GAEZ
Global Agro-ecological Zones

Documentation

GAEZ ver 3.0

Global Agro-ecological Zones

Model Documentation

International Institute for Applied Systems Analysis
IIASA

Food and Agriculture Organization of the United Nations
FAO

Global Agro-Ecological Zones (GAEZ v3.0)

– Model Documentation –

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Preface

The International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization of the United Nations (FAO) have been continuously developing the Agro-Ecological Zones (AEZ) methodology over the past 30 years for assessing agricultural resources and potential. Rapid developments in information technology have produced increasingly detailed and manifold global databases, which made the first global AEZ assessment possible in 2000. Since then global AEZ assessments have been performed every few years, with the data being published on CD or DVD.

In the general context of preparing a global overview of prevailing and future conditions affecting agricultural development and food security, the enlarged knowledge base on global agro-ecological zoning (GAEZ), in particular the expanded number of crops and management techniques evaluated, and new data sets available for use in the crop evaluation, a significant update of GAEZ (Fischer *et al.*, 2002) is timely. This FAO sponsored project, here referred to as GAEZ v3.0, aims to include practical applications such as a significantly updated version, including expanded crop coverage and dry-land management techniques.

In addition to the updating and expansion of GAEZ results, a novel methodology for spatially downscaling of agricultural production statistics has been applied to produce a global gridded inventory of year 2000 agricultural yields and production. The latter information, in conjunction with attainable yield potentials from GAEZ v3.0, is used to quantify yield and production gaps world-wide and at national and sub-national levels.

GAEZ v3.0 includes the following revisions and updates of procedures:

- Substantial updating and tuning of crop potential simulation procedures
- Simulated crops now totaling some 280 crop-LUTs combinations including all globally important food-, feed- and fiber crops as well as number of important bio-energy feedstocks.
- Detailed water supply types including rain-fed agriculture, rain-fed agriculture with water conservation and gravity, sprinkler and drip irrigation systems.
- Edaphic suitability evaluation procedures
- Procedures for spatially downscaling of agricultural production statistics.
- Procedures for establishing yield and production gaps for major crop commodities

New and updated databases:

- Observed climate:Updated CRU and GPCC climate data
- Climate scenarios: Twelve GCM-climate IPCC_AR4 scenario combinations for the 2020s, 2050s and 2080s
- Soils: A new specially developed Harmonized World Soil Database
- Terrain: Elevation data and derived slope and aspect data derived from SRTM
- Irrigated areas: Digital Global Map of Irrigated Areas (GMIA) version 4.01
- Land cover data: New database for major land use land cover categories
- Protected areas: World Database of Protected Areas Annual Release 2009
- Population density inventory for year 2000 (FAO-SDRN)
- Administrative areas: Global Administrative Unit Layers (GAUL) of 2009.

Statistical data:

- Forest resource assessments (FRA 2000, FRA 2005, FRA 2010)
- FAOSTAT
- AQUASTAT
- UN Population Statistics

With each update of GAEZ, the issues addressed, the size of the database and the number of results have multiplied. A new system (GAEZv3.0 Data Portal) was created to make the data accessible to a variety of users.

This report on model documentation provides information on the structure of GAEZ methodology by describing the conceptual framework by individual assessment modules in nine chapters. Relevant data input parameters are provided in a voluminous appendix in printed or digital formats (CD ROM).

This documentation is recommended for GAEZ modelers and users of its results such as researchers, national and international research institutes and multilateral organizations dealing with sustainable utilization of land resources, agricultural development and food security.

Acronyms and abbreviations

AEZ	Agro-ecological Zones
AR4	IPCC fourth Assessment Report
AT2015/30	World Agriculture Towards 2015/2030
C2A2	IPCC SRES A2 Scenario from the Canadian Centre for Climate Modelling and Analysis' Second Generation Coupled Global Climate Model (full scenario name: CCCma CGCM2)
C2B2	IPCC SRES B2 Scenario from the Canadian Centre for Climate Modelling and Analysis' Second Generation Coupled Global Climate Model (full scenario name: CCCma CGCM2 B2)
CGCM2	Canadian General Circulation Model
CGIAR	Consultative Group on International Agricultural Research
CORINE	Coordinate Information on the European Environmemnt
CROPWAT	Computerized irrigation scheduling programme
CRU	Climate Research Unit of East Anglia University
CSA2	Australian Commonwealth Scientific and Research Organization Mark 2 Model (full name: CSIRO Mk2 A2)
CSB1	Australian Commonwealth Scientific and Research Organization Mark 2 Model (full scenario name: CSIRO Mk2 B1)
CSB2	Australian Commonwealth Scientific and Research Organization Mark 2 Model (full name: CSIRO Mk2 B2)
CSIRO	Commonwealth scientific and industrial research organization, Australia
DSMW	Digital Soil Map of the World
ECMWF	European Centre for Medium-Range Weather Forecasts
EDC	Eros Data Centre
EHA2	Max-Planck-Institut für Meterologie GCM model (full scenario name: MPI ECHAM4 A2)
EHB2	Max-Planck-Institut für Meterologie GCM model (full scenario name: MPI ECHAM4 B2)
EROS	Eartgh Resources Observation and Science Center
ESBN	European Soil Bureau Network
FACE	Free-air carbon dioxide enrichment
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO statistics
fc0	Total constraint
fc1	Yield constraint factor due to temperature constraints
fc2	Yield constraint factor due to moisure constraints
fc3	Yield constraint factor due to agro-climatic constraints
fc4	Yield constraint factor due to soil and terrain constraints
Fm	Fournier index
FRA2000	Global forest resources assessment 2000
FRA2005	Global forest resources assessment 2005
GAEZ vs3.0	Global Agro-ecological Zones version 3.0 (Data access facility, research report and documentation)
GAEZ2000	Global Agro-ecological Zones version 1.0 (Website and CD-ROM 2000)
GAEZ2002	Global Agro-ecological Zones version 2.0 (Research report and CD-ROM 2002)
GAUL	Global Administrative Unit Layers
GCM	General circulation model
GLC2000	Global land cover 2000
GLCCD	Global land cover characteristics database
GMIA	Global map of irrigated aereas
GPCC	Global Precipitation Climatology Centre

GTOPO30	Global 30 arc-second elevation
H3A1	UK Met Office Hadley Centre coupled model (full scenario name: Hadley CM3 A1FI)
H3A2	UK Met Office Hadley Centre coupled model (full scenario name: Hadley CM3 A2)
H3B1	UK Met Office Hadley Centre coupled model (full scenario name: Hadley CM3 B1)
H3B2	UK Met Office Hadley Centre coupled model (full scenario name: Hadley CM3 B2)
HadCM3	Headley centre, UK Meteorological Office (climate model 3)
Hi	Harvest index
HWSD	Harmonized world soil database
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernamental Panel on Climate Change
ISRIC	International soil Research and Information Centre - world soil information
ISSCAS	Institute of Soil Science, Chinese Academy of Science
IUCN	International Union for Conservation of Nature
JRC	Joint Research centre of the European Commission
LAI	Leaf areas index
LGP	Length of growing period
LGPeq	Equivalent growing period
LGPt	Temperature growing period
LUC	Land Use Change and Agricultural program of IIASA
LUT	Land utilization types
mS	Marginally suitable land
MS	Moderately suitable land
NATURA 2000	European Union Network of Nature Protection Areas
NS	Not suitable land
PET	Potential evapotranspiration
S	Suitable land
SOTER	Soil and terrain database
SOTWIS	Soter and wise derived soil properties estimates
SQ1	Soil nutrient availability
SQ2	Soil nutrient retention capacity
SQ3	Rooting conditions
SQ4	Oxygen availability to roots
SQ5	Excess salts
SQ6	Toxicity
SQ7	Workability
SRES	Special report on emission scenarios
SRTM	Shuttle radar topography mission
Tsumt	Accumulated temperatures for period when temperatures exceed t ^{o}C
Unesco	United Nations Educational, Scientific and Cultural Organization.
USGS	United States Geological Survey
VASclimO	Variability analysis of surface climate observations
vmS	Marginally suitable land
VS	Very suitable land
WCMC	World conservation monitoring centre
WDPA	World database of protected areas
WISE	World Inventory of soil emission potentials

1 Introduction

1.1 The Agro-Ecological Zones Methodology

The quality and availability of land and water resources, together with important socio-economic and institutional factors, is essential for food security. Crop cultivation potential describes the agronomically possible upper limit for the production of individual crops under given agro-climatic, soil and terrain conditions for a specific level of agricultural inputs and management conditions. The Agro-Ecological Zones (AEZ) approach is based on principles of land evaluation (FAO 1976, 1984 and 2007). The AEZ concept was originally developed by the Food and Agriculture organization of the United Nations (FAO). FAO, with the collaboration of IIASA has over time, further developed and applied the AEZ methodology, supporting databases and software packages. The current Global AEZ (GAEZ v 3.0) provides a major update of data and extension of the methodology compared to the release of GAEZ in 2002 (Fischer, *et. al.*, 2002). GAEZ v 3.0 incorporates two important new global data sets on "Actual Yield and Production' and "Yield and Production Gaps" between potentials and actual yield and production.

Geo-referenced global climate, soil and terrain data are combined into a land resources database, commonly assembled on the basis of global grids, typically at 5 arc-minute and 30 arc-second resolutions. Climatic data comprises precipitation, temperature, wind speed, sunshine hours and relative humidity, which are used to compile agronomically meaningful climate resources inventories including quantified thermal and moisture regimes in space and time.

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, provides maximum potential and agronomically attainable crop yields for basic land resources units under different agricultural production systems 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 particular LUT include crop information such as crop parameters (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 conditions, for rain-fed conditions with specific water-conservation practices, and for irrigated conditions. Calculations are done for different levels of inputs and management assumptions.

Several calculation steps are applied at the grid-cell level to determine potential yields for individual crop/LUT combinations. Growth requirements of the crop species are matched against a detailed set of agro-climatic and edaphic land characteristics derived from the land resources database. Estimation of crop evapotranspiration and crop-specific soil moisture balance calculations are used for detailed assessments of crop/LUT specific suitability and productivity.

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. '

Sequential rebalancing procedures that were developed in this project rely on appropriate optimization principles (Fischer *et al.*, 2006a, 2006b), e.g., cross-entropy maximization, and combine the available samples of real observations in the locations with other "prior" hard (statistics, accounting identities) and soft (expert opinion, scenarios) data.

Actual yields and production are derived through downscaling year 2000 and 2005 agricultural statistics of main food and fiber crops for all rain-fed and irrigated cultivated areas. Results are presented as (i) Crop production value, and (ii) crop area, production and yields for 23 major commodities.

The comparison between simulated potential yields and production with observed yield and production of crops currently grown, provides relevant yield and production gap information. For the 23 main commodities, yield and production gaps are estimated by comparing potential attainable yields with actual achieved yields and production (year 2000 and 2005).

GAEZ generates large databases of (i) natural resources endowments relevant for agricultural uses and (ii) spatially detailed results of individual LUT assessments in terms of suitability and attainable yields, (iii) spatially detailed results of estimate/actual yields of main food and fiber commodities for all rain-fed and irrigated cultivated areas, and (iv) spatially detailed yield and production gaps also for main food and fiber commodities.

These databases provide the agronomic backbone for various applications including the quantification of land productivity. Results are commonly aggregated for current major land use/cover patterns and by administrative units, land protection status, or broad classes reflecting infrastructure availability and market access conditions.

1.2 Structure and overview of GAEZ procedures

The suitability of land for the cultivation of a given crop/LUT depends on crop requirements as compared to the prevailing agro-climatic and agro-edaphic conditions. GAEZ combines these two components by successively modifying grid-cell specific agro-climatic suitabilities according to edaphic suitabilities of location specific soil and terrain characteristics. The structure allows stepwise review of results.

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
(ii) Module II: Crop-specific agro-climatic assessment and water-limited biomass/yield calculation
(iii) Module III: Yield-reduction due to agro-climatic constraints
(iv) Module IV: Edaphic assessment and yield reduction due to soil and terrain limitations
(v) Module V: Integration of results from Modules I-IV into crop-specific grid-cell databases.

Two main activities were involved in obtaining grid-cell level area, yield and production of prevailing main crops, namely:

(vi) Module VI: Estimation of shares of rain-fed or irrigated cultivated land by 5’ grid cell, and estimation of area, yield and production of the main crops in the rain-fed and irrigated cultivated land shares

Global inventories of yield gaps were created through comparison of potential rain-fed yields with yields of downscaled statistical production. The activities include:

(vii) Module VII: Quantification of yield gaps between potential attainable crop yields and downscaled current crop yield statistics of the year 2000 and 2005;

The overall GAEZ model structure and data integration are schematically shown in Figure 1-1

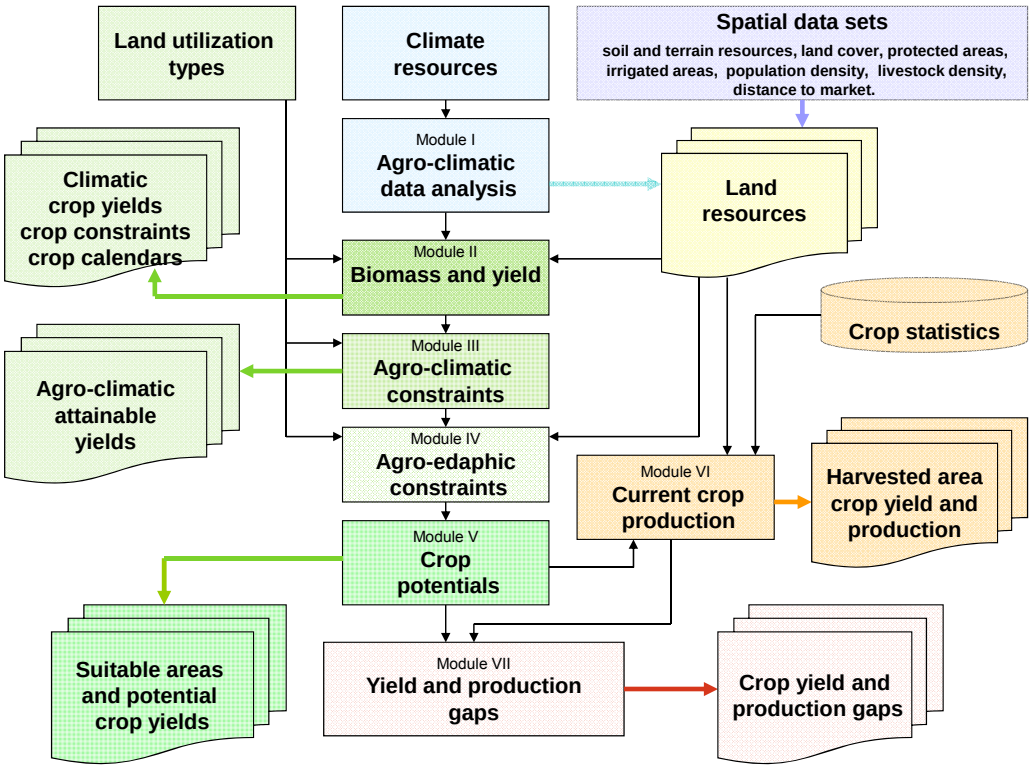

Figure 1-1 Overall structure and data integration of GAEZ v3.0 (Module I-VII)

1.2.1 Module I: Agro-climatic data analysis

Climate data analysis and compilation of general agro-climatic indicators

Module I calculates and stores climate-related variables and indicators for each grid-cell. The module processes spatial grids of historical, base line and projected future climate to create layers of agro-climatic indicators relevant to plant production. First, available monthly climate data are read and converted to variables required for subsequent calculations. Temporal interpolations are used to transform monthly data to daily estimates required for characterization of thermal and soil moisture regimes. The latter includes calculation of reference potential and actual evapotranspiration through daily soil water balances.

Thermal regime characterization generated in Module I includes thermal growing periods, accumulated temperature sums (for average daily temperature respectively above 0°C, 5°C and 10°C), delineation of permafrost zones and quantification of annual temperature profiles. Soil water balance calculations (Section 3.4.1) determine potential and actual evapotranspiration for a reference crop, length of growing period (LGP, days) including characterization of LGP quality, dormancy periods and cold brakes, and begin and end dates of one or more LGPs. Based on a sub-set of these indicators, a multiple-cropping zones classification is produced for rain-fed and irrigated conditions.

1.2.2 Module II: Biomass and yield calculation

Crop-specific agro-climatic assessment and potential water-limited biomass/yield calculation

In Module II, all land utilization types (LUT) are assessed for water-limited biomass and yields, currently 280, crop and pasture, LUTs for each of the assumed input levels (Appendix 4-1). The LUT concept characterizes a range of sub-types within a plant species, including differences in crop cycle

length (i.e. days from sowing to harvest), growth and development parameters. Sub-types differ with assumed level of inputs. For instance, at low input level traditional crop varieties are considered, which may have different qualities that are preferred but have low yield efficiencies (harvest index) and because of management limitations are grown in relatively irregular stands with inferior leaf area index. In contrast, with high input level high-yielding varieties are deployed with advanced field management and machinery providing optimum plant densities with high leaf area index.

Module II first calculates maximum attainable biomass and yield as determined by radiation and temperature regimes, followed by the computation of respective rain-fed crop water balances and the establishment of optimum crop calendars for each of these conditions. Crop water balances are used to estimate actual crop evapotranspiration, accumulated crop water deficit during the growth cycle (respectively irrigation water requirements for irrigated conditions), and attainable water-limited biomass and yields for rain-fed conditions. First, a window of time is determined when conditions permit LUT cultivation (e.g. prevailing LGP in each grid cell). The growth of each LUT is tested for the days during the permissible window of time with separate analysis for irrigated and rain-fed conditions. The growing dates and cycle length producing the highest (water-limited or irrigated) yield define the optimum crop calendar of each LUT in each grid-cell.

Due to the detailed calculations for a rather large number of LUTs, Module II requires a considerable amount of computer time for its processing and is the most CPU-demanding component in GAEZ. 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 soil water deficits, estimated amounts of soil water deficit, potential and actual LUT evapotranspiration, accumulated temperature sums during each LUT crop cycle, and optimum crop calendars.

1.2.3 Module III: Agro-climatic constraints

Yield reduction due to agro-climatic constraints

Module III computes for each grid cell specific multipliers, which are used to reduce yields for various agro-climatic constraints as defined in the AEZ methodology. This step is carried out in a separate module to make explicit the effect of limitations due to soil workability, pest and diseases, and other constraints and to permit time-effective reprocessing in case new or additional information is available. Five groups of agro-climatic constraints are considered, including:

a) Yield adjustment due to year-to-year variability of soil moisture supply; this factor is applied to adjust yields calculated for average climatic conditions
b) Yield losses due to the effect of pests, diseases and weed constraints on crop growth
c) Yield losses due to water stress, pest and diseases constraints on yield components and yield formation of produce (e.g., affecting quality of produce)
d) Yield losses due to soil workability constraints (e.g., excessive wetness causing difficulties for harvesting and handling of produce)
e) Yield losses due to occurrence of early or late frosts.

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

The results of Module III update for each grid cell the output file of Module II by filling in the respective LUT agro-climatic constraints yield reduction factors. At this stage, the results of agro-climatic suitabilities can be mapped for spatial verification and further use in applications.

1.2.4 Module IV: Agro-edaphic constraints

Yield reduction due to soil and terrain limitations

This module evaluates crop-specific yield reduction due to limitations imposed by soil and terrain conditions. Soil suitability is determined on the basis of the soil attribute data contained in the

Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). Soil nutrient availability, soil nutrient retention capacity, soil rooting conditions, soil oxygen availability, soil toxicities, soil salinity and sodicity conditions and soil management constraints are estimated on crop by crop basis and are combined in a crop and input specific suitability rating.

The soil evaluation algorithm assesses for soil types and slope classes the match between crop soil requirements and the respective soil qualities as derived from soil attributes of the HWSD. Thereby the rating procedures result in a quantification of suitability for all combinations of crop types, input level, soil types and slope classes.

1.2.5 Module V: Integration of climatic and edaphic evaluation

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. 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 and slope rules are applied separately for rain-fed and irrigated conditions.

