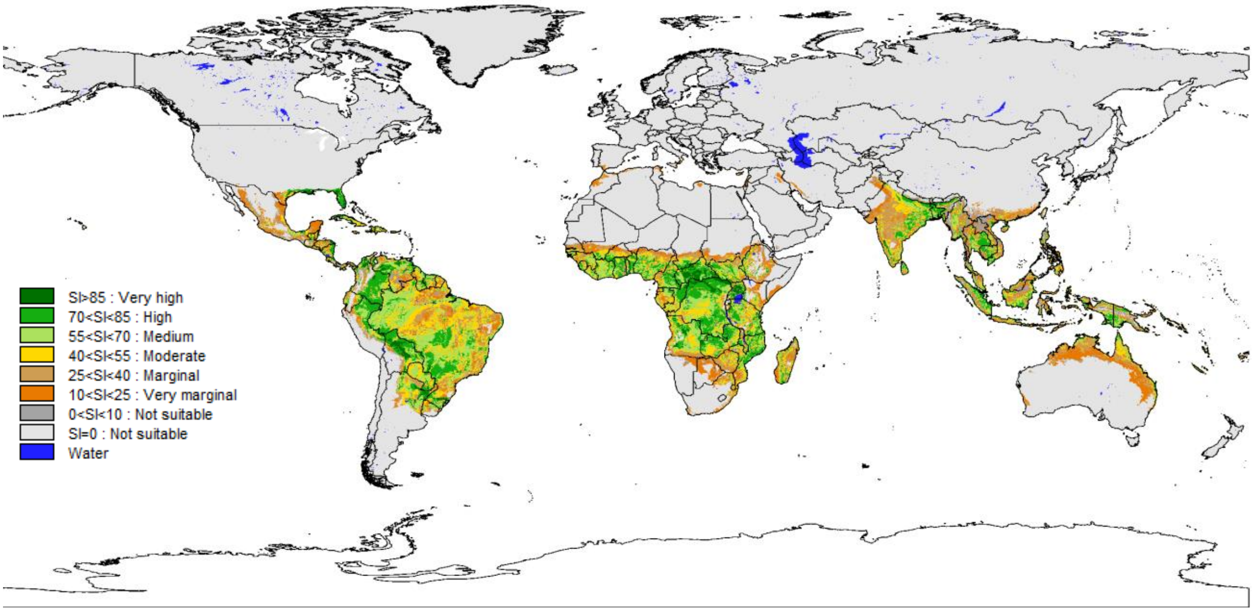
Source: FAO and IIASA, 2021

Figure A7-1.14 Suitability of rain-fed sugar cane, high inputs, climate of 1981–2010



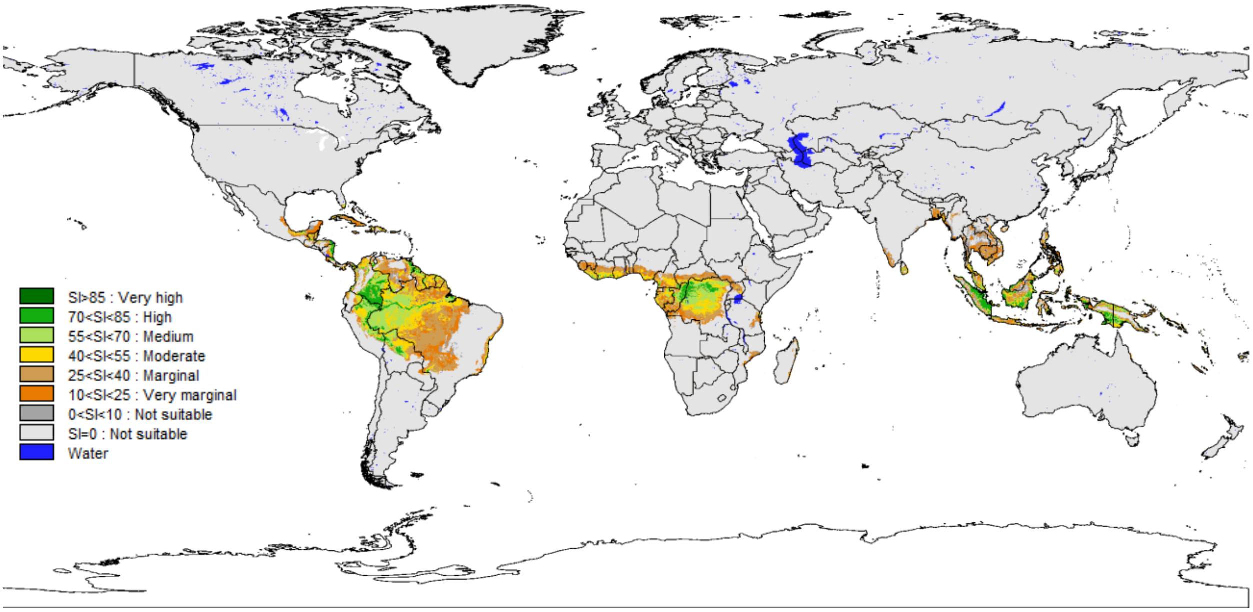
Source: FAO and IIASA, 2021

Figure A7-1.15 Suitability of rain-fed cassava, high inputs, climate of 1981–2010