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. One hundred of these produce the edaphic characterization at 5 arc-minutes, the resolution used for providing GAEZ results.

Cropping activities are the most critical in causing topsoil erosion, because of their particular cover dynamics and management. The terrain-slope suitability rating used in the GAEZ study accounts for the factors that influence production sustainability and 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 Fournier index.

Application of the procedures in the modules described above result in an expected yield and suitability distribution regarding rain-fed and irrigation conditions for each 5-minute grid-cell and each crop/LUT. Land suitability is described in five classes: very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS), and not suitable (NS) for each LUT. Large databases are created, which are used to derive additional characterization and aggregations. Examples include calculation of land with cultivation potential, tabulation of results by ecosystem type, quantification of climatic production risks by using historical time series of suitability results, impact of climate change on crop production potentials, and irrigation water requirements for current and future climates.

1.2.6 Module VI: Actual Yield and Production

Global change processes raise new estimation problems challenging the conventional statistical methods, which are based on the ability to obtain observations from unknown true probability distributions. In contrast, problems such as downscaling of production require recovering information from only partially observable or even unobservable variables. For instance, aggregate data exist at global and national level regarding agricultural production and harvest areas. ‘Downscaling’ methods in this case should achieve plausible estimation of global distributions,

consistent with 'local' data obtained from remote sensing and available aggregate statistics, by using all available evidence.

This module estimates actual yields and production from downscaling year 2000 statistics of main food and fiber crops (statistics derived mainly from FAOSTAT and the FAO study AT 2015/30). Results are presented as (i) crop production value, and (ii) crop area, production and yields for 23 major commodities.

Two main activities were involved in obtaining grid-cell level area, yield and production of prevailing main crops:

(i) Estimation of shares of rain-fed or irrigated cultivated land by 5' grid cell, and
(ii) estimation of area, yield and production of the main crops in the rain-fed and irrigated cultivated land shares

Estimation of cultivated land shares

Land cover interpretations schemes were devised that allow a quantification of each 5-arc-min. grid-cell into seven main land use cover shares. Shares of cultivated land, subdivided into rain-fed and irrigated land, were used for allocating rain-fed and irrigated crop production statistics.

Allocation of agricultural statistics to cultivated land

Agricultural production statistics are available at national scale from FAO. Various layers of spatial information are used to calculate an initial estimate of location-specific crop-wise production priors. The priors are adjusted in an iterative downscaling procedure to ensure that crop areas and production are consistent with aggregate statistical data, are allocated to the available cultivated land and reflect available ancillary data, e.g., selected crop area distribution data (Montfreda *et al.*, 2008) and agronomic suitability of crops estimated in AEZ.

1.2.7 Module VII: Yield and Production Gaps

Yield gaps and production gaps have been estimated by comparing potential attainable yields and production (estimated in GAEZ v3.0) and actual yields and production from downscaling year 2000 and 2005 statistics of main food and fiber crops (statistics derived mainly from FAOSTAT and the FAO study AT 2015/30).

For main commodities, (see list in Appendix 4-1, Table A-4-5), yield and production gaps are estimated by comparing potential attainable yields and production (low and mixed input levels), with actual achieved yields and production (year 2000 and 2005).

2 Description of GAEZ input datasets

2.1 Climate data

2.1.1 Observed climate

For the global agro-ecological zones assessment time series data are used from the Climate Research Unit (CRU) at the University of East Anglia, 10 arc-minute latitude/longitude gridded average monthly climate data, version CRU CL 2.0 (New 2002), and 30 arc-minute latitude/longitude gridded monthly climate data time series for the period 1901-2002, version CRU TS 2.1 (Mitchell 2005). This database revises and extends the earlier version CRU TS 1.0 (New 2000) used in the 2002 GAEZ assessment (Fischer 2002). Seven climatic variables are required for GAEZ climate analysis as shown in Table 2-1.

For precipitation, an alternative data product was obtained from VASClimO (Variability Analysis of Surface Climate Observations), a joint climate research project of the German Weather Service (Global Precipitation Climatology Centre - GPCC) and the Johann Wolfgang Goethe-University Frankfurt (Institute for Atmosphere and Environment - Working Group for Climatology). VASClimO is based on data being selected with respect to a (mostly) complete temporal data coverage and homogeneity of the time series. The current version 1.1 of VASClimO uses time-series of 9,343 stations covering the period 1951-2000 (Beck 2004). Results of gridded data (30 arc-minute latitude/longitude) were available from the VASCLim Website (www.gpcc.dwd.de). These long-term climatological analyses of homogenized area-averaged precipitation time-series are supported by the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).

Original monthly CRU 10 arc-minute and GPCC and CRU 30 arc-minute latitude/longitude climatic surfaces were interpolated at IIASA to a 5 arc-minute grid for all years between 1960 and 2002. Monthly climatic variables used include precipitation; number of rainy days; mean minimum, mean maximum temperature; diurnal temperature range; cloudiness; wind speed (only the average for 1961-90 was available from CRU CL 2.0); and vapor pressure. For all variables except temperature a bilinear interpolation method was applied within ArcGIS. It uses the values of the four nearest input cell centers to determine the value of the 5 arc-minute output raster. The new value for the 5' output cell is a weighted average of these four values, adjusted to account for their distance from the center of the output cell.

In the case of temperature a lapse rate of 0.55^{o}C per 100 meter elevation was applied using the respective digital elevation data (DEM). First, a 30 arc-minute surface provided by CRU was used to calculate temperature values adjusted to sea level. Bilinear interpolation was performed for temperatures at sea level. Second, a 5 arc-minute DEM, derived from Shuttle Radar Topography Mission (SRTM) data, was used to calculate temperatures for actual elevations. The 5 arc-minute DEM was compiled from detailed SRTM 3 arc-second elevations using the median of all 3 arc-second elevation data within each 5 arc-minute grid cell.

Table 2-1 Climatic input variables for the GAEZ assessment

Variable	Symbol	Units	Source[2]
Average Temperature	T_a	^{o}C	CRU
Diurnal Temperature Range	T_{range}	^{o}C	CRU
Sunshine fraction	n/N	%	CRU
Wind speed at 10 m height	U_{10}	m/s	CRU
Relative humidity	RH	%	CRU
Wet-day frequency	WET	days	CRU
Precipitation	P	mm	VASClimO

[2]See text for details

2.1.2 Climate Scenarios

For the analysis of climate change impacts on agricultural production potential, available climate predictions of General Circulation Models (GCM) were used for characterization of future climates. The IPCC data distribution centre (http://www.ipcc-data.org/) provides future climatic parameters obtained as outputs of various GCM experiments for a range of IPCC emission scenarios.

The following four GCMs were used here for calculation of future potential agricultural productivity:

- HadCM3 (Hadley Centre, UK Meteorological Office)
- ECHAM4 (Max-Planck-Institute for Meteorology, Germany)
- CSIRO (Australia's Commonwealth Scientific and Industrial Research Organisation, Australia)
- CGCM2 (Canadian General Circulation Model)

GCM model outputs for individual climate attributes were applied as follows:
Difference of the means for three 30-year periods (the 2020s: years 2011-2040; the 2050s: years 2041-2070; and the 2080s: years 2071-2100) with the GCM 'baseline' climate 1961-1990 were calculated for each grid in the respective GCM. An inverse distance weighted interpolation to a 30 arc-minute grid was performed on these 'deltas' of the centre points of each grid cell in the original GCM. Such changes ('deltas') for monthly climatic variables, i.e. differences for maximum and minimum monthly temperature, precipitation, total surface solar radiation and wind-run, were then applied to the observed climate of 1961-1990 to generate future climate data. Climate change induced alterations in agricultural productivity as a result of climate change can be calculated by running GAEZ for future time slots and compare results to the outcomes for the climatic baseline.

2.1.3 Use of climate data in GAEZ

The average climate and year-by-year historical databases were used to quantify:

(i) Widely used agro-climatic indicators, such as the number of growing period days, thermal climate classification, aridity indices, and
(ii) to estimate for each grid-cell by crop/LUT, average and individual years agro-climatically attainable crop yields and variability.

Monthly 5 arc-minute latitude/longitude grids of average climate and year-by-year climate attributes for the seven climate variables (Table 2-1) were combined into binary random access files – one file for each climate variable containing all monthly values per grid cell, which serve as input to the GAEZ simulation programs.

In a similar way, binary random access files were generated to hold monthly and annual climate change 'deltas' derived from GCM outputs. In this way average future climate conditions have been simulated in GAEZ, as well as time series of future years, by combining respective historical data and GCM-derived 'deltas'.

2.2 Soil data

The Land Use Change and Agriculture Program of IIASA (LUC) and the Food and Agriculture Organization of the United Nations (FAO) have developed a new comprehensive Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). Vast volumes of recently collected regional and national updates of soil information were used for this state-of-the-art database. The work was carried out in partnership with:

- ISRIC-World Soil Information and FAO, which were responsible for the development of various regional soil and terrain databases and the WISE soil profile database;
- the European Soil Bureau Network, which had completed a major update of soil information for Europe and northern Eurasia, and
- the Institute of Soil Science, Chinese Academy of Sciences, which provided the 1:1,000,000 scale Soil Map of China.

The HWSD (Figure 2-1) is composed of a geographical layer containing reference to some 30,000 soil map units. This information is stored as a 30 arc-second raster in a GIS, which is linked to an attribute database in Microsoft Access format containing harmonized soil profile data. For the globe the raster has 21,600 rows and 43,200 columns, of which 221 million grid-cells cover the globe's land territory. Over 16,000 different soil mapping units are recognized in the HWSD that combine existing regional and national updates of soil information worldwide with the information contained within the 1:5,000,000 scale FAO-UNESCO Soil Map of the World (FAO/UNESCO 1974).

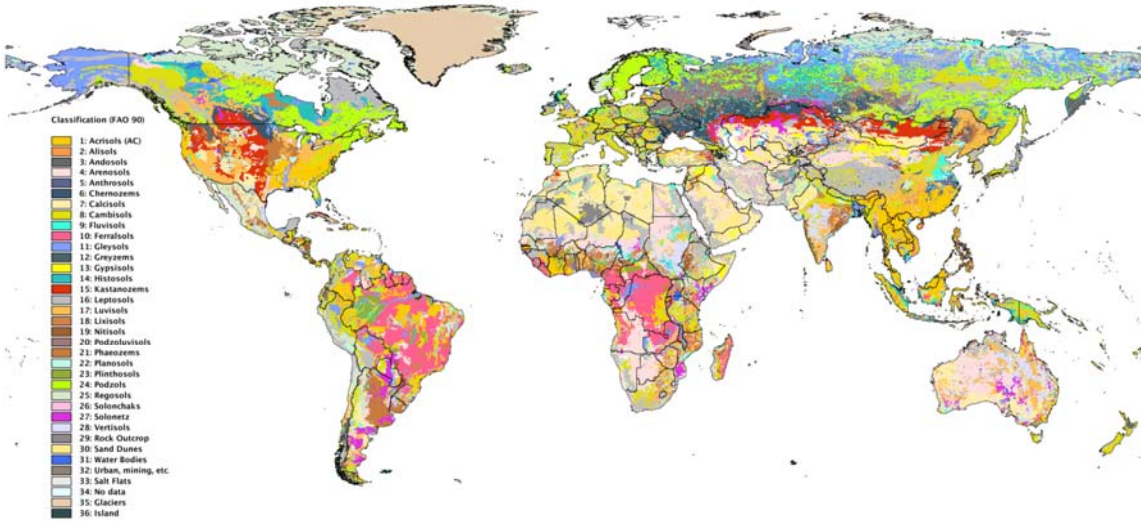

Figure 2-1 Harmonized World Soil database (HWSD)

The use of a standardized structure in HWSD creates a harmonized data product across the various original soil databases. This allows the consistent linkage of the attribute data with the raster map to display or query the composition of soil mapping units and the characterization in terms of selected soil parameters (organic carbon, pH, soil water holding capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry).

Reliability of the information contained in the database is inevitably variable: the parts of the database that make use of the Soil Map of the World such as for North America, Australia, most of West Africa and South Asia are considered less reliable, while most of the areas covered by SOTER databases are deemed to have the highest reliability (Central and Southern Africa, Latin America and the Caribbean, Central and Eastern Europe).

For the agro-edaphic assessment GAEZ applies the most recent Version 1.1 of the HWSD (March 2009). A detailed description of HWSD and the latest version are available for download at: www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HTML/index.html.

GAEZ procedures in Module IV and V make ample use of the soil information provided in the HWSD in order to assess various soil qualities vis-à-vis crop soil requirements.

2.3 Elevation data and derived terrain slope and aspect data

The global terrain slope (Figure 2-2) and aspect (i.e. main direction that the terrain faces) databases have been compiled using elevation data from the Shuttle Radar Topography Mission (SRTM). The SRTM data is available as 3 arc-second DEMs (CGIAR-CSI, 2006).

The high resolution SRTM data have been used for calculating:

1. Terrain slope gradients and classes (for each 3 arc-sec grid cell);
2. Aspect of terrain slopes (for each 3 arc-sec grid cell);
3. Distributions of slope gradient classes and slope aspect classes for a 30 arc second grid.

The SRTM data cover the globe for areas up to 60° latitude. For the areas north of 60° latitude, 30 arc-seconds elevation data and derived slope class information were compiled from GTOPO30 (USGS-GTOPO30 2002).

The global terrain slope and aspect database at 30 arc-seconds used in GAEZ comprises the following elements:

- Median elevation (m) of 3 arc-second grid-cells within each 30 arc-second grid cell
- Distributions (%) of eight slope gradient classes: 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.
- Slope aspect information (%), compiled at 3 arc-seconds and stored at 30 arc-second in distributions of five classes: slopes below 2% (undefined aspect;) slopes facing North (315°–45°); East (45°–135°); South (135°–225°), and West (225°–315°).

A detailed description of the procedures applied can be found in Appendix 10.

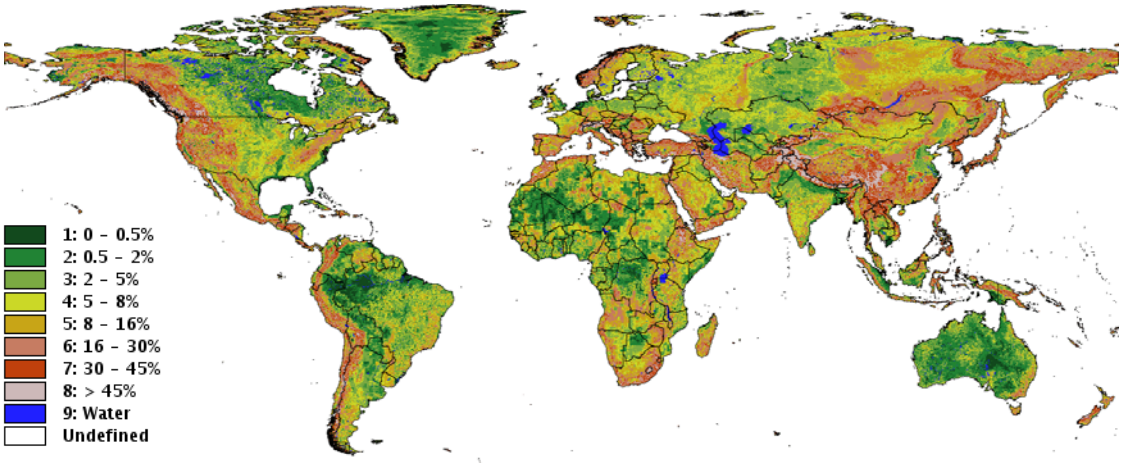

Figure 2-2 Median terrain slopes

Elevation data, slope gradients and slope aspects for both a 5 arc-minute and a 30 arc-second grid are available for download: (www.iiasa.ac.at/Research/LUC/luc07/External-World-soil-database/HTML/global-terrain-slope-download.html?sb=7).

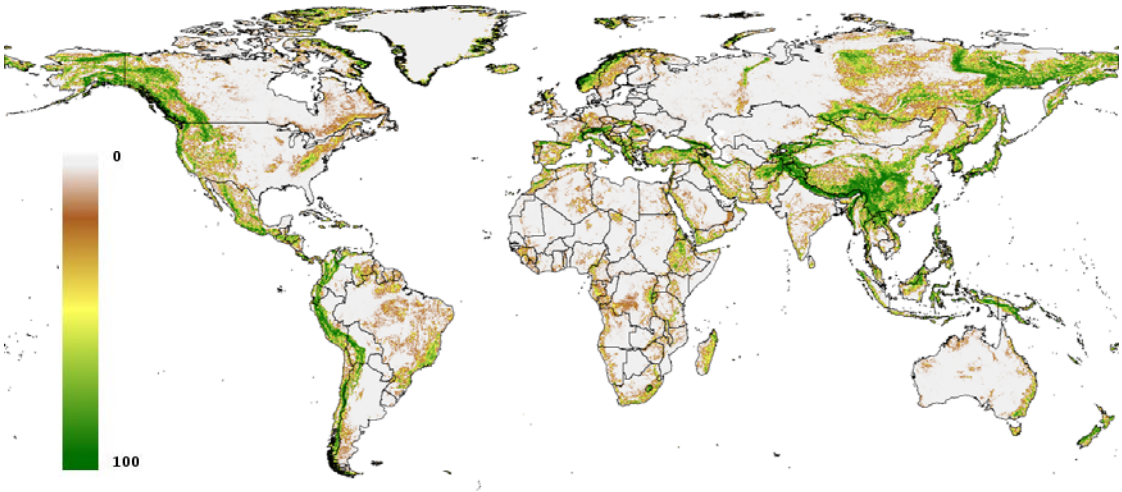

Figure 2-3 Example of calculated terrain slope classes (percent of grid-cell with slope > 16%)

2.4 Land cover data

Six geographic datasets were used for the compilation of an inventory of seven major land cover/land use categories at a 5 arc-minute resolution. The datasets used are:

1. GLC2000 land cover, regional and global classifications at 30 arc-seconds (JRC 2006);
2. IFPRI Agricultural Extent database, which is a global land cover categorization providing 17 land cover classes at 30 arc-seconds (IFPRI 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCCD 2001), EROS Data Centre (EDC 2000);
3. The Global Forest Resources Assessment 2000 and 2005 (FRA 2000 and FRA 2005) of FAO at 30 arc-seconds resolution;
4. Digital Global Map of Irrigated Areas (GMIA) version 4.01 (Siebert 2007) at 5 arc-minute latitude/longitude resolution, providing by grid-cell the percentage land area equipped with irrigation infrastructure;
5. IUCN-WCMC protected areas inventory at 30-arc-seconds (http://www.unep-wcmc.org/world-database-on-protected-areas-wdpa_76.html), and
6. Spatial population density inventory (30 arc-seconds) for year 2000 developed by FAO-SDRN, based on spatial data of LANDSCAN 2003, LandScanTM Global Population Database (http://www.ornl.gov/landscan/), with calibration to UN 2000 population figures.

An iterative calculation procedure has been implemented to estimate land cover class weights, consistent with aggregate FAO land statistics and spatial land cover patterns obtained from (the above mentioned) remotely sensed data, resulting in the quantification of major land use/land cover shares in individual 5 arc-minute latitude/longitude grid-cells. The estimated class weights define for each land cover class the presence of respectively cultivated land and forest. Starting values of class weights used in the iterative procedure were obtained by cross-country regression of statistical data of cultivated and forest land against land cover class distributions obtained from GIS, aggregated to national level. The percentage of urban/built-up land in a grid-cell was estimated based on occurrence of respective land cover classes as well as regression equations, obtained using various sub-national statistical data, relating built-up land with population density. Remaining areas, i.e. areas that are not representing cultivated land, forest land or built-up land, were allocated to:

1. Grassland and other vegetated areas,
2. Barren or very sparsely vegetated areas, and
3. Water bodies

According to the land cover classes indicated at 3 arc-seconds in GLC2000. Barren or very sparsely vegetated areas were delineated by (i) using the respective land cover classes in GLC2000 and/or (ii) a minimum bio-productivity threshold of 100 kg DM/ha/year.