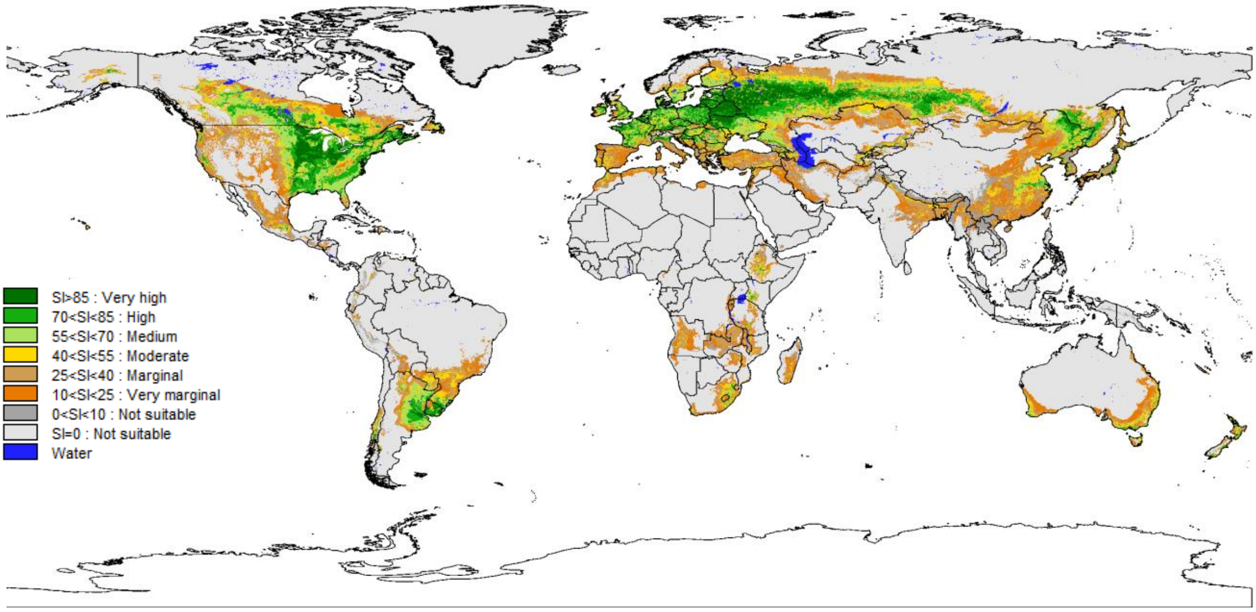
Source: FAO and IIASA, 2021

Figure A7-1.16 Suitability of rain-fed oil palm, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

Figure A7-1.17 Suitability of rain-fed potatoes, high inputs, climate of 1981–2010



Source: FAO and IIASA, 2021

32. Appendix 7-2 Crop summary tables

Crop summary tables provide standardized information for each crop by administrative units (country or country/province for some major countries, and by sub-continental and continental regional aggregations) and by broad hydro-regions. The comprehensive tables summarize by suitability class the suitable extents, attainable production and yields, various constraint factors (due to thermal regime, moisture deficits, agro-climatic constraints due to pest, disease and workability limitations, and due to soil/terrain limitations) and aggregate simulated water deficits (rain-fed conditions) respectively net irrigation requirements (irrigated conditions). Table A7-2.1 gives some explanations of the column headings used in the crop summary tables.

Table A7-2.1 Column heading abbreviations used in crop summary tables

Column heading	Description
ADM0/CTR	Country-level administrative ISO 3166–1 alpha-3 code (admin. Level 0);
ADM1	Province-level administrative code (admin. Level 1);
REG1	Regional aggregation level 1 (sub-continental regions);
REG2	Regional aggregation level 2 (continental regions);
REG3	Regional aggregation level 3 (classification by World Bank income groups);
HYD0	Major hydro-basin 4-digit code
HR1	Code of continental-level hydro-region
LC	Land cover class indicator;
EXC	Protection/exclusion class indicator;
AEZ	AEZ class indicator (by aggregate 33-class system);
CRP	Crop acronym
Land extents	Total area of spatial unit in square kilometers (km^2);
Suitability classes	Suitable area (km^2), by suitability class, for:
VS	- very suitable land;
S	- suitable land;
MS	- moderately suitable land;
mS	- marginally suitable land;
vmS	- very marginally suitable land;
NS	- not suitable land.
Potential production	Attainable production, in 1000 tons dry matter (DM)*, by suitability class. Note, estimates of attainable production account for (input level specific) fallow requirements.
Potential yield	Attainable agro-ecological yield, in kg/ha DM*:

Ymax	- highest occurring class yield in spatial unit
VS, S, etc.	- average class yield by suitability class in spatial unit;
Crop production constraints	Constraint indicators (range 0–10000) are provided by suitability class:
fc1	- thermal constraints indicator;
fc2	- moisture constraints indicator;
fc3	- agro-climatic constraints indicator;
fc4	- soil and terrain constraints indicator.
	Constraint scale runs from 10000 (=no constraint) to 0 (=100 percent constraint).
Water deficits / net irrigation requirement	Provides by suitability class estimates (in mm) of simulated water deficits (rain-fed conditions) respectively net irrigation requirements (irrigated conditions); values are average (wd), minimum (wn) and maximum (wx) levels for each spatial unit.
Area, production and yield aggregated data	Summarizes area (A), production (P) and yield (Yld) results for combinations of suitability classes, by VS+S land, VS+S+MS land and VS+S+MS+mS land.