The resulting seven land use/land cover categories, used for land accounting and to characterize each 5 arc-minute grid-cell, are:

1. Rain-fed cultivated land
2. Irrigated cultivated land
3. Forest
4. Grassland and other vegetated land
5. Barren and very sparsely vegetated land
6. Water
7. Urban land and land used for housing and infrastructure.

An example of land cover database from the Harmonized World Soil Database is shown on Figure 2-4 below.

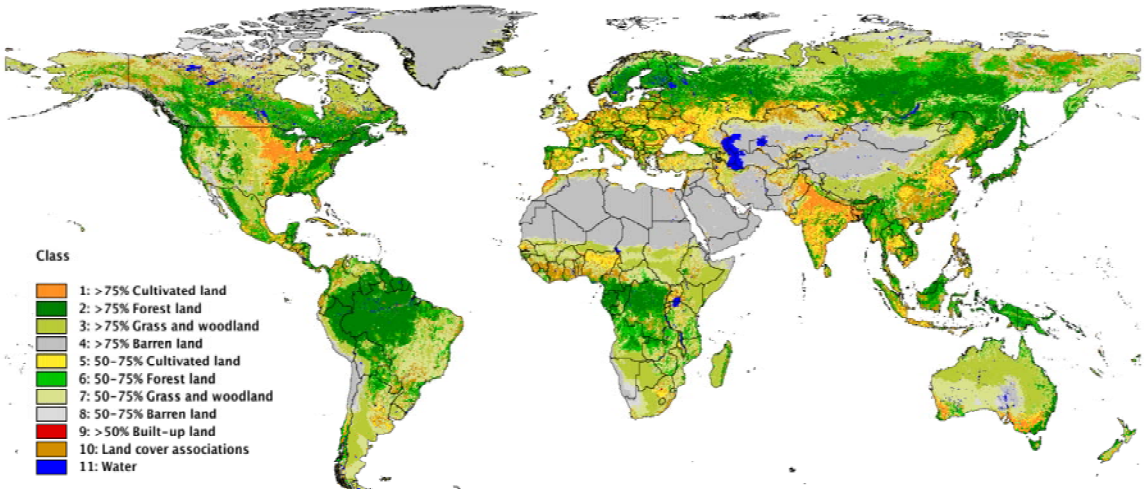

Figure 2-4 Example of land cover data: dominant land cover pattern in the HWSD

2.5 Protected areas

The World Database of Protected Areas Annual Release 2009 (henceforth WDPA 2009) and for the territory of the European Union the NATURA 2000 network, were applied to identify broad categories of protected areas, which are distinguished in the GAEZ analysis:

1. Protected areas where restricted agricultural use is permitted
2. Strictly protected areas where agricultural use is not permitted.

2.5.1 WDPA 2009

The WDPA2009 includes both point and polygon data. The global polygon database was used to delineate 30 arc-second grid cells of protected areas in GAEZ. WDPA 2009 identifies 80,142 different mapping units (termed "Site-ids") with associated attribute data for over 450,000 polygons. The majority of mapping units (51,556) refers to either an international or national convention. The remaining mapping units record the type of protected area, e.g. national park, natural monument, etc. (item DESIG_ENG in WDPA 2009). From these units, 77 designations were considered to be 'strictly protected' and therefore these categories are considered not available for agriculture. The most important designations include 'National Parks', 'Forest Reserves', 'Zapovednik' (a protected area in Russia which is kept "forever wild"), 'Wildlife Management Area', 'Nature Park', 'Resource Reserve', 'Nature Reserve', and 'Game Reserve'.
The European part of the WDPA inventory does not include important protected areas for the EU 27, which are however part of the NATURA 2000 network. WPDA 2009 grid and the NATURA 2000 network information were combined to form the GAEZ protected area layer.

2.5.2 Natura 2000

The European Union has established a network of nature protection areas, known as the NATURA 2000 network, with the aim to assure the long-term survival of Europe's most valuable and threatened species and habitats. It also fulfills an obligation under the UN Convention on Biological Diversity. The network is comprised of Special Areas of Conservation (SAC) designated by Member States under the Habitats Directive, and also incorporates Special Protection Areas (SPAs) which they designate under the Birds Directive. NATURA 2000 currently includes over 26,000 protected areas covering a total area of around 850,000 km^2, representing more than 20% of total EU territory.

To distinguish 'protected' and 'strictly protected' areas CORINE land cover 2000 (CLC2000; http://etc-lusi.eionet.europa.eu/CLC2000) distributions of the NATURA 2000 sites were calculated. CLC2000 data are available at 100 meters resolution and categorized using the 44 land cover classes of the 3-level CORINE nomenclature. The spatial polygon database of NATURA 2000 was converted to a 100 m grid-cell size and overlaid with CLC2000. Where applicable, the CORINE land cover classes

'Arable land', 'Permanent crops' and 'Heterogeneous agriculture' were assigned to the 'protected areas' category, thus permitting restricted agricultural use. The remaining land cover classes were considered to represent 'strictly protected areas', where cultivation of arable crops is not possible.

The 100-meters resolution grid map showing the two types of protected areas was projected to a 30 arc-second longitude/latitude grid map and the respective areas of the 27 countries of the European Union (EU27) were integrated in the GAEZ protected areas layer.

Table 2-2 presents a summary of the various convention types used in the GAEZ protected areas layer. The protected areas are subdivided in types which permit or do not permit agricultural use. The GAEZ protected areas layer comprises 20% of 'protected areas' where agriculture is conditionally permitted and 80% 'strictly protected areas' where agriculture is assumed not to be permitted.

Table 2-2 GAEZ protected areas layer

Code	Convention type	Agricultural use	Share of total protected area
1	IUCN Ia Strict Nature Reserve	no	4.7%
2	IUCN Ib Wilderness Area	no	7.2%
3	IUCN II National Park	no	30.7%
4	IUCN III Natural Monument	no	0.8%
5	IUCN IV Habitat Management	no	12.2%
6	IUCN V Protected Landscape	yes	8.9%
7	IUCN VI Managed Resource	yes	10.9%
8	Ramsar Convention (Wetlands)	no	3.1%
9	World Heritage Convention	no	5.0%
10	UNESCO-MAB Biosphere Reserves	no	1.4%
11	ASEAN Heritage	no	0.2%
12	Natura 2000 (limited agricultural use)	yes	0.7%
13	Natura 2000 (no agricultural use)	no	3.7%
14	National (Non-forest)	no	7.9%
15	National (Forest)t	no	2.5%
	TOTAL (no agricultural use)'		80%
	TOTAL '(limited agricultural use)s'		20%
	TOTAL protected		100%

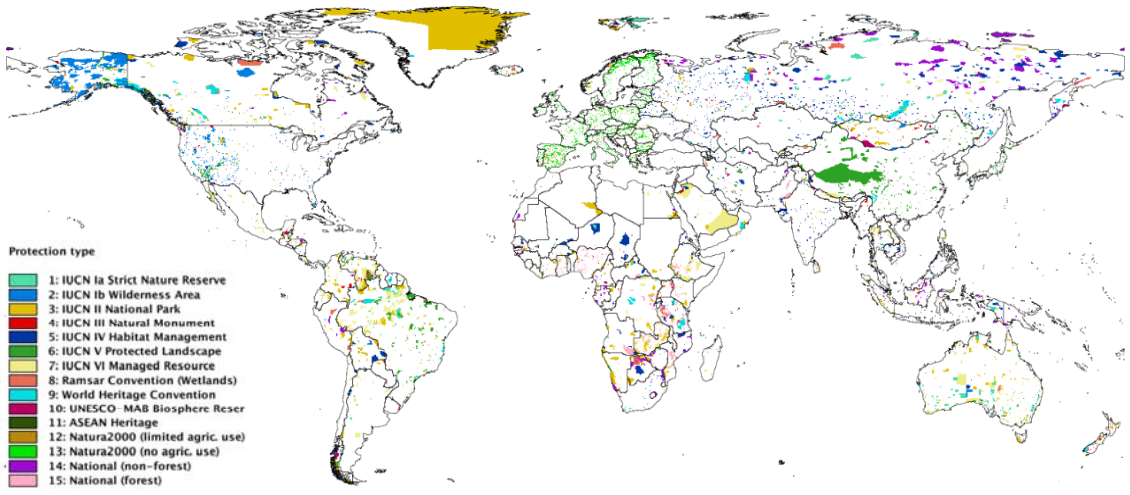

Figure 2-5 Protected Areas

2.6 Administrative areas

The Global Administrative Unit Layers (GAUL) provides authoritative global spatial information on administrative units for all countries in the world. GAUL is an initiative implemented by the Food and Agriculture Organization (FAO) of the United Nations, which has significantly contributed to the standardization of comprehensively recording spatial administrative units.

The GAUL maintains global geographic layers with a unified coding system of national and sub-national administrative levels. Controversial and disputed boundaries are maintained such, that national integrity for all disputing countries is preserved. Once a year, an updated version of the GAUL set is released through Geonetwork (http://www.fao.org/geonetwork/srv/en/main.home). The version of GAUL applied in GAEZ v3.0 was obtained in 2009.

For use in GAEZ the GAUL vector data has been transformed respectively to rasters of 5 arc-minutes and 30 arc-second grid-cells. For aggregating GAEZ country results and information at regional and continental level, the countries included in the GAUL have been codified according to three levels of supra-national regionalization, see Appendix 2-1.

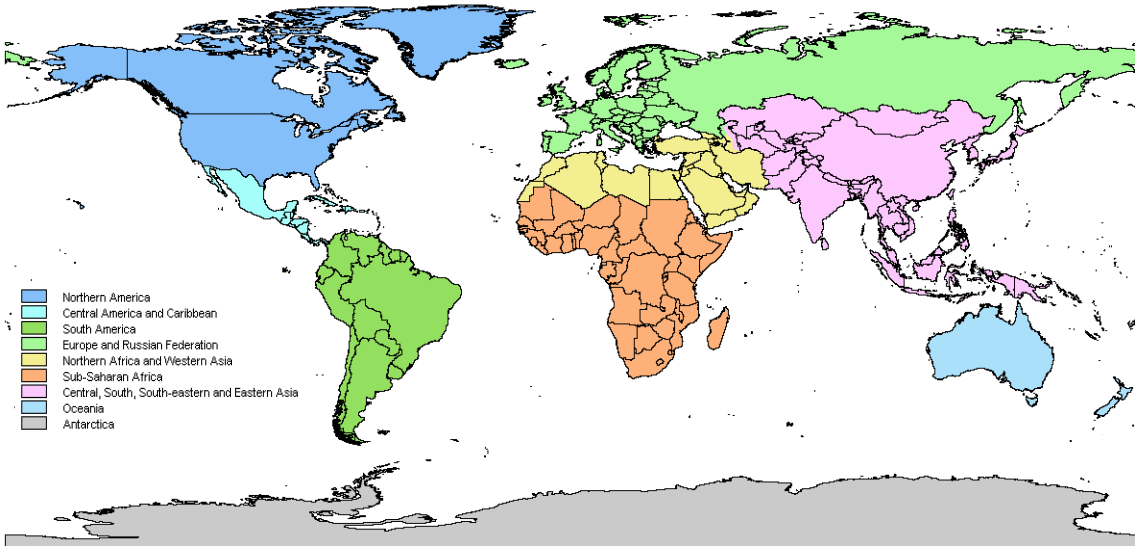

Figure 2-6 GAUL country boundaries layer with continental GAEZ regionalizations

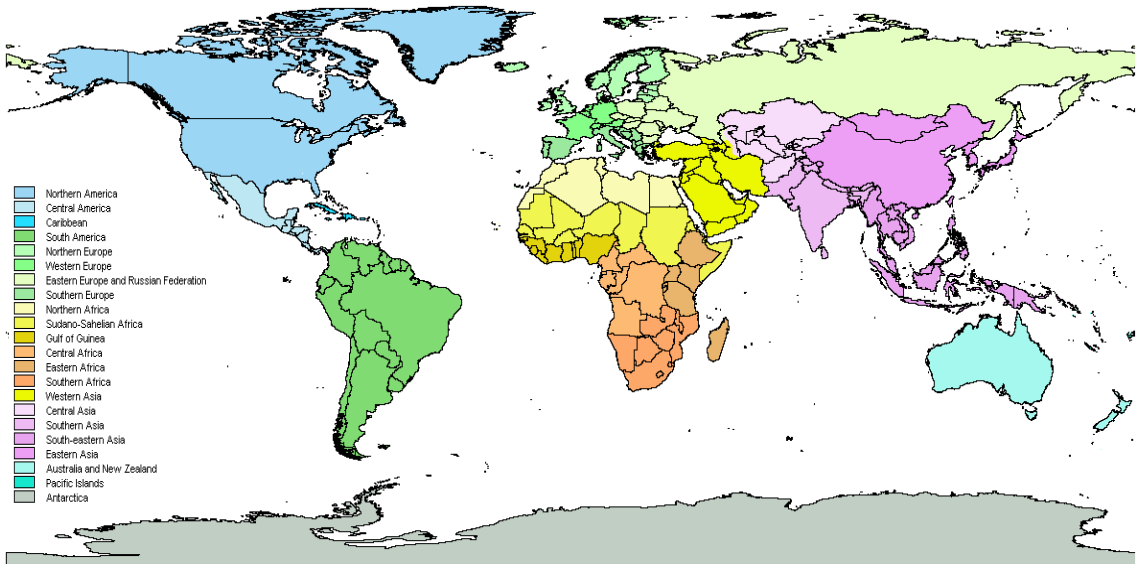

Figure 2-7 GAUL country boundaries layer with sub-continental GAEZ regionalizations

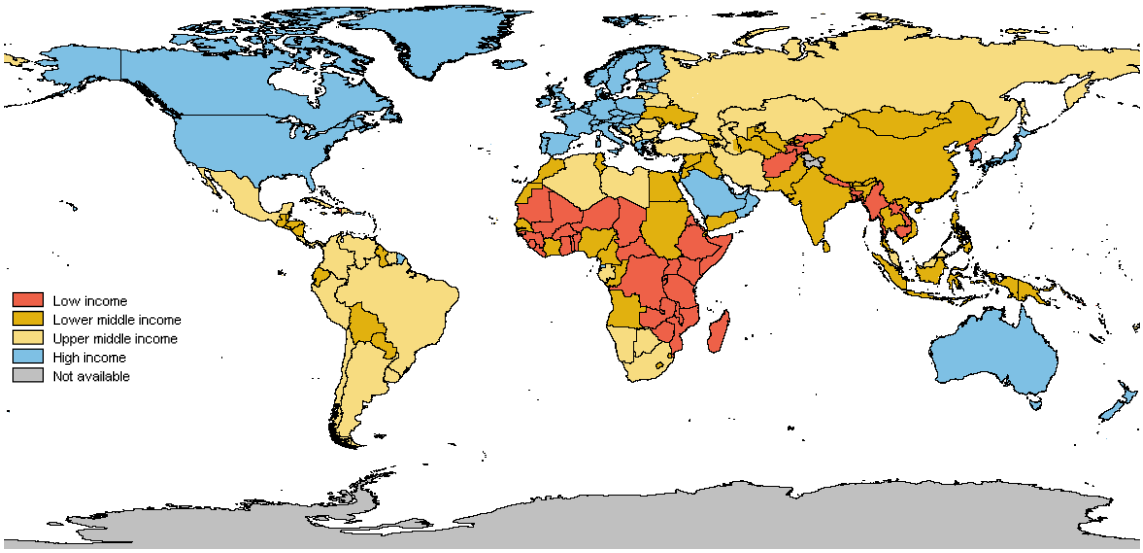

Figure 2-8 GAUL country boundaries layer income level regionalizations

3 Module I (Agro-climatic analysis)

3.1 Overview Module I

Module I deals with temporal, interpolation, analysis and classification of climate data and creation of historical, base line and future gridded agro-climatic indicators relevant to plant production. The main objective in Module I is the compilation of geo-referenced climatic resources inventory containing relevant agro-climatic indicators. The inventory is used for the evaluation of land suitability and estimation of crop yields and production in: Module II (biomass and yield calculation), Module III (agro-climatic yield constraints) and Module V (integration of climatic and edaphic evaluation). Figure 3-1 presents the information flow in Module I.

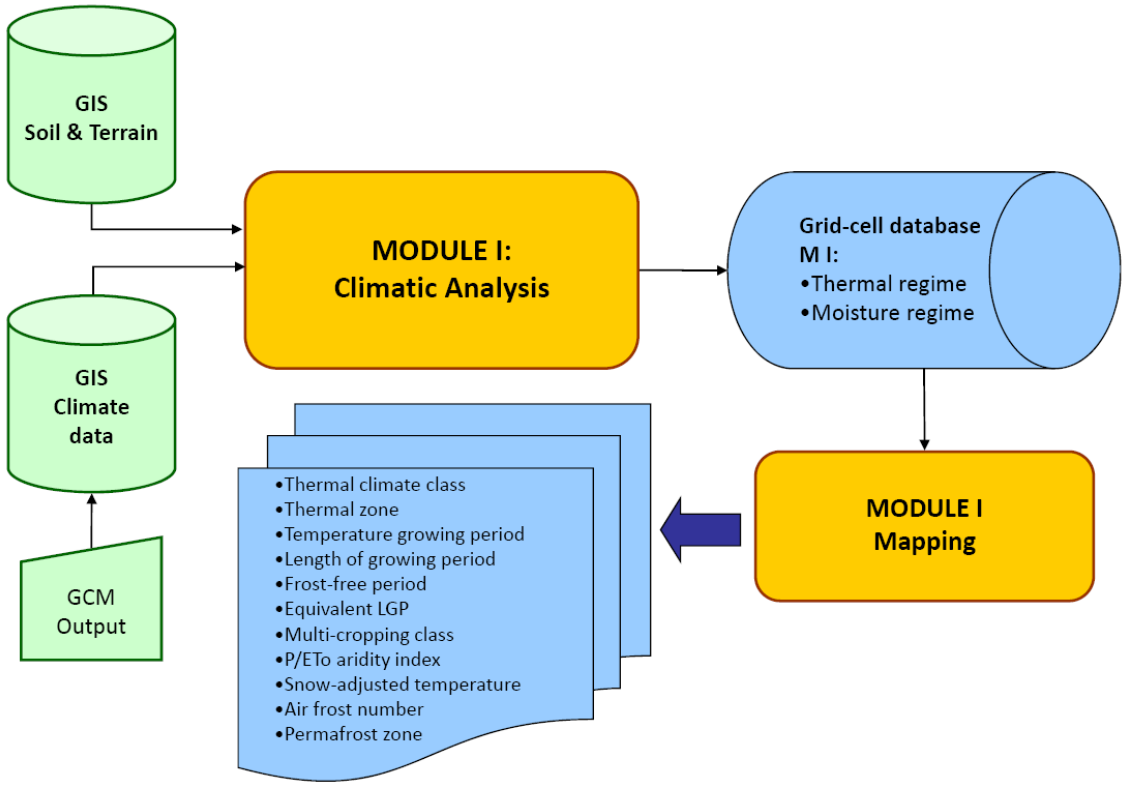

Figure 3-1 Information flow in Module I of the GAEZ model framework

Spatially explicit climatic databases provide the main input data for Module I. Available monthly climate data and their spatial interpolation to a 5 arc-minute grid for the globe are presented in Section 2.1.

3.2 Preparation of climatic variables

Climatic variables are prepared for the use in GAEZ through conversions and temporal interpolations Temporal interpolations of the gridded monthly climatic variables into daily data, provides the basis for the calculation of soil water balances and agro-climatic indicators relevant to plant production.

Wind run and wind speed

Wind data is used for the estimation of evapotranspiration. For the agro-climatic calculations observed, wind speed (U10) at 10 m height is converted to windspeed (U2) and wind run at 2 m height that is standard crop canopy height in agro-climatologic analysis. (FAO 1992)

Wet day frequency

Wet day frequency (WET) is used to derive daily precipitation events from monthly totals. For historical or future time periods for which wet day frequency is not available as input data it is established through the relationship:

$$WET = WET^{ref} \times \left(\frac{P}{P^{ref}} \right)^{0.45}$$

where P and P^{ref} are respectively the monthly precipitation of the historical or future time periods and monthly precipitation of the 1961-1990 reference climate period. WET^{ref} represents the monthly wet day frequency in the reference climate. Additional climatic indicators, necessary to assess crop suitability and yield in Module II, are calculated in the Module I of GAEZ. These are sunshine duration, day-length, day-time and night-time temperatures, temperature profiles and air frost number.