** For most crops the yields are given in kg dry weight per hectare. For alfalfa, miscanthus, napier grass, reed canary grass, pasture legumes and grasses the yields are in 10kg dry weight per hectare. For sugar beet and sugar cane the yields are in kg sugar per hectare and for oil palm in kg oil per hectare. Cotton yields are given as kg lint per hectare.*

LC class codes (column LC) include: 1. Cropland; 2. Built-up/Artificial surfaces; 3. Tree-covered land; Mangroves; 4. Shrub-covered land; 5. Grassland; Herbaceous vegetation, aquatic or regularly flooded; 6. Sparse vegetation; Bare soil; Snow and glaciers; 7. Water bodies; 8. Cropland, rain-fed; 9. Cropland, equipped with irrigation; 10. LC not assigned, and 11. Total land.

Exclusion class codes (column EXC) comprise of: 1. No protection/exclusion; 2. Protected area recorded in WDPA 2017; 3. Exclusion status due to presence in KBA 2017, GLWD-3 classes 4–9, or in 1-pixel buffer zone around WDPA 2017 polygon; 4. Dominantly forest, and 5. Total land. The class 'Dominantly forest' is defined as land in 30 arc-second grid cells where the share of tree-covered land and mangroves is 90% or more and which are not marked as exclusion classes 2 or 3.

Agro-ecological Zones class codes (column AEZ): 1. Tropics, lowland; semi-arid; 2. Tropics, lowland; sub-humid; 3. Tropics, lowland; humid; 4. Tropics, highland; semi-arid; 5. Tropics, highland; sub-humid; 6. Tropics, highland; humid; 7. Subtropics, warm; semi-arid; 8. Subtropics, warm; sub-humid; 9. Subtropics, warm; humid; 10. Subtropics, moderately cool; semi-arid; 11. Subtropics, moderately cool; sub-humid; 12. Subtropics, moderately cool; humid; 13. Subtropics, cool; semi-arid; 14. Subtropics, cool; sub-humid; 15. Subtropics, cool; humid; 16. Temperate, moderate; dry; 17. Temperate, moderate; moist; 18. Temperate, moderate; wet; 19. Temperate, cool; dry; 20. Temperate, cool; moist; 21. Temperate, cool; wet; 22. Boreal/Cold, no permafrost; dry; 23. Boreal/Cold, no permafrost; moist; 24. Boreal/Cold, no permafrost; wet; 25. Dominantly very steep terrain; 26. Land with severe soil/terrain limitations; 27. Land with ample irrigated soils; 28. Dominantly hydromorphic soil; 29. Desert/Arid climate; 30. Boreal/Cold, with permafrost; 31. Arctic/Very cold climate; 32. Dominantly urban/built-up; 33. Dominantly water; 34. Undefined, and 35. Total land.

A numerical example for wheat under historical climate conditions of period 1981–2010 is provided by continental regions in the Table A7-2.2 (Crop summary table by continental spatial units) and by sub-national administrative units of major countries in the Table A7-2.3 (Crop summary table by sub-national administrative units). Both examples are included in the supplementary Excel file available on the GAEZ v4 data platform under the following worksheets:

- Table A7-2.2: Crop summary table by continental spatial units (REG2)
- Table A7-2.3: Crop summary table by sub-national administrative units (ADM1)

33. Appendix 8-1 Downscaling of area, production and yield of crops

The estimation of global processes consistent with local data and, conversely, local implications emerging from long-term global tendencies challenge the traditional statistical estimation methods. These methods are based on the ability to obtain observations from unknown true probability distributions. In fact, the justification of these methods, e.g., their consistency and efficiency, rely on asymptotic analysis requiring an infinite number of observations. For the new estimation problems referred to above, which can also be termed as “downscaling” problems, we often have only limited or incomplete samples of real observations describing the phenomena and variables of interest. Additional experiments to achieve more observations may be expensive, time consuming, or simply impossible.

A main motivation for developing sequential downscaling methods initially was the spatial estimation of agricultural production values. Agricultural production and land data are routinely available at national scale from FAO and other sources, but these data give no indication as to the spatial heterogeneity of agricultural production within country boundaries. A “downscaling” method in this case achieves a plausible attribution of aggregate national land and production statistics to individual spatial land units, say pixels, by using all available evidence from observed or inferred geo-spatial information, such as remotely sensed land cover, soil, climate and vegetation distribution, population density and distribution, transportation infrastructure, etc.

The ‘downscaling’ algorithm applied in GAEZ v4 proceeds iteratively. It starts with constructing or retrieving an initial ‘prior’ allocation of individual crops based on available data of geographical crop distribution and employs GAEZ crop suitability and attainable yield information to ensure allocation occurs only where agronomical possible. Each iteration step then determines the discrepancy between statistical totals available at the level of spatial units (countries or sub-national units) and the respective totals calculated by summing harvested areas and production over grid-cells. The magnitude of these deviations is then used to revise the land and crop allocation and to recalculate discrepancies. The process is continued until all accounting constraints are met (Fischer *et al*., 2006a).