Sunshine duration

Actual sunshine duration (n) is used for the calculation of incoming solar radiation, for evapotranspiration and biomass calculations. Sunshine duration is calculated from the ratio actual sunshine hours over maximum possible sunshine hours (n/N).

Day-time and night-time temperatures

The temperature during day-time (Tday, ^{o}C) and night-time (Tnight, ^{o}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, 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 depends on the latitude of a grid-cell and 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 (Monteith 1965; Monteith 1981; FAO 1992). A detailed 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 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). The kc factors are related to phenological development and leaf area. The kc values are crop and climate specific. They vary generally between 0.4-0.5 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 (LGP_{t5} equals 365 days), i.e. when average daily temperature stays above 5°C for the entire year, the kc value applied for the reference crop is always 1.0. When LGPt5 < 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 ETm are available from various sources (FAO 1998) and differ by the development stage of the crop (see section 4.5.1).

Actual evapotranspiration (ETa)

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

(i) Adequate soil water availability (ETa=ETm)
(ii) Limiting soil water availability (ETa<ETm)

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

ETa for adequate soil water availability

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). 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

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. All precipitation (P) falls as snow (P^{snow}) when maximum temperature (Tx) is below a temperature threshold (Ts).
Snowmelt (Sm) is calculated as a function of daily maximum temperature, the snow melt parameter (δ) and is subject to the previously accumulated snow balance. The snow melt factor δ is set to 5.5 mm/^{o}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^{o}C in GAEZ
ks = 0.1, when Tx > Ts and Ta < 0^{o}C
ks = 0.2, when Tx > Ts and 0^{o}C <Ta<5^{o}C

Once the water balance for the 'reference crop' is calculated, five variables are produced and used for further computations in GAEZ modules. 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)
5. Excess water of 'reference' crop water balance (We)

3.2.1 Temporal interpolation

GAEZ uses quadratic spline interpolation to derive daily values from available monthly data (from the CRU and GPCC climate data).

With data available for several periods ($i = \overline{1:N}$), the goal of the interpolation procedure is to fill intermediate data points within the given observations. The quadratic spline interpolation assumes that the data between subsequent data points (t_i, y_i) and (t_{i+1}, y_{i+1}) can be estimated by a piecewise quadratic polynomial ($y = a_i t^2 + b_i t + c_i$) connecting the given points - where i denotes the available monthly observations ($i = \overline{1:N}$). As there are N observations and, therefore, $3N$ unknown parameters (a_i, b_i, and c_i), also $3N$ equations are required to estimate these

parameters. $2N$ equations are derived from the requirement of a continuous function, i.e. that neighboring segments meet at the points they have in common (note that the last segment joins the first one:

$$y_{i+1} = a_i t_{i+1}^2 + b_i t_{i+1} + c_i = a_{i+1} t_{i+1}^2 + b_{i+1} t_{i+1} + c_{i+1}$$

Then another N equations are derived from the requirement that in each internal point ($i = \overline{2:N-1}$) as well as the last segment joining the first one, the first derivatives of the joining quadratic functions are equal:

$$2a_i t_{i+1} + b_i = 2a_{i+1} t_{i+1} + b_{i+1}$$

Thus, all parameters a_i, b_i, and c_i ($i = \overline{1:N}$) of the polynomials $y = a_i t^2 + b_i t + c_i$ are established.

In this way, the following eight climatic variables are converted by spline interpolation from monthly to pseudo-daily values:

1. Minimum temperature (Tn)
2. Daytime temperature (Tday)
3. Maximum temperature, (Tx)
4. Reference evapotranspiration (ETo)
5. Wind speed at 2 m height (U2)
6. Relative humidity (RH)
7. Sunshine hours (n)

For distributing monthly precipitation (P) within a month, in addition the input data on observed number of monthly precipitation events (wet day frequency) is used together with precipitation trends according to the spline interpolation of monthly precipitation values.

3.3 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 five types of indicators: (i) thermal climates; (ii) thermal zones; (iii) length of temperature growing periods; (iv) temperature sums, and (v) temperature profiles.

3.3.1 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 is based on (i) the average monthly temperature, (ii) proportions of respectively summer, winter rainfall[1], 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°C/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.

[1] Rainfall has been represented with summer respectively, winter P/Eto ratios.

Table 3-1 Classification of thermal climates

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.	
Climate	**Rainfall and Temperature Seasonality**
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

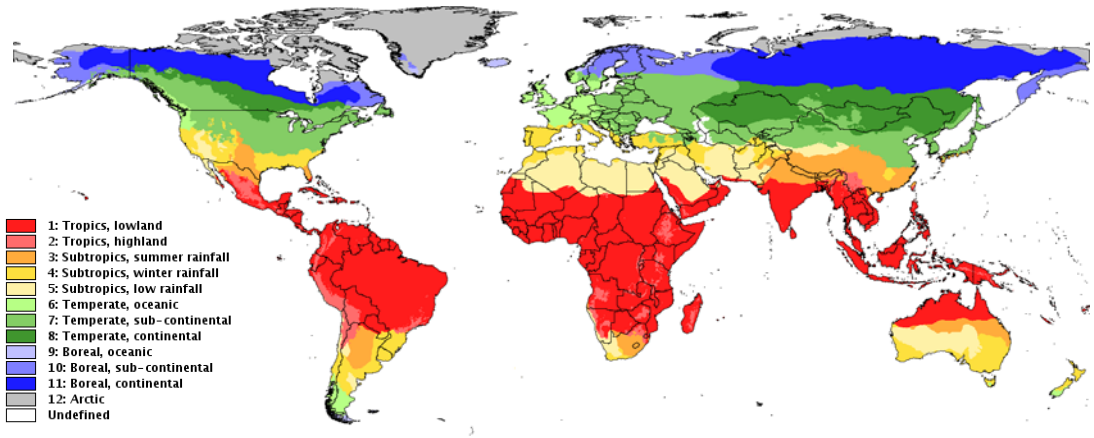

Figure 3-2 Thermal climates

3.3.2 Thermal Zones

Thermal zones reflect the prevailing temperature regimes of major thermal climates. The classification is presented in Figure 3-3:

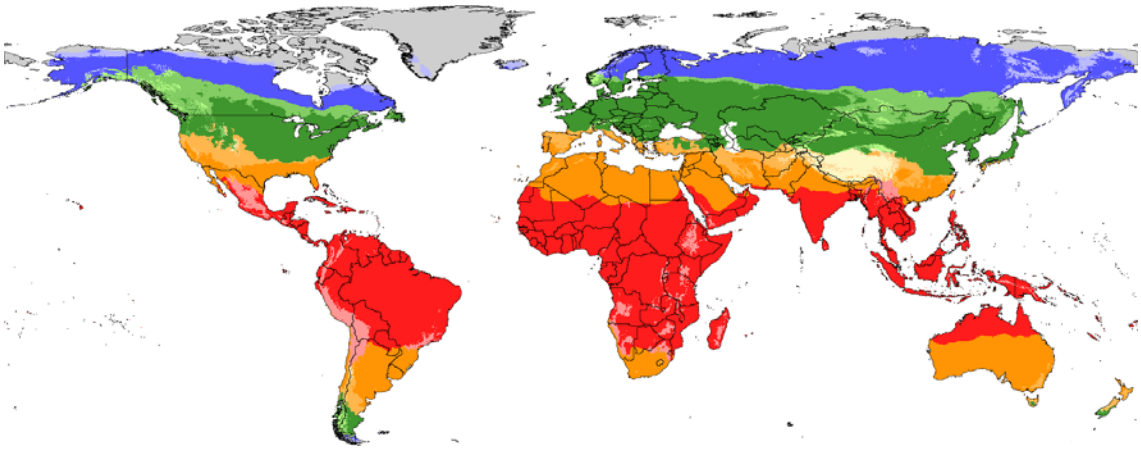

Figure 3-3 Thermal Zones

(i) ***Warm*** in tropical zones refers to annual mean temperatures above 20°C, *cool, cold, very cold* tropics refers to annual mean temperature below 20 °C;

(ii) ***Moderately cool*** refers to actual temperature conditions characterized by one or more months with monthly average temperatures below 18°C but all above 5 °C and 8-12 months above 10 °C;

(iii) ***Cool*** refers to conditions with at least one month with monthly mean temperatures below 5 °C and four or more months above 10 °C;

(iv) ***Cold*** refers to conditions with at least one month with monthly mean temperatures below 5 °C and 1-3 months above 10 °C, and

(v) **V*ery cold*** refers to polar conditions i.e. all months with monthly mean temperatures below 10 °C.

3.3.3 Temperature growing periods (LGPt)

The length of the 'temperature growing period' (LGPt) is calculated as the number of days in the year when average daily temperature (Ta) is above a temperature threshold "t". In GAEZ three standard temperature thresholds for temperature growing periods are used: (i) periods with Ta > 0°C, (ii) periods with Ta > 5°C, which is considered as the period conducive to plant growth and development, and (iii) periods with Ta > 10°C, which is used as a proxy for the period of low risks for late and early frost occurrences.

Therefore, GAEZ calculates the following three LGPt's:

(i) $LGPt_0$ period when Ta > 0°C

(ii) $LGPt_5$ period when Ta > 5°C

(iii) $LGPt_{10}$ period when Ta > 10°C

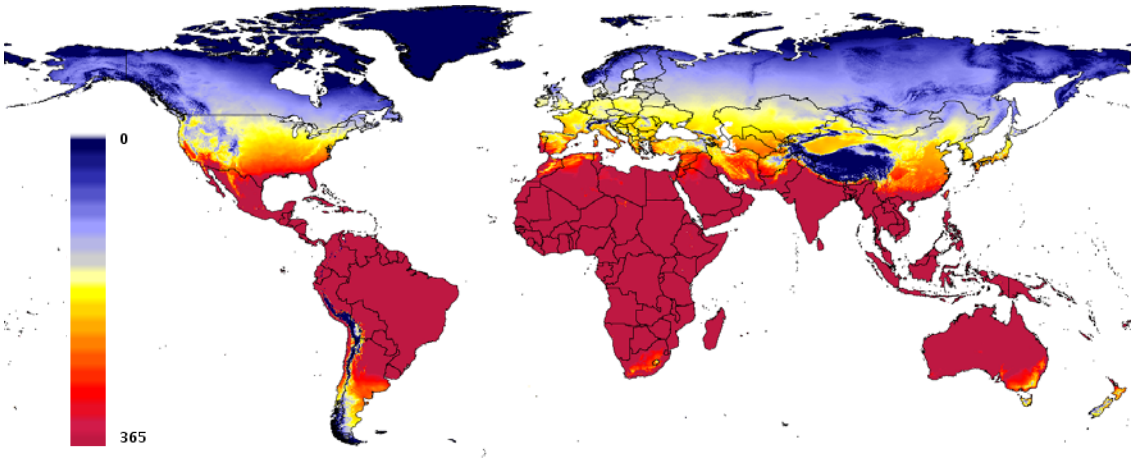

Figure 3-4 'Frost-free' period (LGPt10)

3.3.4 Temperature sums (Tsum)

Heat requirements of crops are expressed in accumulated temperatures. Reference temperature sums (Tsum) are calculated for each grid-cell by accumulating daily average temperatures (Ta) for days when Ta is above the respective threshold temperatures "t" as follows:

(i) $0^{o}C$ ($Tsum_0$)
(ii) $5^{o}C$ ($Tsum_5$)
(iii) $10^{o}C$ ($Tsum_{10}$)

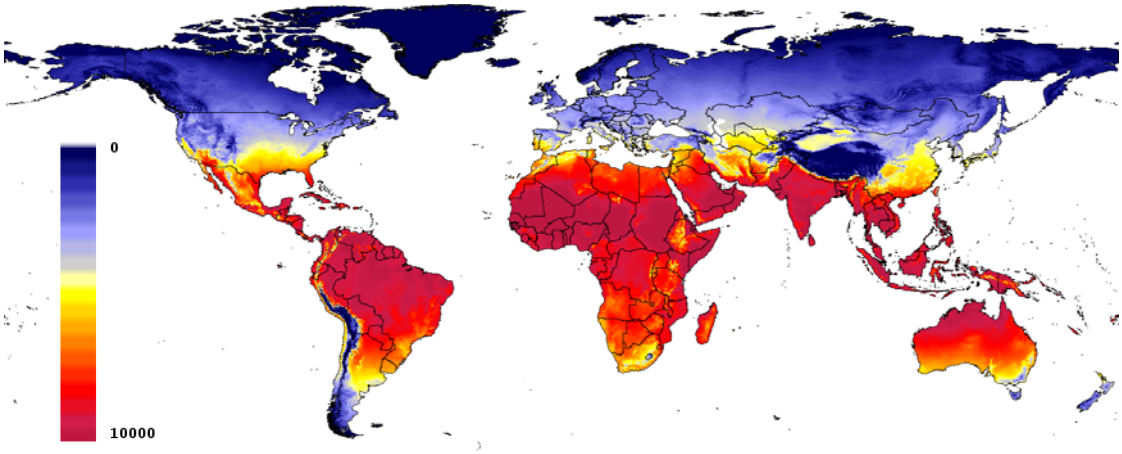

Figure 3-5 Temperature sums for the 'frost-free' period with Ta> 10oC

3.3.5 Temperature profiles

Temperature profiles (Table 3-2) are defined in terms of 9 classes of "temperature ranges" for days with Ta <-5°C to >30°C (at 5°C 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 rendering a crop not suitable for the respective location.

Table 3-2 Temperature profile classes

Average temperature (Ta, °C)	Temperature trend	
	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

3.3.6 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
(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°C, are used to calculate the thawing index (DDT) and the freezing index (DDF).
The thawing index DDT is calculated as:

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

The freezing index (DDF) is calculated as:

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

The frost index (FI) is then calculated (Nelson 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).

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.**

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 3-6 presents the reference permafrost zones map.

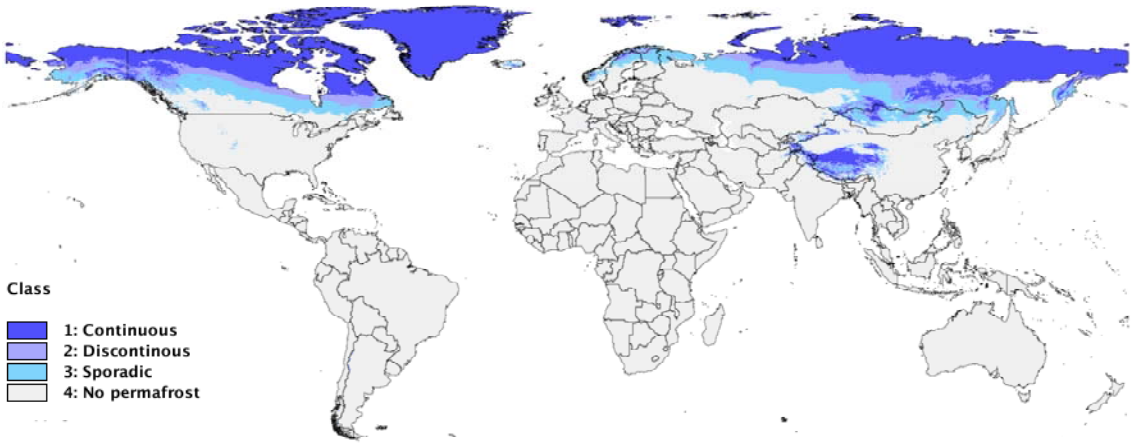

Figure 3-6 Reference permafrost zones

3.4 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.

3.4.1 Soil moisture balance

Daily soil moisture balance calculation procedures follow the methodologies outlined in CROPWAT (FAO 1986, 1992) and "Crop Evapotranspiration" (FAO, 1998). The quantification of a crop-specific water balance determines crop "actual" evapotranspiration (ETa) used for water-constrained crop yield calculations.

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 total soil water holding capacity (Sa). By definition, Wx is the product of total soil water holding capacity (Sa) and rooting depth (D).

$$Wx = Sa \times D$$

The 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, actual soil water content (Wb) will be available to plants if Swp < Wb < Sfc (Figure 3-9). 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 soil water holding capacity (Sa).

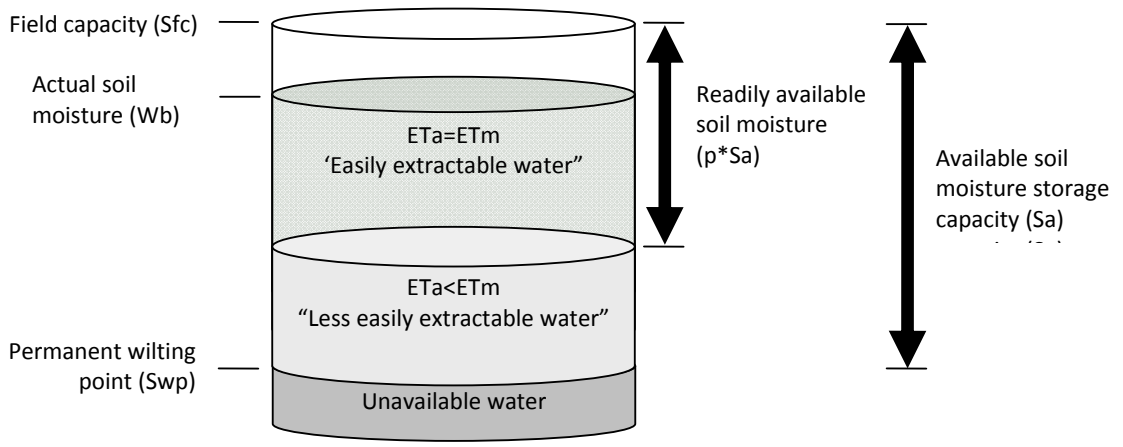

Figure 3-7 Schematic representation of water balance calculations

The values of Sa and rooting depth limitations due to soil are derived from soil information contained in the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). FAO has developed procedures for the estimation of Sa (FAO 1995; Fischer *et al.* 2002). Any water input into the soil that exceeds Wx is "lost" as excess water (We) and considered "not available" in further GAEZ calculations. It accounts for the water lost either by runoff or deep percolation.

3.4.2 Soil moisture balances with soil moisture conservation

In arid and semi arid zones warer conservation management practices are used to copy with marginal and unreliable, but where still sufficient rainfall occurs to build up adequate soil moisture storage for successful growing of crops. These areas typical receive annual rainfall between 300 and 600 mm and reference growing periods of 30-120 days. Figure 3-7 shows the occurrence of these zones that have a total extent of 3.2 billion hectares, almost 24 % of the total world land surface (excluding Antarctica). The majority of these areas occur in the United States, Argentina, Southern Africa, North Africa, the Sahel, West and Central Asia and Australia.

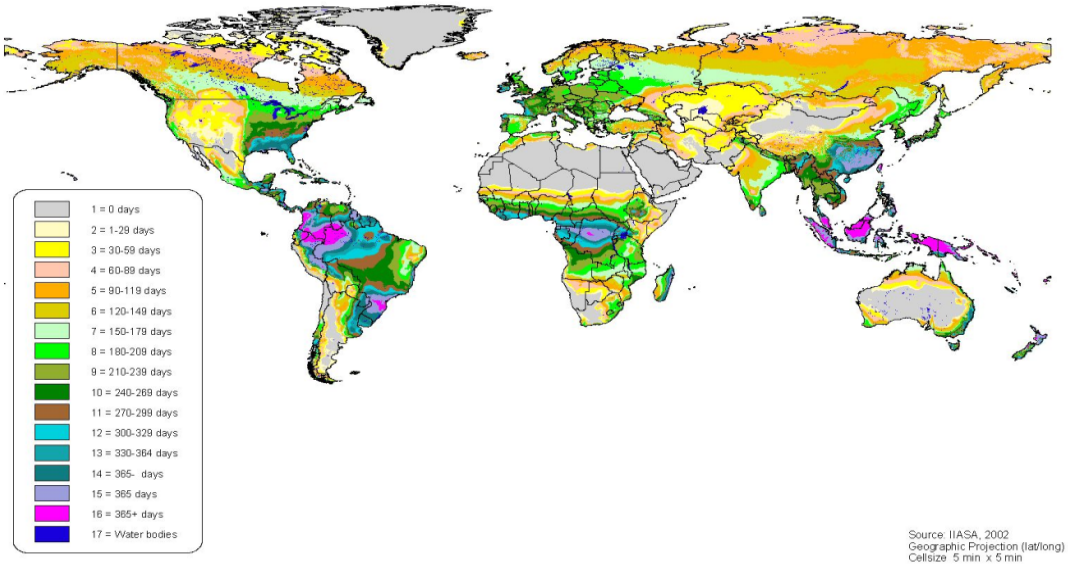

Figure 3-8 Reference Length of Growing Period Zones

For rain-fed production with soil moisture conservation, GAEZ calculates an alternative soil moisture balance with three major modifications compared to regular rain-fed conditions (i.e., regular water balance without assuming specific soil moisture management practices), namely (i) land management reducing soil evaporation outside the period of crop growth (assuming soil evaporation rate of 20% of reference evapotranspiration during non-cropped periods), (ii) different rooting patterns with increased available soil moisture in the soil profile (increasing available soil moisture holding capacity by about 50%), and (iii) simulating crop growth only when start season available soil moisture exceeds minimum threshold levels, otherwise conserving soil moisture through fallow.