Below, the list of input data required at the level of spatial units (countries or sub-national administrative units), the geographical layers used at 5 arcminutes spatial resolution, and the equations and accounting constraints imposed, are provided.

Input data used at administrative unit level

Statistical and non-spatial information

Total cropland (arable land and land under permanent crops)	(TC)	FAOSTAT
Total cropland equipped with full control irrigation	(TC^I)	FAOSTAT
Harvested area, by crops	(TH_j)	FAOSTAT
Production, by crops	(TQ_j)	FAOSTAT
Producer price, by crops	(P_j)	FAOSTAT
Share of irrigated harvested area in total crop *j* harvested area	(α_j^I)	FAO
Share of irrigated production in total crop *j* production	(β_j^I)	FAO
Crop allocation relative yield threshold, irrigated crop *j*	(γ_j^I)	IIASA
Crop allocation relative yield threshold, rain-fed crop *j*	(γ_j^R)	IIASA

GIS data (at 5 arc-minutes)

Administrative boundaries and codes	(*adm*) FAO	
Grid-cell area extent	(*TA*) IIASA	
Grid-cell share of total cropland	(c^T) IIASA	
Grid-cell share of land equipped with full control irrigation	(c^I)	AQUASTAT
Cultivation intensity class factor, for rain-fed cultivation of annual crops	($\overline{m}^R$)	IIASA, AEZ
Cultivation intensity class factor, for irrigated cultivation of annual crops	($\overline{m}^I$)	IIASA, AEZ
Attainable potential crop yield, rain-fed, high input level, by crops	($\overline{Y}_{ij}^{R,high}$)	GAEZ v4
Attainable potential crop yield, rain-fed, low input level, by crops	($\overline{Y}_{ij}^{R,low}$)	GAEZ v4
Attainable potential crop yield, irrigated, high input level, by crops	($\overline{Y}_{ij}^{I,high}$)	GAEZ v4
Location crop priority factor for rain-fed crops	(φ_{jz}^R)	FAO/IIASA

Location crop priority factor for irrigated crops (φ^I_{jz}) FAO/IIASA

Crop distribution layers, for selected crops[25] (ε_j) Monfreda *et al.*

Portmann *et al.*

Main equations and constraints

Total irrigated production of allocation unit, by crops

$$TQ^I_j = \beta^I_j \, TQ_j \qquad j \in \text{crops}$$

Total rain-fed production of allocation unit, by crops

$$TQ^R_j = (1-\beta^I_j)\, TQ_j \qquad j \in \text{crops}$$

Total irrigated harvested area of allocation unit, by crops

$$TH^I_j = \alpha^I_j \, TH_j \qquad j \in \text{crops}$$

Total rain-fed harvested area of allocation unit, by crops

$$TH^R_j = (1-\alpha^I_j)\, TH_j \qquad j \in \text{crops}$$

Grid-cell cropland

$$TC_i = c^T_i \; TA_i \qquad i \in \text{grid cells}$$

Grid-cell (full control) irrigated cropland

$$TC^I_i = c^I_i \; TA_i \qquad i \in \text{grid cells}$$

Grid-cell share of rain-fed cropland

$$c^R_i = c^T_i - c^I_i \qquad i \in \text{grid cells}$$

Grid-cell rain-fed cropland

$$TC^R_i = c^R_i \; TA_i \qquad i \in \text{grid cells}$$

Grid-cell rain-fed cropping intensity applicable for annual crops[26]

$$m^R_i = \rho^R \; \overline{m}^R_i \qquad i \in \text{grid cells}$$

Grid-cell irrigated cropping intensity applicable for annual crops

[25] In the current downscaling application for year 2010, information from the studies by Monfreda, Ramankutty and Foley, (2008) and Portmann, Siebert and Döll, (2010) was used for selected crops in countries where it was reported that more than 50% of crop data was covered by sub-national statistics.

[26] Note, this cropping intensity factor accounts for sequential multi-cropping of land within a year as well as for idle cultivated land due to fallow requirements. The intensity factor is applied to annual crops with growth cycle < 180 days.

$$m_i^I = \rho^I \ \overline{m}_i^I \qquad i \in \text{grid cells}$$

Grid-cell total rain-fed harvested area

$$H_i^R = m_i^R \ TC_i^R \qquad i \in \text{grid cells}$$

Grid-cell total irrigated harvested area

$$H_i^I = m_i^I \ TC_i^I \qquad i \in \text{grid cells}$$

Grid-cell rain-fed harvested area, by crops[27]

$$AH_{ij}^R = \begin{cases} m_i^R s_{ij}^R TC_i^R & j \in annual\, crops \\ m^P s_{ij}^R TC_i^R & j \in perennial crops \end{cases} \qquad i \in \text{grid cells}$$