Enhanced soil moisture balance

Reference evapotranspiration, stored soil moisture and rainfall are used together with crop transpiration water requirements of dryland cropping systems and evaporation losses during clean fallow (no-tillage or reduced tillage) in a year round water balance.

The amount of soil moisture stored in the soil profile, and available to a crop, varies, e.g., with depth of the soil profile, the soil physical characteristics, and the rooting pattern of the crop. For crops relying on rainfall during the crop cycle and stored soil moisture available soil moisture (AWC) is set to a maximum of 150mm, assuming that the bulk of roots occur mainly in the top 100 cm of the soil profile (Fischer et al., 2002).

For crops for a large extent relying on residual soil moisture AWC is 200-250 mm soil moisture can be used since the bulk of the roots in deep soils may move with retracting soil moisture down to a depth of about 150 cm. This implies an adjustment of the AEZ water balance model parameters concerns the AWC for crops grown on residual moisture.

Water conservation by means of zero tillage and reduced tillage systems (which include the use of herbicides or mechanical means for the removal of weeds to avoid additional transpiration losses) leads to reduced soil evaporation.

In rain-fed assessments conventional tillage systems are assumed. For the rain-fed with water conservation assessments tillage systems are assumed that help conserving soil moisture in the soil profile. A number of factors have been considered namely: (i) improvement of soil moisture intake, (ii) reduction of soil evaporation losses, (iii) reduction of percolation losses and (vi) optimal use of soil moisture.

Box 1 Tillage systems

Improving soil moisture intake
Plant cover: slows runoff
Crop stubble and debris: slows runoff and captures drifting snow
Tillage: improves infiltration into poorly permeable soils

Reduction of evaporation losses
Mulching: reduces evaporation, discourages weed growth (transpiration)
Tillage of topsoil: May reduce evaporation by breaking soil capillary water movement towards soil surface.
Weeding: reduces interception losses and evaporation.

Reducing of percolation losses
Increase of organic matter: Improve available water holding capacities of soil profile

Optimizing soil moisture
Reduce seed rate/increase spacing: Increases moisture available per plant
Fallowing: (clean fallow reduces transpiration of weeds)
No tillage: Reduces evaporation losses
Reduced tillage: Reduces evaporation losses
Sub-tillage: Reduces evaporation losses and may reduce soil capillary water movement towards soil surface.

Measures as described in box 1 have been accounted for. It has been assumed that depending on soil and terrain conditions adapted measures are taken to achieve optimal water conservation from rainfall while preventing soil erosion. Where possible (for instance in absence of problems like runoff due to low soil infiltration rates because of heavy topsoils or sealing characteristics of the soil surface) zero tillage with clean fallow is assumed. For soils with runoff due to low infiltration rates, prevalence of topsoil sealing and other specific topsoil characteristics and unfavorable soil capillary conditions, reduced tillage and sub-tillage systems are assumed (FAO, 1984). Also it is assumed that crop stubble, crop debris and mulching practices are used where practical and beneficial for soil moisture conservation. In summary best practice vis-à-vis soil moisture conservation is assumed in the AEZ water balance.

Soil moisture conditions at planting

The planting of a crop is assumed when sufficient moisture has been accumulated in the soil profile (AWC) to cover water requirements of a major part of the crop cycle. This latter value is a model parameter, which may vary according to expected rainfall, specific crop water requirements and evaporative demand of the atmosphere. The required AWC has been set to 175 mm. In case the water balance shows that the 175 mm are not met the crop is assumed not planted and a fallow period to conserve additional soil moisture is introduced until a next feasible planting date.
Crop/LUTs for for rain-fed with water-conservation assessments of suitability and productivity include LUTs of wheat, barley, grain and silage maize, sorghum, millets, chickpea, cowpea, soybean and rape.
A schematic overview of various temperature/cover phases of the water balance calculations as performed in AEZ for both rainfall dependent crop growth as well as crops growth relying on residual soil moisture is presented in Table 3-4. It shows how the various steps of AEZ water balance are parameterized and how calculations are influenced by temperature and snow cover conditions.

Table 3-4 Water balance parameters by temperature and cover

Periods	←P1a→	←P1b→	←P2a→	←P2b→	← P3 →	← P4 →	← P5 →	← P6 →	← P7 →	← P8 →	← P9 →	← P10→	←P11→
Cover (1)	**Fallow**							**Crop Stage1**	**Crop Stage2**	**Crop Stage3**	**Fallow**		
Mean Temperature	Tm<0	Tm<0	Tm<0	Tm<0	Tm 0-5	Tm 0-5	Tm>5	Tm>5	Tm>5	Tm>5	Tm>5	Tm 0-5	Tm<0
Maximum temperature	Tmax <0	Tmax <0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0	Tmax >0
Snow cover	Snow	No snow	Snow	No snow	Snow melt	No snow		No snow			No snow		
Evapo(transpi)ration	EVsnow	EVfroz1	EVsnow.	EVfroz2	EVsnow	ETsoil/ EVsoil	ETsoil/ EVsoil	ETm	ETm	ETm	ETsoil/ EVsoil	ETsoil/ EVsoil	EVfroz
Rainfed/ conventional tillage	0.2ETo	0.2Eto	0.2ETo	0.2ETo	0.2ETo	0.3ETo	0.4ETo	kc* ETo	kc* ETo	kc* ETo	0.4ETo	0.3ETo	0.2ETo
Rainfed/ zero tillage + weed removal or reduced tillage	0.2ETo	0.2Eto	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	kc* ETo	kc* ETo	kc* ETo	0.2ETo	0.2ETo	0.2ETo

Cover (2)	**Fallow**												
Evapo(transpi)ration	EVsnow	EVfroz1	EVsnow	EVfroz2	EVsnow	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	ETsoil/ EVsoil	EVfroz
Rainfed/ conventional tillage	0.2ETo	0.2Eto	0.2ETo	0.2ETo	0.2ETo	0.3ETo	0.4ETo	0.4ETo	0.4ETo	0.4ETo	0.4ETo	0.3ETo	0.2ETo
Rainfed/ zero tillage + weed removal or reduced tillage	0.2ETo	0.2Eto	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo	0.2ETo

Tm=mean temperature, Tmax=maximum temperature; ETo= reference evapotranspiration; EVsnow=sublimation rate of snow (= 0.2*ETo); EVfroz.= evaporation from frozen soil (= 0.2*ETo); EVsoil= evaporation from non frozen bare soil (= 0.2*ETo); ETsoil= evapotranspiration from non frozen soil and weeds (= 0.3 or 0.4*ETo). ETm= maximum crop evapotranspiration (= kc*ETo, where crop coefficient kc ranges are crop stage dependent).

3.4.3 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 a reference crop. In a formal sense, LGP refers to the number of days when average daily temperature is above 5°C (i.e. within LGP_{t5}) and ETa is above a specific fraction of ETo. In the current GAEZ parameterization, LGP days are considered when ETa ≥ 0.5 ETo (FAO 1978-81; FAO 1992), which aims to capture periods when sufficient soil moisture is available to allow the establishment of a reference crop. Figure 3-9 presents a map of reference length of growing period, which is based on soil moisture holding capacity of 100 mm.

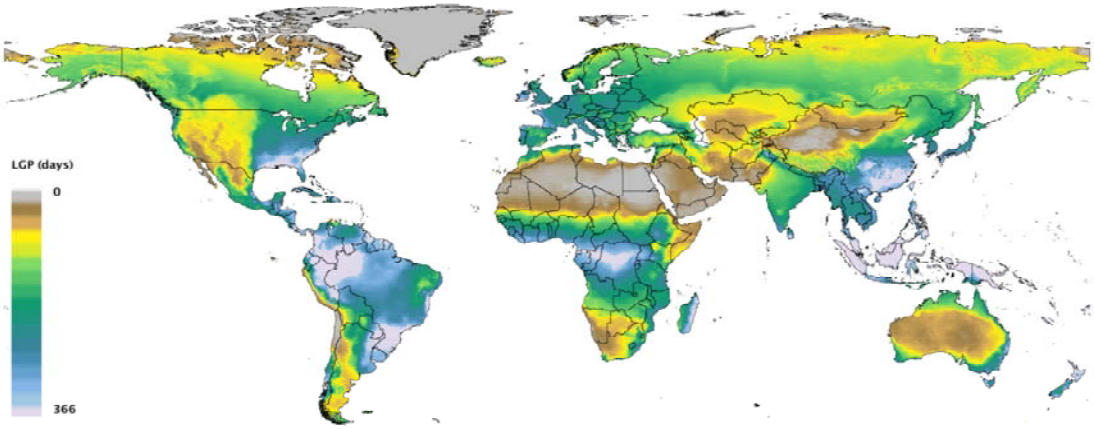

Figure 3-9 Reference length of growing period

The length of growing period data is also used for the classification of general moisture regimes classes. The GAEZ moisture regimes nomenclature and 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 a LGP is characterized by different water supply conditions as follows: *Growing period days without water stress (ETa=ETm):* When ETa equals ETm' 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 stored soil moisture is less than field capacity (Wb<Sfc). Excess rainfall now adds to replenish the soil moisture storage.
2. Daily rainfall is higher than crop water requirements, P>ETm, and soil moisture is at field capacity (Wb=Sfc). 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 (Wb>(ETm-P)+Wr. In this case ETa equals ETm and the soil moisture content in the soil profile is decreasing.

Growing period days with water stress (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 moisture becomes insufficient (ETa < 0.5 ETo), 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 determines individual continuous LGPs. Various soil moisture supply stages during the LGP are recorded and various indicators are calculated as follows:

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. Length of individual growing periods
6. Number of growing period days in individual growing periods
7. Number of days when P>ETm in individual growing periods
8. Begin date of individual growing periods
9. End date of individual growing periods
10. Temperature profile, i.e., number of growing period days occurring in 5°C steps between <-5°C to >30°C, with increasing temperature trend.
11. Temperature profile, i.e., number of growing period days occurring in 5°C steps between <-5°C to >30°C, with decreasing temperature trend.
12. Temperature sums for growing period days above respectively 0°C, 5°C and 10°C
13. Temperatures sums during the longest LGP above respectively 0°C, 5°C and 10°C

3.4.4 Multiple cropping zones for rain-fed crop production

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 do not reflect the full potential of total time and space available per unit area of land for rain-fed 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.

For the definition of multiple cropping zones four types of crops are distinguished: thermophilic crops requiring warm temperatures, cryophilic crops performing best under cool and moderately cool conditions, hibernating crops, and wetland crops with specific water requirements. Furthermore, the crops are subdivided according to growth cycle length, namely of less or more than 120 days duration, respectively. According to the above criteria, the following nine zones were classified and mapped (see Figure 3-10):

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* (sequential cropping; double cropping with wetland rice not possible)
E. *Zone of double cropping* (sequential cropping; wetland rice crop possible)
F. *Zone of limited triple cropping* (partly relay cropping; no third crop possible in case of two wetland rice crops)

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

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

$LGP_{t=5}$ number of days with mean daily temperatures above 5°C.

$LGP_{t=10}$ number of days with mean daily temperatures above 10°C.

$TS_{t=0}$ accumulated temperature (degree-days) on days when mean daily temperature ≥ 0°C.

$TS_{t=10}$ accumulated temperature (degree-days) on days when mean daily temperature ≥ 10°C.

$TS\text{-}G_{t=5}$ accumulated temperature during growing period when mean daily temperature ≥ 5°C.

$TS\text{-}G_{t=10}$ accumulated temperature during growing period when mean daily temperature ≥ 10°C.

Table 3-5 and 3-6 summarize the delineation criteria for multiple cropping zones under rain-fed conditions in respectively the tropics and the subtropics/temperate zones.

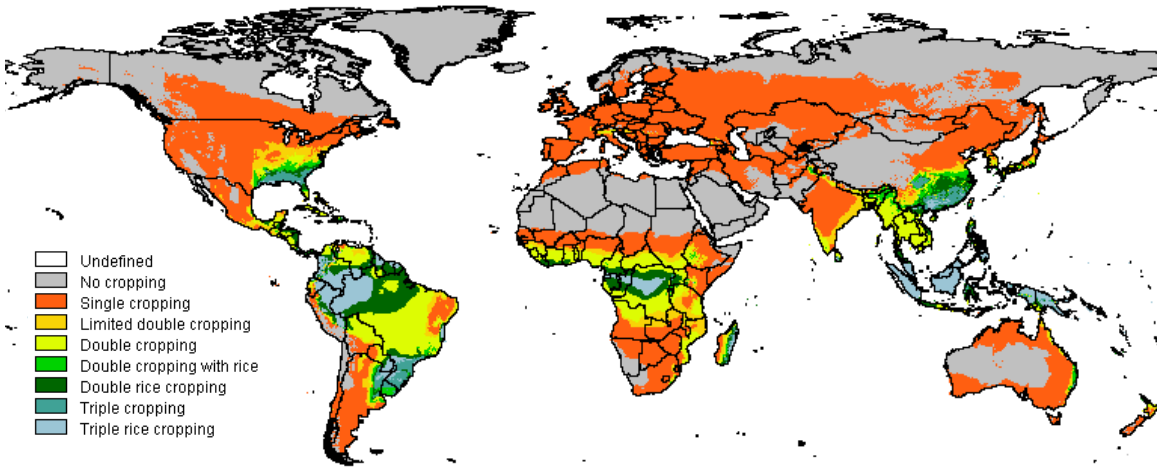

Figure 3-10 Multiple cropping zones for rain-fed conditions

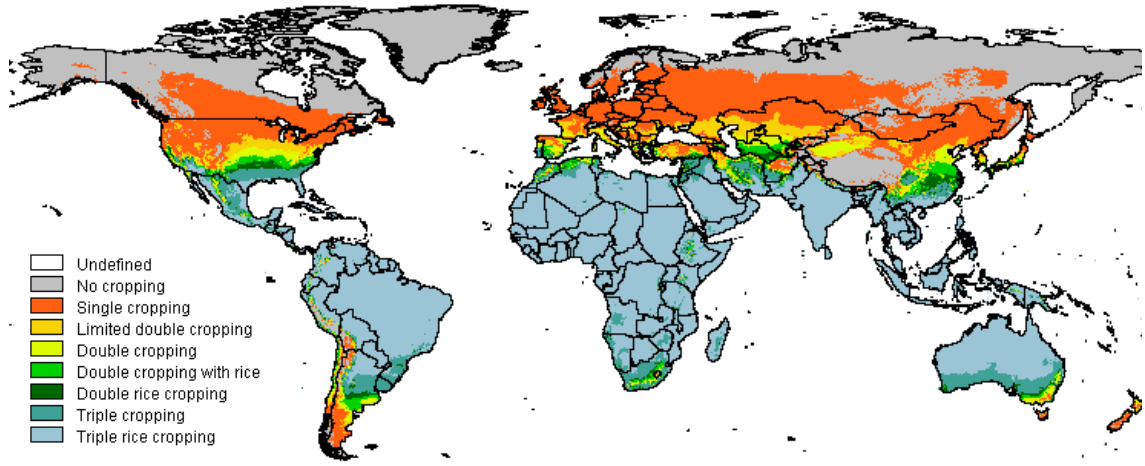

Figure 3-11 Multiple cropping zones for irrigated conditions

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

Zone	LGP	$LGP_{t=5}$	$LGP_{t=10}$	$TS_{t=0}$	$TS_{t=10}$	$TS\text{-}G_{t=5}$	$TS\text{-}G_{t=10}$
A[19]	-	-	-	-	-	-	-
B[20]	≥ 45	≥120	≥90	≥1600	≥1000	-	-
C[21]	≥220	≥220	≥	≥5500		≥	≥
	≥200	≥200	≥120	≥6400	n.a.	≥3200	≥2700
	≥180	≥200	≥	≥7200		≥	≥
D[22]	≥270	≥270	≥	≥5500		≥	≥
	≥240	≥240	≥165	≥6400	n.a.	≥4000	≥3200
	≥210	≥240	≥	≥7200		≥	≥
E	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
F	≥300	≥300	≥240	≥7200	≥7000	≥5100	≥4800
G	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
H	**≥360**	**≥360**	**≥360**	**≥7200**	**≥7000**	**-**	**-**

Table 3-7 Delineation of multiple cropping zones under rain-fed conditions in subtropics and temperate zones

Zone	LGP	$LGP_{t=5}$	$LGP_{t=10}$	$TS_{t=0}$	$TS_{t=10}$	$TS\text{-}G_{t=5}$	$TS\text{-}G_{t=10}$
A[19]	-	-	-	-	-	-	-
B[20]	≥ 45	≥120	≥90	≥1600	≥1000	—	-
C	≥180	≥200	≥120	≥3600	≥3000	≥3200	≥2900
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] Applies if conditions for zone B ('single cropping') are not met.

[20] The program tests if at least one of the crop/LUTs is agro-climatically suitable in the respective grid-cell.

[21], [22] Refers to, respectively, high-land, mid high-land, and lowland areas in the tropics.

3.4.5 Equivalent length of the growing period

To account for significant differences in wetness conditions of long LGPs (> 225 days) equivalent The reference LGP accounts for both temperature and soil moisture conditions. Therefore, the wetness conditions in different locations can be better compared by the so-called equivalent LGP (LGPeq, days) which is calculated on the basis of regression analysis of the correlation between reference LGP and the humidity index P/ETo.

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.

3.4.6 Net Primary Productivity (NPP)

Net primary production (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. In GAEZ, NPP is estimated according to Zhang (1995) as follows:

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

The ∑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, 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 the 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, which results in a maximum for the function term approximating the A_0/d ratio:

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

3.5 Grid cell analysis Module I

Results of the calculation procedures of Module I are presented for a sample gridcell in Appendix 3-4. The example provides output data of the agro-climatic data analysis for reference climate (1962-1990) for a gridcell near Ilonga, Tanzania.

3.6 Description of Module I outputs

Module I produces two detailed output files, which respectively contain the calculated indicators of thermal and moisture conditions in each grid cell. These files are then used to generate various GIS raster maps of the agro-climatic analysis results for visualization and download, but primarily as input to the computations in Modules II, III, and V.

The output variables from Module I are described in Appendix 3-2. Subroutine descriptions of Module I are described in Appendix 3-3.

4 Module II (Biomass calculation)

4.1 Introduction

The main purpose of Module II is the calculation of agro-climatically attainable biomass and yield for specific 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, with and without water conservation measures. 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.