Grid-cell irrigated harvested area, by crops

$$AH_{ij}^I = \begin{cases} m_i^I s_{ij}^I TC_i^I & j \in annual\, crops \\ m^P s_{ij}^I TC_i^I & j \in perennial crops \end{cases} \qquad i \in \text{grid cells}$$

Total rain-fed harvested area of allocation unit, by crops

$$TH_j^R = \sum_{i \in grid\ cells} AH_{ij}^R \qquad j \in \text{crops}$$

Total irrigated harvested area of allocation unit, by crops

$$TH_j^I = \sum_{i \in grid\ cells} AH_{ij}^I \qquad j \in \text{crops}$$

Grid-cell rain-fed yield, by crops

$$Y_{ij}^R = \mu_j^R((1-\psi_{ij}^R)\overline{Y}_{ij}^{R,low} + \psi_{ij}^R \ \overline{Y}_{ij}^{R,high}) \qquad j \in \text{crops}, i \in \text{grid cells}$$

The spatial layer of location factors ψ_{ij} is used to reflect differences in farm management intensity and input use. Observations to portray relative spatial input intensities may be obtained from remote sensing products or be based on geo-referenced household survey data providing, for instance, information on farm size, input use and market orientation of households. Alternatively, factors such as population density, type of suitable crops, and distance to market can be used to differentiate among land units.

Grid-cell irrigated yield, by crops

$$Y_{ij}^I = \mu_j^I \overline{Y}_{ij}^{I,high} \qquad \text{j} \in \text{crops, i} \in \text{grid cells}$$

[27] The cropping intensity of perennial crops in both rain-fed and irrigated cultivated land was fixed at a value of 0.95. This implies that 5% of the land under permanent crops is assumed idle for reestablishment.

Total rain-fed production of allocation unit, by crops

$$TQ_j^R = \sum_{i \in grid\ cells} AH_{ij}^R \, Y_{ij}^R \qquad j \in \text{crops}$$

Total irrigated production of allocation unit, by crops

$$TQ_j^I = \sum_{i \in grid\ cells} AH_{ij}^I \, Y_{ij}^I \qquad j \in \text{crops}$$

Grid-cell relative yield factor, by rain-fed crops

$$\varphi_{ij}^R = \overline{Y}_{ij}^{R,high} \,/ \max_{k \in grid\ cells} (\overline{Y}_{kj}^{R,high}) \qquad j \in \text{crops, } i \in \text{grid cells}$$

Grid-cell relative yield factor, by irrigated crops

$$\varphi_{ij}^I = \overline{Y}_{ij}^{I,high} \,/ \max_{k \in grid\ cells} (\overline{Y}_{kj}^{I,high}) \qquad j \in \text{crops, } i \in \text{grid cells}$$

Grid-cell crop share allocation

Allocation of cropland to cropping activities at grid cell level is computed in a 2-stage nested way. First, land is allocated to two broad sets of crops, described by index set I_1 (crops for which a spatial distribution layer with shares ε_{ij} is available) and index set I_2 (crops for which a spatial layer is lacking).

The share of total rain-fed cropland allocated to crops in index set I_1

$$S_{1i}^R = \frac{\sum_{j \in I_1^R} m_i^R Y_{ij}^R P_j \lambda_j^R \varphi_{ij}^R}{\sum_{j \in I_1^R \cup I_2^R} m_i^R Y_{ij}^R P_j \lambda_j^R \varphi_{ij}^R} \qquad i \in \text{grid cells}$$

where index set I_1^R of relevant rain-fed crops in I_1 is defined as:

$$I_1^R = \{ j \in I_1 \wedge \varepsilon_{ij} > 0 \wedge \varphi_{ij}^R \geq \gamma_j^R \}$$

and index set I_2^R of relevant rain-fed crops in I_2 is defined as:

$$I_2^R = \{ j \in I_2 \wedge \varphi_{ij}^R \geq \gamma_j^R \}$$

Similarly, the share of total irrigated cropland allocation to crops in index set I_1 is

$$S_{1i}^I = \frac{\sum_{j \in I_1^I} m_i^I Y_{ij}^I P_j \lambda_j^I \varphi_{ij}^I}{\sum_{j \in I_1^I \cup I_2^I} m_i^I Y_{ij}^I P_j \lambda_j^I \varphi_{ij}^I} \qquad i \in \text{grid cells}$$

with index set I_1^I of relevant irrigated crops in I_1 defined as:

$$I_1^I = \{ j \in I_1 \wedge \varepsilon_{ij} > 0 \wedge \varphi_{ij}^I \geq \gamma_j^I \}$$

and index set I_2^I of relevant irrigated crops in I_2 defined as:

$$I_2^I = \{ j \in I_2 \wedge \varphi_{ij}^I \geq \gamma_j^I \}$$

Shares of total cultivated land allocated to crops within index set I_2 are then computed respectively for rain-fed and irrigated conditions as:

$$S_{2i}^R = 1 - S_{1i}^R \text{ and } S_{2i}^I = 1 - S_{1i}^I \qquad i \in \text{grid cells}$$

In a second step, the crop-level area shares s_{ij}^R and s_{ij}^I for respectively rain-fed and irrigation conditions are calculated for the two sets of crops. For rain-fed land the shares are:

$$s_{ij}^R = \begin{cases} 0 & j \in I_1 \wedge j \notin I_1^R \\ S_{1i}^R \dfrac{\varepsilon_{ij}^R \lambda_j^R}{\sum_{k \in I_1^R} \varepsilon_{ik}^R \lambda_k^R} & j \in I_1 \wedge j \in I_1^R \\ 0 & j \in I_2 \wedge j \notin I_2^R \\ S_{2i}^R \dfrac{m_{ij}^R Y_{ij}^R P_j \lambda_j^R \varphi_{ij}^R}{\sum_{k \in I_2^R} m_{ik}^R Y_{ik}^R P_k \lambda_k^R \varphi_{ik}^R} & j \in I_2 \wedge j \in I_2^R \end{cases} \qquad i \in \text{grid cells}$$

and for irrigated land

$$s_{ij}^I = \begin{cases} 0 & j \in I_1 \wedge j \notin I_1^I \\ S_{1i}^I \dfrac{\varepsilon_{ij}^I \lambda_j^I}{\sum_{k \in I_1^I} \varepsilon_{ik}^I \lambda_k^I} & j \in I_1 \wedge j \in I_1^I \\ 0 & j \in I_2 \wedge j \notin I_2^I \\ S_{2i}^I \dfrac{m_{ij}^I Y_{ij}^I P_j \lambda_j^I \varphi_{ij}^I}{\sum_{k \in I_2^I} m_{ik}^I Y_{ik}^I P_k \lambda_k^I \varphi_{ik}^I} & j \in I_2 \wedge j \in I_2^I \end{cases} \qquad i \in \text{grid cells}$$

With cultivated land allocated according to these computed land shares, the crop specific harvested areas in grid cell *i* can be written as:

$$AH_{ij}^R = c_i^R \, TA_i \left(\frac{\rho^R \sum_{k \in crops} s_{ij}^R m_{ij}^R}{\sum_{k \in crops} s_{ij}^R} \right) s_{ij}^R \qquad j \in \text{crops}, i \in \text{grid cells}$$

and

$$AH_{ij}^{I} = c_i^I \, TA_i \left(\frac{\rho^I \sum_{k \in crops} s_{ij}^I m_{ij}^I}{\sum_{k \in crops} s_{ij}^I} \right) s_{ij}^I \qquad j \in \text{crops}, \; i \in \text{grid cells}$$

Solution algorithm

After initialization of all variables, the solution algorithm of the iterative rebalancing method updates the various crop-specific multipliers which drive the outcomes, namely λ_j^R and λ_j^I for area allocation, ρ^R and ρ^I for cropping intensity, and the factors μ_j^R and μ_j^I for yield and production, by evaluating the crop-wise discrepancies between the resulting calculated area and production and observed crop harvested area and production. While converging, the algorithm proceeds with iterative updates of theses multipliers until all conditions and accounting constraints are met.

As a result, the method produces a crop and grid-cell specific allocation of harvested area and production, separately and consistently for rain-fed and irrigated cropland (i.e., the physical land units). In this process the final values of the respective cropping intensity factors m_i^R and m_i^I for rain-fed and irrigated conditions are estimated. When a solution is reached, i.e., when calculated and observed historical harvested area and production are identical, the multipliers ρ^R and ρ^I provide a measure of the ratio of actual cropping intensity compared to the potential intensity calculated on the basis of GAEZ multi-cropping class factors. The multipliers μ_j^R and μ_j^I represent the ratios of actual achieved to attainable potential crop yields as estimated in GAEZ Module V. These last multipliers give for each allocation unit (country or province) an indication of the apparent yield gaps on the basis of the estimated cropping pattern (i.e., distribution of harvested areas over grid cells), the production potential estimated for such crop distribution, and actual historical observed production.

34. Corrigendum

The following corrections were made to the document after its publication (last updated, 03/12/2021).

Page	Location	Text in published PDF	Text in corrected PDF
159	Table 10.3	Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid	Subtropics, mod. cool; semi-arid Subtropics, mod. cool; sub-humid Subtropics, mod. cool; humid Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid
161	Table 10.4	Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid	Subtropics, mod. cool; semi-arid Subtropics, mod. cool; sub-humid Subtropics, mod. cool; humid Subtropics, cool; semi-arid Subtropics, cool; sub-humid Subtropics, cool; humid
206	Title	Appendix 4-3 Temperature profile tequirements	Appendix 4-3 Temperature profile requirements
207	Body text (bullet points)	• CY: (Annuals) Length of growth cycle • CYa: (Hybernating annuals) Length of pre-dormancy growth cycle • CYb: (Hybernating annuals) Length of post-dormancy growth cycle • Dormancy: Period with mean daily temperatures < 5^0C and a maximum length of 200 days. For hibernating crops to be suitable, on all days below 5^0C the mean daily temperatures must stay above a crop type specific minimum tolerated temperature. • LGPT00: Number of days in a year with mean daily temperatures above 0^0C • LGPT05: Number of days in a year with mean daily temperatures above 5^0C	• CY: (Annuals) Length of growth cycle • CYa: (Hybernating annuals) Length of pre-dormancy growth cycle • CYb: (Hybernating annuals) Length of post-dormancy growth cycle • Dormancy: Period with mean daily temperatures < 5^0C and a maximum length of 200 days. For hibernating crops to be suitable, on all days below 5^0C the mean daily temperatures must stay above a crop type specific minimum tolerated temperature. • LGPT00: Number of days in a year with mean daily temperatures above 0^0C • LGPT05: Number of days in a year with mean daily temperatures above 5^0C • LGPT10: Number of days in a year with mean daily temperatures above 10^0C • RHmin: Minimum mean monthly relative humidity