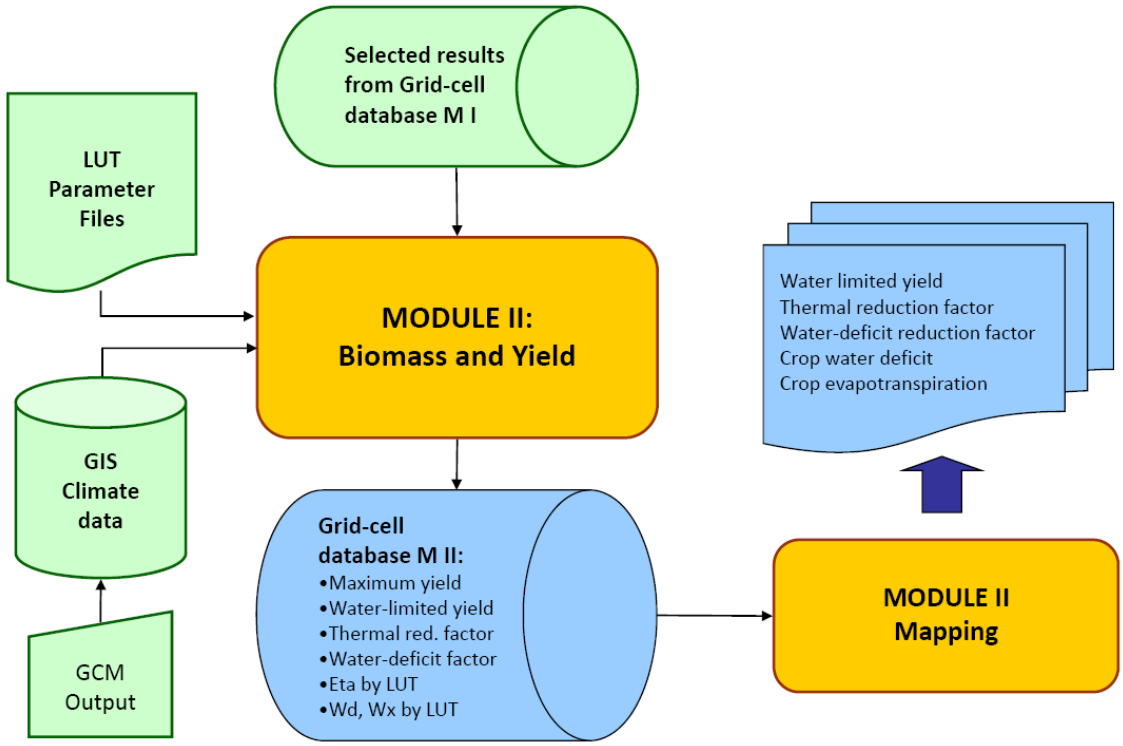

Figure 4-1 Information flow of Module II

4.2 Land Utilization Types

Differences in crop types and production systems are empirically characterized by the concept of Land Utilization Types (LUTs). A LUT consists of a set of technical specifications for crop production within a given socioeconomic setting. Attributes specific to a particular LUT include agronomic information, nature of main produce, water supply type, cultivation practices, utilization of produce, and associated crop residues and by-products. The GAEZ v3.0 framework distinguishes nearly 900 crop/LUT and management combinations, which are separately assessed forr rain-fed with and without moisture conservation and iirigated conditions. These LUts are made-up of 49 different food, feed, fiber, and bio-energy crops (Appendix 4-1, Table A-4-2). The calculated yield of each

crop/LUT is affected by water source and the intensity of input and management assumed to be applied. In GAEZ, three generic levels of input/management are defined: (i) 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 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
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, uses some fertilizer application and chemical pest disease and weed control, 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 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 are varied depending on the assumed input/management level to which LUTs are subjected.

4.3 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 conditions with the LUT's temperature requirements.
There are several steps applied to test the match between thermal conditions and LUT temperature (and relative humidity) requirements: (i) Thermal (latitudinal) climatic conditions; (ii) permafrost conditions; (iii) length of temperature growing period ($LGP_{t=5}$); (iv) length of frost free period ($LGP_{t=10}$); (v) temperature sums ($Tsum_t$); (vi) temperature profiles; (vii) vernalization conditions; (viii) diurnal temperature ranges (for selected tropical perennials); and (ix) relative humidity conditions (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. The thermal suitability screening procedure is sketched in Figure 4-2.

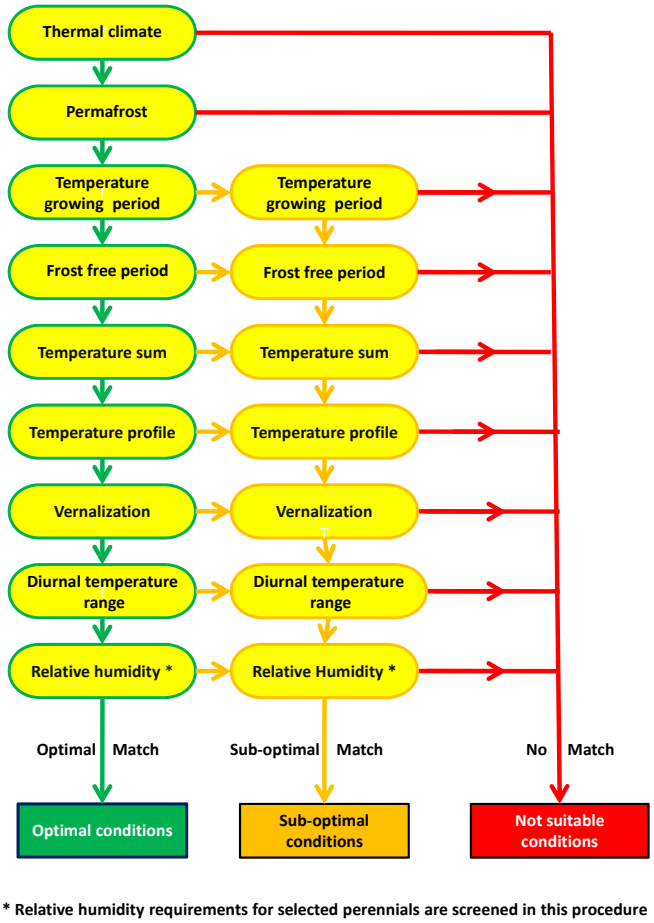

Figure 4-2 Schematic representation of thermal suitability screening

Thermal climate

In Module II, the GAEZ model first checks if an LUT is deemed suitable to grow in the climate prevailing in a grid-cell. The procedure aims to capture compatibility of the LUT requirements in terms of overall temperature requirements, climatic seasonality and seasonal day-length enabling the screening for respectively long-day, day neutral and short days crop LUTs.

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

Permafrost

Areas with reference continuous and discontinuous permafrost are considered not suitable. Gelic soils, indicating permafrost, that occur outside the reference continuous and discontinuous permafrost zones are dealt with 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^{o}C, also referred to as $LGP_{t=5}$. Growth cycle lengths of crop/LUTs are

matched with $LGP_{t=5}$. The result of the matching provides optimum match when the growth cycle can generously be accommodated within $LGP_{t=5}$. Otherwise the match is considered sub-optimum or not suitable.

Hibernating crops survive low temperatures, e.g. during a winter season, by entering into a dormancy period. GAEZ considers four hibernating crop species: winter wheat, winter barley, winter rye and winter rape. These are the only crop/LUTs allowed to prevail at daily average temperatures <5°C. A dormancy period is considered when Ta ranges between 5°C and the crop-specific critical low temperature for cold-break. If the dormancy period is longer than 200 days, or daily average temperatures drop bellow critical thresholds (see below), the LUT is considered to be not suitable. For effect of snow cover on low temperature thresholds for cold break, see 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 10 °C ($LGP_{t=10}$). 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.

Temperature sum

Individual crop/LUT heat unit requirements are matched with temperature sums 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 0°C.

The match of the crop LUT heat unit requirements with the prevailing TSUM are optimum, when the requirements are falling within the optimum $Tsum^c$ range, sub-optimum when falling in $Tsum^c$ range conditions and not suitable when prevailing $Tsum^c$s are too high are too low. Optimum and sub-optimum $Tsum^c$ ranges are presented for all crop/LUTs in the Appendix 4-3.

Temperature profile

The temperature profile requirements are crop/LUT-specific rules that take into account classes of mean daily temperatures (Ta). These classes in 5°C intervals are defined separately by days with increasing or decreasing temperature trends (Fischer *et al.,* 2002). GAEZ has defined in detail for all crop/LUTs temperature profile requirements. Two temperature profile requirements data sets for respectively optimum conditions and for sub-optimum condition have been specified for use in GAEZ (Appendix 4.3)

Potential crop calendars of each LUT are tested for the match of crop/LUT temperature profile requirements and prevailing temperature profiles, while considering growth cycle starting days within the length of the growing period for rain-fed conditions, and within the year for irrigated conditions separately. For all feasible crop calendars within the LGP (rain-fed) or within the year the prevailing 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 a number of tropical perennial crops such as coconut, cacao and oil palm diurnal temperature ranges as well as 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 relative humidity have been defined.

Combining temperature related constraints.

In case of a suboptimum conditions for crop cultivation, the degree of sub-optimality is derived through 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' and sub-optimum' matches. 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. The "most limiting" temperature related constraint factor is then used to reduce potential yields calculated in Module II. For that a yield reduction factor $fc_1 = \min_k \{fc_{1k}, k = 1, \dots, K\}$ is calculated representing the minimum, i.e., most severe, of the individual temperature reduction factors.

4.4 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 by A.H. Kassam (1977)

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) Length of growth cycle (days from emergence to full maturity); (b) minimum temperature requirements for emergence; (c) maximum rate of photosynthesis, (d) respiration rates for leguminous and non leguminous crops as functions of temperature; (e) length of yield formation period; (f) leaf area index (LAI) at maximum growth rate; (g) harvest index (Hi); (h) crop adaptability group, and (i) sensitivity of crop growth cycle length to heat provision. The biomass calculation also includes simple procedures to account for different levels of atmospheric CO2 concentrations. 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 timing of 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 with optimum or sub-optimum temperature conditions, and starting within the duration of the moisture growing period, the period resulting in the highest expected (moisture-limited) yield is selected to represent maximum biomass and yield for rain-fed conditions of the respective crop/LUT for 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 calendar ('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 kilos 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). For details see Table 9-11.

4.5 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, water requirements for each LUT are calculated and taken into account in the calculation of LUT-specific waterbalance 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 potential yield (Yp) calculated.

4.5.1 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 are given as input parameters.

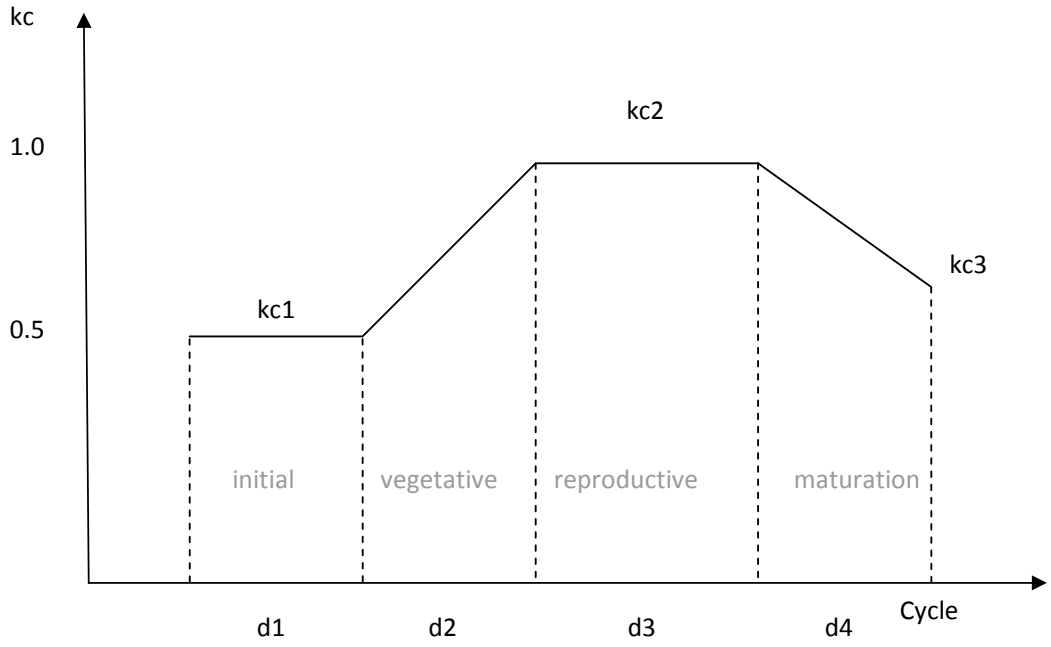

Figure 4-3 Schematic representation of kc values for different crop development stages

The four stages of crop development (days) are denoted as initial (d1), vegetative (d2), reproductive (d3) and maturation stage (d4). For each stage, input parameters define the length of each crop stage as a percentage of total cycle length (GC). Three input parameters define the crop coefficient for water requirement (kc, fractional) throughout stages d1 (kc1) and d3 (kc2) and at the end point of stage d4 (kc3). The values of kc throughout period's d2 and d4 are then calculated by linear interpolation. Alternatively, an average kc parameter representative for the entire growth cycle (kc0) can be specified to calculate an overall water requirement of the crop.

The value of kc for a particular day j is defined by:

$$kc_j = \begin{cases} kc1 & j \in D_1 \\ kc1 + (j - d1) \times \dfrac{kc2 - kc1}{d2} & j \in D_2 \\ kc2 & j \in D_3 \\ kc2 + \left(j - (d1 + d2 + d3)\right) \times \dfrac{kc3 - kc2}{d4} & j \in D_4 \end{cases}$$

4.5.2 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 (∑ETa, mm/day) and maximum crop evapotranspiration (∑ETm, mm/day), both accumulated within the four crop stages. 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 soil water depletion fraction (p) varies with the particular crop.

The sensitivity of each crop to water stress is expressed by the value of the water stress coefficient (ky, fractional), an LUT-specific parameter which changes with crop development stage. There are ky values for each of the four development stages (ky1, ... , ky4) and also an average ky value for the overall crop growth cycle (ky0). GAEZ uses both the crop stage specific coefficients and estimated water deficits and the overall value of kc0 to calculate a water-stress yield reduction factor (fc_2).

$$fc_2^T = 1 - ky0 \times \left(1 - \frac{\sum_{1}^{TCL} ETa}{\sum_{1}^{TCL} ETm} \right)$$

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

$$fc_2^{CS} = \prod_{j=1}^{4} \left(1 - ky_j \times \left(1 - \frac{TETa_j}{TETm_j} \right) \right)^{\lambda_j}$$

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

where $TETa_j$ and $TETm_j$ are respectively total actual evapotranspiration and total potential evapotranspiration for days during crop stage d_j.

The weighting coefficients λ_j add to one and are taken as the relative length of each crop development stage, Hence, fc_2 is taken as the minimum of factor fc^T_2 representing the effect of overall water deficit and the factor fc^{cs}_2 represents the weighted effect 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.

$$Y_w = Y_p \times fc_2$$

4.5.3 Adjustment of LAI and Hi in 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 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 related to the length of the effective growing period (LGP_{eff}, days).

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

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

For each respective variable, two parameters are used to calculate the adjustment factors for HI and LAI of perennials. These parameters relate to the critical and limiting effective length of the growing period 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 LGP_{eff} well above α_{Hi} or α_{LAI}.The effective growing period (LGP_{eff}, days) accounts for the days in the year when perennial crops are effectively growing. Under rain-fed conditions it falls within the LGP determined for a particular grid cell and therefore the period of vigorous growth may be limited by rainfall and soil moisture availability. It excludes the period of dormancy or resting of perennial crops.

The parameterization for perennial crops used in GAEZ is given in Table 4-1.

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

	fP_{LAI}		fP_{HI}	
Crop	α_{LAI}.	β_{LAI}.	α_{Hi}	β_{Hi}
Cassava	0	240	40	140
Sugarcane	0	250	90	270
Banana	0	330	210	120
Oil palm	0	360	210	150
Olive	0	216	0	0
Yellow yam	0	270	110	220
Cocoyam	0	270	110	220
Citrus	0	150	90	60
Cocoa	0	270	120	150
Tea	0	270	120	150
Coffee (arabica)	0	270	120	120
Coffee (robusta)	0	270	120	150
Alfalfa	0	180	30	150
Miscanthus	30	135	30	135
Switchgrass	30	135	30	135
Reed canary grass	**0**	**135**	**0**	**135**

The final Hi and LAI for perennials are then calculated as:

$$Hi_{per} = Hi_{max} \times fP_{Hi}$$

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

4.6 Crop calendar

The crop calendar (i.e. sowing and harvesting dates) for a given LUT and grid-cell is determined by identifying the sowing date that leads to the highest attainable yield. GAEZ tests all possible LUT/sowing-dates combinations within each grid-cell.

For each LUT, the total crop cycle expected for the 'average climate' (30-year time period from 1961-1990) is given in days as an input parameter. For the average base climate, an accumulated temperature sum ($Tsum_5$) is calculated during each crop LUT. This crop-specific value of $Tsum_5$ 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 $Tsum_5$ is reached, as calculated for average climate conditions, e.g. is shortened in years warmer than normal.

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 particular crop/LUT, the optimum combination of radiation regime, temperature regime and soil moisture availability.

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°C) and selects the period with highest attainable yields, thus driven mainly by radiation and temperature regime. Alternatively, GAEZ could also use a selection criterion which would account for the trade-off between additional water use and additional additional yield generated.

4.7 CO2 fertilization effect on crop yields

The "fertilization" effect of increasing atmospheric CO_2 on crop yield 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 $f_{CO2:}$

$$f_{CO_2} = 1 + (ax[CO_2]^2 + b)x[CO_2] + c)xf_{sui_CO_2}$$

Where a, b and c are parameters (by broad crop groups) used to capture the different CO_2 responses of four crop groups (Table 4-9). The factor f_{sui_CO2} is an empirical correction accounting for land suitability as explained below.

Table 4-2 Crop-specific coefficients for the calculation of CO2 fertilization effect

	Crop Group(*)			
Coefficients(1)	**1**	**2**	**3**	**4**
a	-0.000029051	-0.00002408	-0.000035537	-0.000053184
b	0.075951	0.06933	0.062189	0.11551
c	-21.9	-20.26	-16.652	-32.327

I: wheat, barley, rye, oat, buckwheat, potato, sugarbeet, highland/temperate beans. chickpea, dry pea, temperate sunflower, rape, temperate cotton, flax, olive, coffee arabica, temperate onion, temperate tomato, cabbage, carrot, tea, alfalfa, reed canary grass.
II: rice, cassava, sweet potato, lowland beans, cowpea, gram, pigeon pea, groundnut, tropical sunflower, tropical cotton, banana oilpalm, yam, cocoyam, tobacco, citrus, cocoa, coffee robusta, subtropical onions, subtropical tomato, subtropical carrots, coconut, jathropa.
III: maize, sorghum, millet, sugarcane, switchgrass, miscanthus.
IV: soybean.
V: pasture legume, grass (average C3 and C4).

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 a given grid-cell. Under very suitable conditions it is assumed that a fertilization effect of two-thirds that derived from laboratory experiments could be realized in

farmers' fields. For marginally suitable conditions this share is set to one-third see Table 4-4)). On average this results in about half of the CO_2 fertilization effect measured in laboratory experiments to be applied in GAEZ, as is broadly consistent with results reported in free-air CO_2 enrichment (FACE) experiments.

Table 4-3 Yield adjustment factors for CO2 fertilization effect according to land suitability ratings

	VS	S	MS	mS
$f_{sui\ CO2}$	0.667	0.555	0.444	0.333

Land suitability classes are very suitable (VS), suitable (S), moderately suitable (MS), marginally suitable (mS).

In GAEZ various scenarios were simulated as published by IPCC (Nakicenovic *et al.* 2000) in the special reports on emission scenarios (SRES) 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 4-4.

The correction increment for CO_2 without land suitability constraints is shown in Figure 4-4.

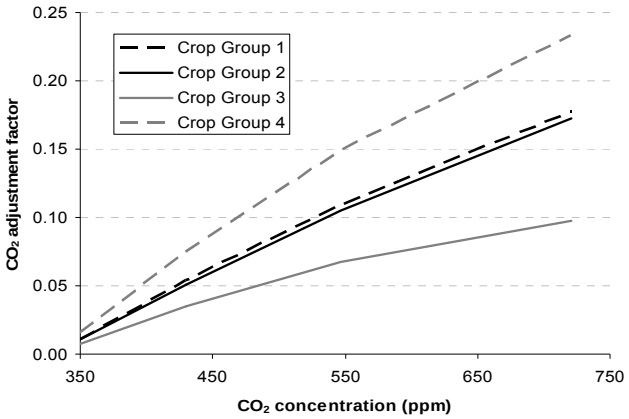

Figure 4-4 Yield response to elevated ambient CO2 concentrations

Table 4-4 The CO2 concentrations (ppm) used to model fertilization effect in GAEZ according to different IPCC scenarios and time points

Scenario[1]	Year[2]		
	2020s	2050s	2080s
A2	430	547	721
B2	417	488	568
B1	422	494	534
A1b	440	547	649
A1f	434	594	834

[1] SRES scenarios from IPCC

[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 mid point of the period from 2011 to 2040).

4.8 Grid cell analysis Module II

Results of the calculation procedures of Module II are presented for a sample gridcell in Appendix 4-9. The example provides output data of the biomass and yield calculations for rain-fed high input crop production for reference climate (1962-1990) for a gridcell near Ilonga, Tanzania.

4.9 Description of Module II outputs

The output of Module II requires large amounts of file storage as it records for each grid-cell and LUT the relevant results of the biomass calculation, including potential yields, yield-reducing factors, and actual crop evapotranspiration, accumulated temperatures, water deficits and crop calendar.
The main output information provided by Module II is given in Appendix 4-7 and 4-8.

5 Module III (Agro-climatic yield-constraints)

5.1 Introduction

At the stage of computing potential biomass and yields, no account is taken of the climatic–related effects operating through pests and diseases, and workability. Such effects need to be included to arrive at realistic estimates of attainable crop yields. Precise estimates of their impacts are very difficult to obtain for a global study. Here it has been achieved by quantifying the constraints in terms of reduction ratings, according to different types of constraints and their severity for each crop, varying by length of growing period zone and by level of inputs. 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 growing period zones. While some constraints are common to all input levels, others (e.g., poor workability through excess moisture) are more applicable to high input conditions with mechanized cultivation.

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 FAO1978-81a. Details of the conditions that are influencing yield losses are listed below.

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 by the use of control measures. It has therefore been attempted to approximate the impact of these yield constrains on the basis of prevailing climatic conditions. The efficacy of control of these constraints (e.g. pest management) is accounted for through the assumed three levels of inputs. Due to the relatively high level of uncertainty, this assessment of agro-climatic constraints has been applied separately in Module III, such that effects are transparent, well separated and GAEZ assessments can be made with and without these constraints (Figure 5-1).

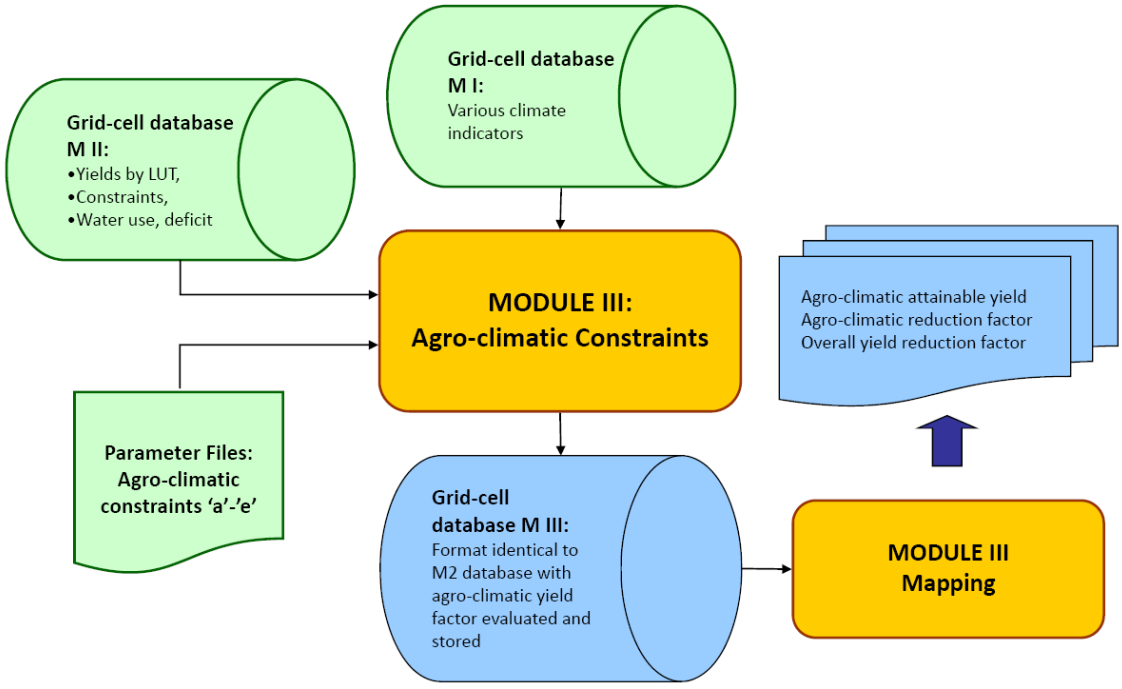

Figure 5-1 Information flows of Module III

In Module III, yield losses caused by agro-climatic constraints are subtracted from the yield calculated in Module II. Five different yield constrains (i.e. yield-reducing factors) are taken into account:

a. Long-term limitation to crop performance due to year-to-year rainfall variability
b. Pests, diseases and weeds damage on plant growth
c. Pests, diseases and weeds damage on quality of produce
d. Climatic factors affecting the efficiency of farming operations
e. Frost hazards

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 cannot get onto the land to carry out operations. In practice, these 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 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 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 300 days in the example.

In this sense, agro-climatic constraints are assumed to represent any direct or indirect losses in the yield and quality of produce. An explanation of the main yield-reducing components addressed by agro-climatic constraints is provided in the following paragraphs.

5.2 Conceptual basis

Matching crop growth cycle and the length of 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 growth cycles. These losses operate through yield and quality reducing effects of (i) pests, diseases and weeds, (ii) climatic factors affecting yield components and yield formation, and (iii) 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 effects of water-stress varies 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 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) have been separated 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, cultivation 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 essentially workability constraints, which primarily account for excessive wetness conditions. 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. Hence, length of the thermal growing period with temperatures above 10°C (LGPT10) in a grid-cell has been compared with growth cycle length of frost sensitive crops. When the crop growth cycle is slightly shorter than LGPT10 the constraints related to frost risk are adjudged moderate, when the growth cycle is very close or equal to LGPT10, the constraints have been adjudged as severe.

Box 5-1

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 300 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 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'.

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. However the 'a' constraint has been retained in the agro-climatic constraints database for use with data sets containing average rainfall data and for comparison with results of the presently used year-by-year analysis.

The 'b', and 'd' constraints and part of the 'c' are related to wetness. The ratings of these constraints have been linked to the LGP. It appears however, that in different climate zones, wetness conditions, traditionally expressed as *P/ETo* ratios, vary considerably for similar LGPs. Long LGPs with relatively low *P/ETo* ratios occur generally in subtropical, temperate and boreal zones, while relatively high ratios occur in the tropics.

To account for these significant differences in *wetness* conditions of long LGPs (> 225 days), agro-climatic constraints have been related to *P/ETo* ratios by calculating *equivalent LGPs*, i.e., adjustments where *P/ETo* ratios where below average. The equivalent LGPs are then used in the application of the 'b', 'c', and 'd' constraints (See section 3.4.4).

Table 5-1 presents an example of agro-climatic constraints for winter wheat. For irrigated production only the agro-climatic constraints related to excess wetness apply. A listing of the agro-climatic constraint parameters considered for all the crop/LUTs are presented in Appendix 5-1

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

SUBTROPICS, TEMPERATE AND BOREAL												
Growth-cycle	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												
a*	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	25	25	25	25	25	25
c	25	25	25	0	0	0	0	0	25	25	50	50
d	0	0	0	0	0	0	0	0	0	25	50	50
Intermediate Inputs												
a	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	25	25	25	25	25
c	25	25	25	0	0	0	0	0	25	25	50	50
d	0	0	0	0	0	0	0	0	0	25	50	50
High inputs												
a	50	50	25	25	0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	0	0	25	25	25	25
c	25	25	0	0	0	0	0	0	0	25	25	50
d	0	0	0	0	0	0	0	25	25	25	50	50
$LGP_{t=10}$	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 historical rainfall data sets.**

The application of the agro-climatic constraints to the combined results of temperature suitability and the biomass and yield calculations provides agro-climatic attainable yields.

5.3 Calculation procedures

The values of the yield reducing factors for agro-climatic constraints are systematically organized in lookup tables (Appendix 5-1) accessed by GAEZ accordingly to:

(i) Land utilization type, LUT
(ii) Thermal climate
(iii) Input level
(iv) Length of the growing period, LGP, length of the equivalent LGP (LGP_{eq}), and the frost-free period ($LGP_{t=10}$)

By combining the five agro-climatic yield reducing factors $fct_a, \ldots, fct_e$ for constraint types 'a' to 'e', an overall yield reducing factor (fc_3) is calculated:

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

With agro-climatic constraints quantified, the agronomically atttainable crop yields have been calculated by applying the factor (fc_3) to the agro-climatic yields as calculated in Module II. Note that the evaluation is done separately for rain-fed and irrigated conditions.

5.1 Description of Module III outputs

The output format of Module III is the same as for Module II. The information provided by Module III is described in Appendix 5-2 and 5-3. Various utility programs have been developed to map the contents of Module III crop databases in terms of agro-climatically attainable yield, agro-climatic reduction factor and overall yield reduction factor. Figure 5-2 shows the agro-climatically attainale yields for rain-fed, high-input wheat.

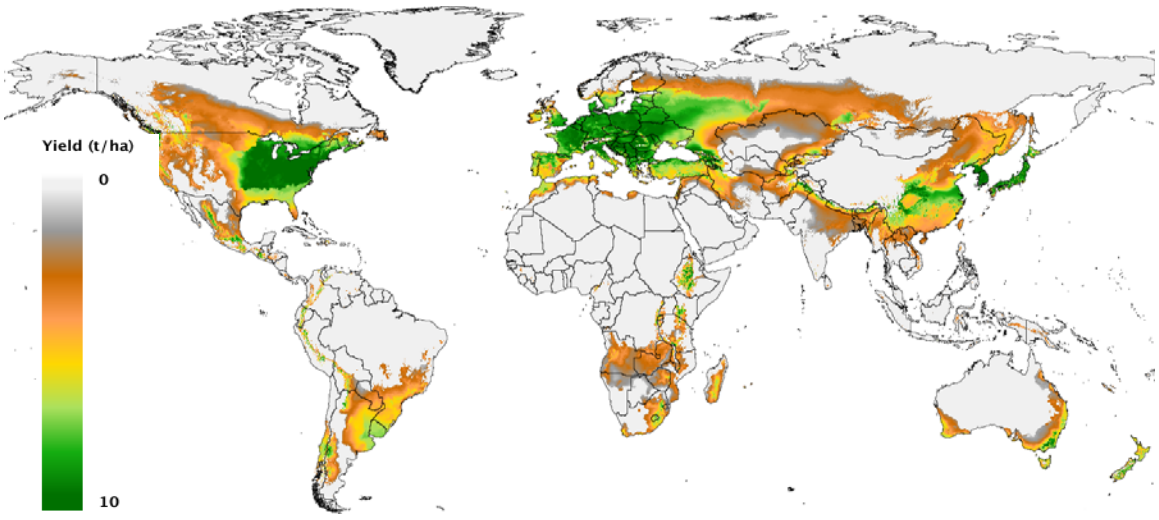

Figure 5-2 Agro-climatically attainable yield of wheat

6 Module IV (Agro-edaphic suitability)

6.1 Introduction

In the context of this complete update of the global agro-ecological zones study, FAO and IIASA recognized that there was an urgent need to combine existing regional and national updates of soil information worldwide and incorporate these with the information contained within the FAO-UNESCO Soil Map of the World which was in large parts no longer reflecting the actual state of the soil resource. In order to do this, partnerships were sought with the International Soil Resources Information Centre (ISRIC) who had been largely responsible for the development of regional Soil and Terrain databases and with the European Soil Bureau Network (ESBN) who had undertaken a major update of soil information for Europe and northern Eurasia in recent years. The incorporation of the 1:1,000,000 scale Soil Map of China was an essential addition obtained through the cooperation with the Academia Sinica. In order to estimate soil properties in a harmonized way the use of actual soil profile data and the development of pedotransfer rules was undertaken in cooperation with ISRIC and ESBN drawing on the WISE soil profile database and earlier work of Batjes *et al.* and Van Ranst *et al*.

The resulting global database uses raster grids at 30 arc-seconds which are linked to a harmonized attribute database quantifications of composition of soil units within soil associations and characterization of these soil units by the following soil parameters: Organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry.

The four source databases used in this Harmonized World Soil Database (HWSD), are the European Soil Database (ESDB), the CHINA 1:1 million soil map, various regional SOTER databases (SOTWIS Database), and the Soil Map of the World of FAO/Unesco. Figure 6-1 presents the regional distribution of the data sources.

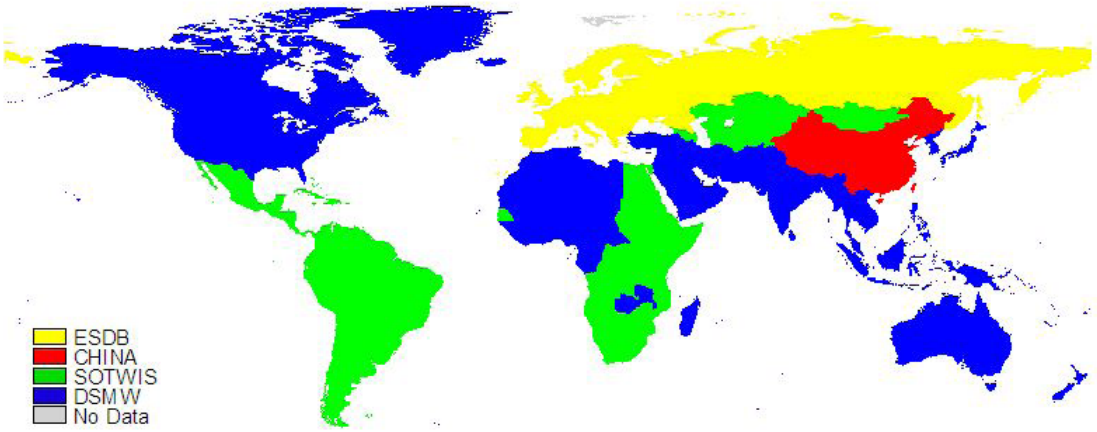

Figure 6-1 Regional distribution of soil data sources

This Module IV of GAEZ estimates for yield reductions caused by constraints induced by prevailing soil and terrain-slope conditions. Crop yield impacts from sub-optimum soil and terrain conditions are assessed separately. The soil suitability is assessed through crop/LUT specific evaluations of seven major soil qualities. Terrain suitability is estimated from terrain-slope and rainfall concentration characteristics. Soil and terrain characteristics are read from 30 arc-second grid-cells in which prevailing soil and terrain combinations have been quantified. This module calculates suitability distributions for each grid-cell by considering all occurring soil-unit and terrain slope

combinations separately. The calculations are crop/LUT specific and are performed for all three basic input levels and five water supply systems separately.

The agro-edaphic assessment, which is an integral part of the GAEZ modeling framework is schematically presented below.

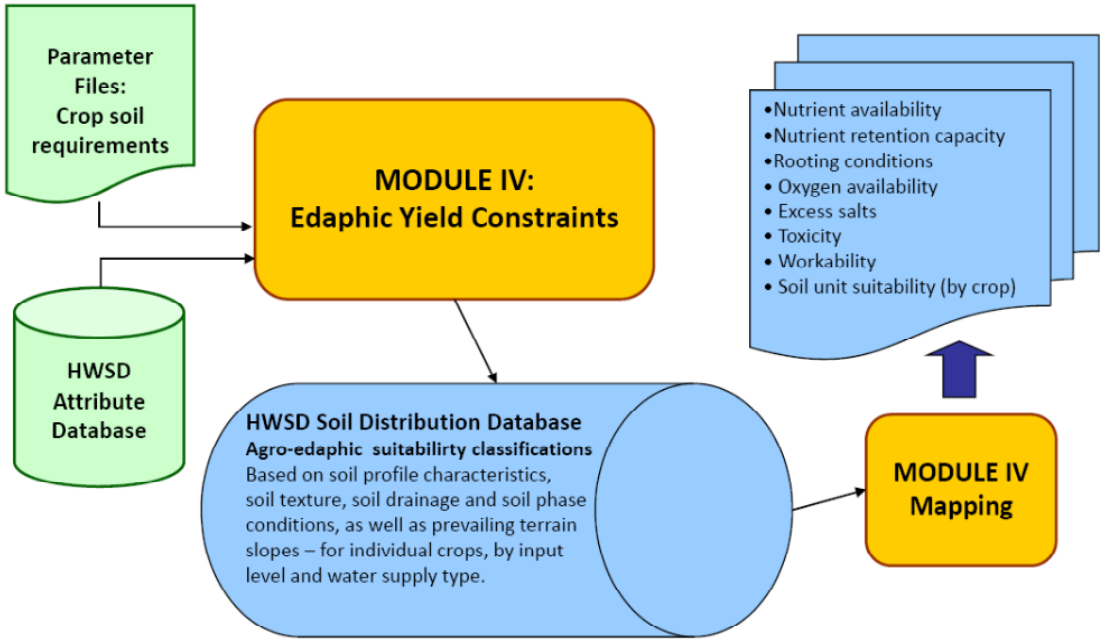

Figure 6-2 Information flow in Module IV

6.1.1 Levels of inputs and management

Individual soil and terrain characteristics have been related to requirements and tolerances of crops at three basic levels of management and inputs circumstances, 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 fallows 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.

Mixed level of inputs

Under mixed level of inputs only the best land is assumed to be used for high level input farming, moderately suitable and marginal lands are assumed to be used at intermediate or low level input and management circumstances. The following procedures were applied to individual grid-cells.

(1) Determine all land very suitable and suitable at high level of inputs.

(2) of the balance of land after (1), determine all land very suitable, suitable or moderately suitable at intermediate level of inputs, and

(3) of the balance of land after (1) and (2), determine all suitable land (i.e. very suitable, suitable, moderately suitable or marginally suitable) at low level of inputs.

6.1.2 Water supply systems

Five water supply systems have been separately evaluated. Apart from evaluating crop production systems based on rain-fed cultivation and rain-fed with water conservation, specific soil requirements for three major irrigation systems have been established namely for gravity, sprinkler and drip irrigation. Table 6-1 presents the water supply system/crop associations that are considered in the assessment.

Table 6-1 Water supply system/crop associations

	Water Supply Systems				
	Rain-fed	Rain-fed with soil moisture conservation	Irrigation		
			Gravity	Sprinkler	Drip
Input Levels	H, I, L	H, I.[2]	H, I	H, I	H
Crops					
Wheat	v	v	corrugation/border	v	-
Wetland_Rice	v	-	basin	-	-
Dryland_Rice	v	-	-	-	-
Maize	v	v	furrow	v	-
Barley	v	v	corrugation/border	v	-
Sorghum	v	v	furrow	v	-
Rye	v	v	corrugation/border	v	-
Pearl_Millet	v	-	furrow	v	-
Foxtail_Millet	v	-	furrow	v	-
Oat	v	v	corrugation/border	v	-
Buckwheat	v	-	corrugation/border	v	-
White_Potato	v	-	furrow	v	-
Sweet_Potato	v	-	furrow	v	-
Cassava	v	-	-	-	-
Yam	v	-	-	-	-
Cocoyam (Taro)	v	-	-	-	-
Sugarcane	v	-	basin/furrow	v	-
Sugar beet	v	-	furrow	v	-
Phaseolus_Bean	v	-	furrow	v	v
Chickpea	v	v	furrow	-	-
Cowpea	v	-	furrow	-	-
Dry Pea	v	-	furrow	v	-
Gram	v	-	furrow	-	-
Pigeonpea	v	-	furrow	-	-
Soybean	v	v	furrow	v	-
Sunflower	v	-	furrow	v	-
Rape	v	v	furrow	-	-
Groundnut	v	-	furrow	-	-
Oil Palm	v	-	-	-	v
Olive	v	-	basin/furrow	-	v

	Water Supply Systems				
	Rain-fed	Rain-fed with soil moisture conservation	Irrigation		
			Gravity	Sprinkler	Drip
Input Levels	H, I, L	H, I.[2]	H, I	H, I	H
Crops					
Jatropha	v	-	furrow	v	-
Cabbage	v	-	furrow	v	v
Carrot	v	-	furrow	v	v
Onion	v	-	furrow	v	v
Tomato	v	-	furrow	v	v
Banana_Plantain	v	-	basin/furrow	v	v
Citrus	v	-	basin/furrow	v	v
Coconut	v	-	furrow	v	v
Cacao	v	-	furrow	v	v
Cotton	v	-	furrow	-	-
Flax	v	-	furrow	v	-
Coffee	v	-	furrow	v	v
Tea	v	-	-	v	v
Tobacco	v	-	furrow	v	-
Alfalfa	v	-	corrugation/border	v	-
Switchgrass	v	-	-	v	-
Reed Canary Grass	**v**	**-**	**-**	**v**	**-**

H: High inputs, I: Intermediate inputs, L: Low inputs

6.1.3 Soil 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 interactions (flooding regimes, soil erosion and soil nutrient maintenance) are treated separate from those land qualities specifically related to soil properties and conditions as reflected in the Harmonized World Soil Database and the GAEZ terrain-slope database.