Page	Location	Text in published PDF	Text in corrected PDF
		• LGPT10: Number of days in a year with mean daily temperatures above 10^{o}C • RHmin: Minimum mean monthly relative humidity • RHavg: Average annual relative humidity • DTRavg: Difference between annual average maximum and minimum temperatures • DTRhigh: Largest difference of average monthly maximum and minimum temperatures • NDN16: Number of days with minimum daily temperature < 16°C • WSTRT: Accumulated P minus soil evaporation for up to 90 days before starting date	• RHavg: Average annual relative humidity • DTRavg: Difference between annual average maximum and minimum temperatures • DTRhigh: Largest difference of average monthly maximum and minimum temperatures • NDN16: Number of days with minimum daily temperature < 16°C • WSTRT: Accumulated precipitation minus soil evaporation for up to 90 days before starting date • TSM10: For days in LGPT10, accumulated temperature sum $\sum_{j \in LGPT10} \max(0, Ta_j - 10)$ • TSM05: For days in LGPT05, accumulated temperature sum $\sum_{j \in LGPT05} \max(0, Ta_j - 5)$ • T trend: “Upward” indicates that the crop cycle starting date should fall in the part of the year when temperature is generally increasing, i.e., temperature profile classes N1a to N9a. “Downward” refers to days with decreasing temperature trends, i.e., to classes N1b to N9b.
208	Body text (first sentence, second paragraph)	The “most limiting” evaluated related constraint factor is then used to reduce potential yields.	The “most limiting” evaluated constraint factor is then used to reduce potential yields.

<table>
<tr><th>Page</th><th>Location</th><th>Text in published PDF</th><th>Text in corrected PDF</th></tr>
<tr><td>209</td><td>Table A4-3.2 Example of temperature and humidity profile constraint parameters</td><td>
Table A4-3.2 Example of temperature and humidity profile constraint parameters
<table>
<tr><th>Common crop name</th><th>Constraint subject</th><th>Constraint type</th><th>'Optimum' threshold</th><th>'Sub-optimum' threshold</th><th>'Not suitable' threshold</th></tr>
<tr><td>Winter wheat</td><td>L6a</td><td>≤</td><td>0.500×CYb</td><td>0.667×CYb</td><td>0.667×CYb</td></tr>
<tr><td></td><td>L6b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L2a+L2b</td><td>≤</td><td>0.333×CYb</td><td>0.400×CYb</td><td>0.333×CYb</td></tr>
<tr><td></td><td>L1a+L1b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L2b+L3b+L4b+L5b</td><td><</td><td>0.500×CYb</td><td>0.500×CYb</td><td>0.500×CYb</td></tr>
<tr><td></td><td>N3b+N4b+N5b+N6b-(L3b+L4b+L5b)</td><td>≥</td><td>CYa</td><td>CYa</td><td>CYa</td></tr>
<tr><td></td><td>Dormancy*</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Vernalization**</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Soybean, subtropical</td><td>L6a+L6b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L5a+L5b</td><td>≤</td><td>0.167×CY</td><td>0.333×CY</td><td>0.333×CY</td></tr>
<tr><td></td><td>L4a+L3a+L3b+L4b</td><td>≥</td><td>0.167×CY</td><td>0.083×CY</td><td>0.0416×CY</td></tr>
<tr><td></td><td>L4a+L3a+L2a+L2b+L3b+L4b</td><td>≥</td><td>0.667×CY</td><td>0.500×CY</td><td>0.333×CY</td></tr>
<tr><td></td><td>L1a+L1b</td><td>≤</td><td>0.333×CY</td><td>0.500×CY</td><td>0.667×CY</td></tr>
<tr><td></td><td>T trend upward</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Coffee arabica</td><td>LGP_{T10}</td><td>≥</td><td>365</td><td>305</td><td>305</td></tr>
<tr><td></td><td>N9+N8+N7</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>N6</td><td>≤</td><td>0</td><td>0.167×365</td><td>0.167×365</td></tr>
<tr><td></td><td>N5</td><td>≤</td><td>0.333×365</td><td>0.500×365</td><td>0.500×365</td></tr>
<tr><td></td><td>N2</td><td>≤</td><td>0.333×365</td><td>0.500×365</td><td>0.667×365</td></tr>
<tr><td></td><td>N1</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>RHmin</td><td>≤</td><td>80%</td><td>90%</td><td>90%</td></tr>
<tr><td></td><td>RHmin</td><td>≥</td><td>40%</td><td>30%</td><td>30%</td></tr>
</table>
</td><td>
Table A4-3.2 Example of temperature and humidity profile constraint parameters
<table>
<tr><th>Common crop name</th><th>Constraint subject</th><th>Constraint type</th><th>'Optimum' threshold</th><th>'Sub-optimum' threshold</th><th>'Not suitable' threshold</th></tr>
<tr><td>Winter wheat</td><td>L6a</td><td>≤</td><td>0.500×CYb</td><td>0.667×CYb</td><td>0.667×CYb</td></tr>
<tr><td></td><td>L6b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L2a+L2b</td><td>≤</td><td>0.333×CYb</td><td>0.400×CYb</td><td>0.333×CYb</td></tr>
<tr><td></td><td>L1a+L1b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L2b+L3b+L4b+L5b</td><td><</td><td>0.500×CYb</td><td>0.500×CYb</td><td>0.500×CYb</td></tr>
<tr><td></td><td>N3b+N4b+N5b+N6b-(L3b+L4b+L5b)</td><td>≥</td><td>CYa</td><td>CYa</td><td>CYa</td></tr>
<tr><td></td><td>Dormancy*</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>Vernalization**</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Soybean, subtropical</td><td>L6a+L6b</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>L5a+L5b</td><td>≤</td><td>0.167×CY</td><td>0.333×CY</td><td>0.333×CY</td></tr>
<tr><td></td><td>L4a+L3a+L3b+L4b</td><td>≥</td><td>0.167×CY</td><td>0.083×CY</td><td>0.0416×CY</td></tr>
<tr><td></td><td>L4a+L3a+L2a+L2b+L3b+L4b</td><td>≥</td><td>0.667×CY</td><td>0.500×CY</td><td>0.333×CY</td></tr>
<tr><td></td><td>L1a+L1b</td><td>≤</td><td>0.333×CY</td><td>0.500×CY</td><td>0.667×CY</td></tr>
<tr><td></td><td>T trend ~~upward~~</td><td></td><td>upward</td><td>upward</td><td>upward</td></tr>
<tr><td>Coffee arabica</td><td>LGP_{T10}</td><td>≥</td><td>365</td><td>305</td><td>305</td></tr>
<tr><td></td><td>N9+N8+N7</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>N6</td><td>≤</td><td>0</td><td>0.167×365</td><td>0.167×365</td></tr>
<tr><td></td><td>N5</td><td>≤</td><td>0.333×365</td><td>0.500×365</td><td>0.500×365</td></tr>
<tr><td></td><td>N2</td><td>≤</td><td>0.333×365</td><td>0.500×365</td><td>0.667×365</td></tr>
<tr><td></td><td>N1</td><td>≤</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td></td><td>RHmin</td><td>≤</td><td>80%</td><td>90%</td><td>90%</td></tr>
<tr><td></td><td>RHmin</td><td>≥</td><td>40%</td><td>30%</td><td>30%</td></tr>
</table>
</td></tr>
<tr><td>210</td><td>Body text (last paragraph)</td><td>Profile constraint parameters for all crops evaluated in this release are provided in a separate Excel document available on the GAEZ v4 platform.</td><td>Profile constraint parameters for all crops evaluated in this release are provided in a separate Excel document available on the GAEZ v4 platform in the following worksheets:
• Table A4-3.3: Temperature profile constraint parameters for cereal crops
• Table A4-3.4: Temperature profile constraint parameters for root and tuber crops
• Table A4-3.5: Temperature profile constraint parameters for sugar crops
• Table A4-3.6: Temperature profile constraint parameters for pulses
• Table A4-3.7: Temperature profile constraint parameters for annual oil crops
• Table A4-3.8: Temperature and humidity profile constraint parameters for industrial crops
• Table A4-3.9: Temperature and humidity profile constraint parameters for vegetables
• Table A4-3.10: Temperature and humidity profile constraint parameters for perennial fruits and stimulants
• Table A4-3.11: Temperature profile constraint parameters for selected fodder and bioenergy crops</td></tr>
<tr><td>280</td><td>Body text (first line)</td><td>32. Dominantly water; 33. Dominantly urban/built-up</td><td>32. Dominantly urban/built-up; 33. Dominantly water</td></tr>
</table>

Global Agro-Ecological Zones (GAEZ v4)

Model documentation

The Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) have cooperated over several decades to develop and implement the AEZ modelling framework and databases. Both FAO and IIASA have been employing AEZ for evaluating land utilization potentials of natural resources in numerous assessments at global, regional and national scales.

The AEZ methodology was initially implemented in the 1980s to assess the capacity of the world's natural resources to meet the needs of a fast-growing global population, particularly in developing countries. Rapid developments in computing and geo-information technology have produced increasingly detailed global databases and IT resources, which made possible the first global AEZ assessment in 2000 (GAEZ v1). Since then, global AEZ assessments have released in 2002 (GAEZ v2) and 2012 (GAEZ v3).

This model system documentation provides updated information on the GAEZ v4 methodological structure and describes the conceptual framework of individual assessment modules in ten chapters. Model input parameters and additional technical information are provided in appendices. The document will support users of the GAEZ v4 data portal and is specifically recommended for AEZ modelers and users such as researchers and planners at national and international research institutes and multilateral organizations dealing with sustainable utilization of land resources, agricultural development and food security.

ISBN 978-92-5-134426-2

9 789251 344262

CB4744EN/1/06.21