Table 6-2 Land qualities

Land Qualities	AEZ Procedures
Climate regime (temperature, moisture, radiation)	Climatic suitability classification
Flooding regime	Moisture regime analysis of water collecting sites
Soil erosion	Assessment of sustainable use of sloping terrain
Soil nutrient maintenance	Fallow period requirement assessments
Soil physical and chemical properties	Soil suitability classification

Procedures and activities employed are schematically represented below:

[2] All LUTs of marked crops except for tropical highland maize and sorghum. Only arid and semi- arid moisture and the dryer part subhimid moisture regimes are considered. (LGP < 210 and P/PET between 20 and 80%) Cold areas are excluded ($LGP_{t=5}$ <165 days).

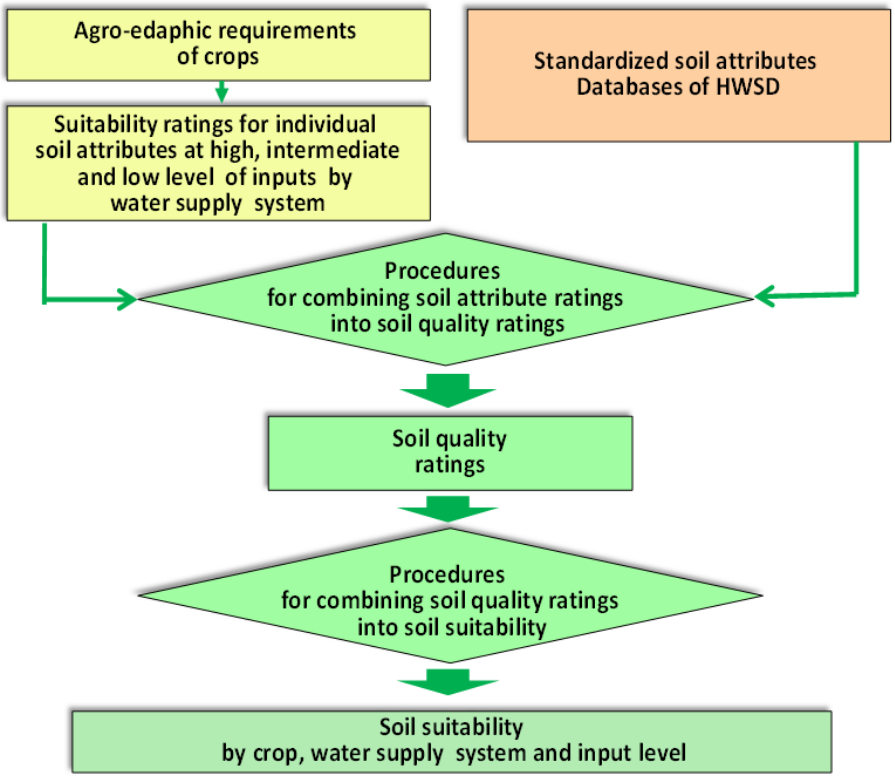

Figure 6-3 Soil suitability rating procedures

The individual soil profile attributes, soil drainage conditions and soil phases prevalence, that have been related to requirements and tolerances of crops at three generic levels of management and inputs circumstances, high , intermediate and low, for five different water supply systems, need to be combined ultimately into land utilization specific soil suitability ratings.

In the GAEZ approach, first individual soil qualities are defined and quantified. Table 6-3 below provides an overview of the seven soil qualities in relation to relevant soil profile attributes, including soil drainage conditions and soil phase prevalence.

Table 6-3 Soil qualities and soil attributes

Soil Qualities		Soil quality related soil profile attributes, 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 textures, 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	Excess salts.	Soil salinity, soil sodicity and soil phases influencing soil salinity and sodicity conditions.
SQ6	Toxicity.	Calcium carbonate and gypsum.
SQ7	Workability (constraining field management).	Soil texture, effective soil depth/volume, and soil phases constraining soil management (soil depth, rock outcrop, stoniness, gravel/concretions and hardpans).

6.2 Soil characteristics

Thye seven soil qualities (SQ1-7) are estimated from soil characteristics (e.g. organic carbon content, soil pH, texture) read from the Harmonized World Soil Database. 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); toxicities (SQ5); salinity and sodicity (SQ6), and workability (SQ7). Each of the seven SQ ratings is derived from specific soil characteristics.

6.2.1 Soil profile attributes

Soil profile attributes considered for both top-soil (0-30 cm) and sub-soil (30-100cm) separately include: soil texture; 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. In addition prevalence of soil phases, soil drainage characteristics, vertic soil properties and gelic soil conditions are considered.

Soil texture

Soil texture influences nutrient availability, nutrient retention, rooting conditions, drainage and soil workability.

Soil texture is a soil property used to describe the relative proportion of different grain sizes of mineral particles in a soil. Particles are grouped according to their size into what are called soil separates (clay, silt, and sand). The soil texture class (e.g., sand, clay, loam, etc) corresponds to a particular range of separate fractions, and is diagrammatically represented by the soil texture triangle. Coarse textured soils contain a large proportion of sand, medium textures are dominated by silt, and fine textures by clay (see diagram) and table 6-4.

Figure 6-4 Soil texture classification

Table 6-4 Soil texture separates

Soil separates	Diameter limits (mm) (*USDA* classification)
Clay	less than 0.002
Silt	0.002 - 0.05
Sand	0.05 - 2.00

Organic carbon content

Organic carbon is, together with pH, the best simple indicator of the health status of the soil. Moderate to high amounts of organic carbon are associated with fertile soils with a good structure.

Soils that are very poor in organic carbon (<0.2%), need organic or inorganic fertilizer application to be productive. Soils with an organic matter content of less than 0.6% are considered poor in organic matter.

Soil acidity (pH value)

The pH, measured in a soil-water solution, is a measure for the acidity and alkalinity of the soil. pH has a strong on the availability of nutrients to the plant. Optimum pH values range between 5.5 and 7.0.

Cation exchange capacity of clay

The type of clay mineral dominantly present in the soil often characterizes a specific set of pedogenetic factors in which the soil has developed. Tropical, leaching climates produce the clay mineral kaolinite, while confined conditions rich in Ca and Mg in climates with a pronounced dry season encourage the formation of the clay mineral smectite (montmorillonite).

Clay minerals have typical 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.

Cation exchange capacity of soil

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 can not 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.

Base saturation

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).

Total exchangeable bases

Total exchangeable bases represent for the sum of exchangeable cations in a soil: sodium (Na), calcium (Ca), magnesium (Mg) and Potassium (K).

Calcium carbonate

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.

Calcium sulphate (gypsum)

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.

Exchangeable sodium percentage

The exchangeable sodium percentage (ESP) has been used to indicate levels of sodium in soils. It is calculated as the ratio of Na in CEC:

$$ES = \frac{Na \times 100}{CEC}$$

Sodium adsorption ratio (SAR) has been also used to indicate levels of sodium hazards for crops:

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$

Electrical conductivity

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 $dS.m^{-1}$ others can stand up to 16 $dS.m^{-1}$.

6.2.2 Soil drainage

Ratings based on FAO' 95 "Guidelines to estimation of drainage classes based on soil type, texture, soil phase and terrain slope". Ratings have been applied to all soil type, texture, soil phase and broad slope classes and results have been distributed over eight GAEZ slope classes. The drainage classes are defined as follows (FAO 1995).

Excessively drained (E):

Water is removed from the soil very rapidly The soils are commonly very coarse textured or rocky, shallow or on steep slopes.

Somewhat excessively drained (SE):

Water is removed from the soil rapidly. The soils are commonly sandy and very pervious.

Well drained (W):

Water is removed from the soil readily but not rapidly. The 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 the soils are wet within the rooting depth. They commonly have an almost impervious layer.

Imperfectly drained (I):

Water is removed slowly so that the 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 the soils are commonly wet at a shallow depth for considerable periods. The soils commonly have a shallow water table which is usually the result of an almost impervious layer, or seepage.

Very poorly drained (VP):

Water is removed so slowly that the soils are wet at shallow depths for long periods. The soils have a very shallow water table and are commonly in level or depressed sites.

The algorithm used are as follows for the FAO/Unesco soil classification used in the Digital Soil Map of the World (DSMW) (FAO 1995):

1. **Histosols** (O) are considered to be very poorly drained (100% VP).
2. All **Gleysols (G)** and **Fluvisols (J)** with clayey topsoil textures are considered to be partly very poorly and partly poorly drained (50% VP and 50% P).
3. All **Planosols (W)**, and the **gleyic** soil units of other FAO soil groups, such as **Zg, Sg, Hg, Mg, Lg, Dg, Pg,** and **Ag** are considered to be partly poorly drained and partly imperfectly drained (50% P and 50% I).
4. All **Vertisols (V)** are considered for 2/3 of their area to be imperfectly drained, the remainder is considered poorly drained (66% I and 34% P).
5. **Plinthic Ferralsols (Fp), Plinthic Acrisols (Ap),** and **Gleyic Cambisols (Bg)** are considered partly imperfectly drained and partly moderately well drained (50% I and 50% MW).
6. All **Arenosols (Q)**, **non-gleyic Podzols (P)** and **Regosols (R)** with coarse topsoil textures and occurring on gentle slopes (<8%) are considered to be partly excessively, and partly somewhat excessively drained (50% E and 50% SE). If the same soils occur on steeper slopes (>8%) then they are considered to be excessively drained (100% E).
7. **Lithosols (I), Rankers (U)** and **Rendzinas (E)** with sandy topsoil and when occurring on gentle slopes are considered moderately well drained (100% MW). When the same soils have a loamy or clayey topsoil and occur on gentle slopes they are considered imperfectly drained (100% I). When these soils occur on steeper slopes they are considered to be partly well drained and partly somewhat excessively drained (50% W and 50% SE).
8. All other soils with an argic horizon such as **Luvisols (L), Acrisols (A), Podzolluvisols (D), Nitosols (N)** and **luvic** soil units in other FAO soil groups such **as Xl, Yl, Kl, Cl** and **Hl** when having a sandy topsoil texture and occurring on flat (<8% slope) terrain are considered to be partly well drained and partly moderately well drained (50% MW and 50% W). When these

soils have a finer topsoil texture and occur on slopes of less than 8% they are considered dominantly moderately well drained and partly well drained (75% MW and 25% W). When these soils occur on steeper slopes they are considered to be dominantly well drained, partly moderately well drained and partly somewhat excessively drained (25% MW, 50% W and 25% SE).

9. All other soils with sandy topsoil textures occurring on flat terrain are considered to be dominantly well drained, partly excessively and partly somewhat excessively drained (50% W, 25% SE and 25% E). When these soils are finer and occur on flat or gently sloping terrain they are considered these soils have a sandy topsoil texture and occur on steeper slopes (>8%) they are considered to be partly moderately well and partly well drained (50% MW and 50% W)>. When these soils are loamy or clayey and occur on steeper slopes (>8%) they are considered to be dominantly well drained, partly somewhat excessively drained and partly moderately well drained (50% W, 25% SE and 25% MW).

10. Soils discussed under 8. and 9. above and having a **Petrocalcic, Petrogypsic Petroferric**, or **Duripan** are less deep than the typical soil units. Therefore half of their area is considered to have similar drainage as those considered under rule 7. (**Lithosols** etc.).

Results of the soil drainage evaluation for the FAO 1974 and the FAO 1990 soil classification are presented in the Appendix 6-1.

6.2.3 Soil phases

Phases are sub-classifications of soil units based on characteristics which are significant for the use or management of the land but are not diagnostic for the separation of the soil units themselves. In HWSD soil phases numbered 1 to 12 were used in the Soil Map of the World (FAO-74), phases 13 to 22 were used in association with the Revised Legend of the Soil Map of the World (FAO-90), while phases 23 to 33 are specific for the European Soil Database.

Table 6-5 Soil phases

Code	Phase	Code	Phase
0	No phase	17	Placic
1	Stony	18	Rudic
2	Lithic	19	Salic
3	Petric	20	Skeletic
4	Petrocalcic	21	Takyric
5	Petrogypsic	22	Yermic
6	Petroferric	23	Erosion
7	Phreatic	24	No limitation to agricultural use
8	Fragipan	25	Gravelly
9	Duripan	26	Concretionary
10	Saline	27	Glaciers
11	Sodic	28	Soils disturbed by man
12	Cerrado	29	Excessively drained (set to 0)
13	Anthraquic	30	Flooded
14	Gelundic	31	Obstacles to roots
15	Gilgai	32	Impermeable Layer
16	Inundic	33	Wetness

Each soil phase is explained in the following paragraphs.

Stony phase:

Marks areas where the presence of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable. Hand tools can normally be used and also simple mechanical equipment if other conditions are particularly

favorable. Fragments up to 7.5 cm are considered as gravel; larger fragments are called stones and boulders.

Lithic phase:

This phase is used when continuous coherent and hard rock occurs within 50 cm of the soil surface. For Leptosols the lithic phase is not shown as it is implied in the soil unit name.

Petric phase:

The petric phase marks soils with a layer consisting of 40 % or more, by volume, of oxidic concretions or of hardened plinthite, or ironstone or other coarse fragments with a thickness of at least 25 cm, the upper part of which occurs within 1 m of the surface. The petric phase differs from the petroferric phase in that the concretionary layer of the petric phase is not cemented.

Petrocalcic phase:

Marks soils in which the upper part of a petrocalcic horizon (> 40% lime, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface.

Petrogypsic phase:

Used for soils in which the upper part of a petrogypsic horizon (> 60% gypsum, cemented, usually thicker than 10 cm) occurs within 100 cm of the surface.

Petroferric phase:

The petroferric phase marks soils in which the upper part of the petroferric horizon occurs within 100 cm from the soil surface. A petroferric horizon is a continuous layer of indurated material in which iron is important cement and organic matter is absent.

Phreatic phase:

The phreatic phase marks soils which have a groundwater table between 300 and 500 cm from the surface.

Fragipan phase:

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

Duripan phase:

The duripan phase marks soils in which the upper level of a duripan occurs within 100 cm of the soil surface. A duripan is a subsurface horizon that is cemented by silica and contains often accessory cements mainly iron oxides or calcium carbonate.

Saline phase:

The saline phase marks soils in which in some horizons within 100 cm of the soil surface show electric conductivity values higher than 4 dS m^{-1}. The saline phase is not shown for Solonchaks because their definition implies a high salt content.

Sodic phase:

The sodic phase marks soils which have more than 6 % saturation with exchangeable sodiumin some horizons within 100 cm of the soil surface. The sodic phase is not shown for Solonetz because their definition implies a high ESP.

Cerrado phase:

Cerrado is the Brazilian name for level open country of tropical savannas composed of tall grasses and low contorted trees. This type of vegetation is closely related to the occurrence of nutrient depleted soils on old land surfaces.

Anthraquic phase:

The anthraquic phase marks soils showing stagnic properties within 50 cm of the surface due to surface water logging associated with long continued irrigation, particularly of rice.

Gelundic phase:

The gelundic phase marks soils showing formation of polygons on their surface due to frost heaving.

Gilgai phase:

Gilgai is a microrelief typical of clayey soils, mainly Vertisols. The microrelief consists of either a succession of enclosed micro-basins and micro-knolls in nearly level areas, or of micro-valleys and micro-ridges that run up and down the slope.

Inundic phase:

The inundic phase is used when standing or flowing water is present on the soil surface for more than 10 days during the growing period.

Placic phase:

The placic phase refers to the presence of a thin iron pan, a black to dark reddish layer cemented by iron with manganese or organic matter. Its thickness varies from 2 to 10 mm.

Rudic phase:

The rudic phase marks areas where the presence of gravel, stones, boulders or rock outcrops in the surface layers or at the surface makes the use of mechanized agricultural equipment impracticable.

Skeletic phase:

The skeletic phase refers to soil material which contains more than 40 % coarse fragments or oxidic concretions.

Takyric phase:

The takyric phase applies to heavy textured soils with cracks into polygonal elements that form a platy or massive surface crust.

Yermic phase:

The yermic phase applies to soils which are low in organic carbon and have features associated with deserts or very arid conditions (desert varnish, presence of palygorskyte, cracks filled with sand, presence of blown sands on a stable surface.

Gravelly phase:

The gravelly phase is used in ESDB and indicates over 35% gravels with diameter < 7.5 cm.

Concretionary phase:

The concretionary phase is used in ESDB and indicates over 35% concretions, diameter < 7.5 cm near the surface.

Glaciers (Miscellaneous unit):

Permanent snow covered areas and glaciers.

Soils disturbed by man phase:

Areas filled artificially with earth, trash, or both, occur most commonly in and around urban areas.

Obstacles to roots

Soils which have physical or chemical obstacles to root penetration are classified in relation to the depth of the layer.

Impermeable layer phase

Soils which have an impermeable layer impeding drainage and root penetration are classified in relation to the depth of the layer.

Wetness phase

Soils that have severe wetness conditions in the soil profile. Wetness is classified by depth occurrence and its duration during the year.

6.3 Soil suitability ratings

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

6.3.1 Soil profile attributes ratings

The soil profile attribute suitability ratings are empirical coefficients. They have been compiled by input level (high, Intermediate and low) and by five water supply systems (rain-fed, rain-fed with water conservation, gravity irrigation, sprinkler irrigation and drip irrigation systems). The soil profile attribute ratings iaccount for *gelic* soil conditions and *vertic* soil properties. The ratings presented below (Table 6-3) refer to the rain-fed production of wheat. The rating system is adapted from Sys *et al* 1993 and uses six classes namely:

S0 No constraint (100%)
S1 Slight constraint (90%)
S2 Moderate constraint (70%)
S3 Severe constraint (50%)
S4 Very severe constraint (30%)
N Not suitable (<10%)

The characteristics and properties are organized by soil quality to which they apply and by level of input and management where applicable.

Table 6-6 Soil profile attribute ratings for rain-fed wheat

Soil profile attributes, vertic soil properties and gelic soil	Soil Quality and Input Level	Soil profile attribute Ratings					
		S0 100%	S1 90%	S2 70%	S3 50%	S4 30%	N 10%
Organic Carbon	SQ1, SQ2	1.5	0.8	-	-	-	-
Low pH (H2O)	SQ1/SQ2 (LOW+INT)	6.5	6	5.6	5.2	4.7	4.2
Low pH (H2O)	SQ2 (HIGH)	6	5.6	5.2	4.7	4.5	3.9
High pH (H2O)	SQ1, SQ2 (LOW+INT)	7.5	8.2	8.3	8.5	-	8.6
High pH (H2O)	SQ2 (HIGH)	7.5	8.2	8.3	8.5	-	8.6

Soil profile attributes, vertic soil properties and gelic soil	Soil Quality and Input Level	Soil profile attribute Ratings					
		S0 100%	S1 90%	S2 70%	S3 50%	S4 30%	N 10%
TEB	SQ1	8	5	3.5	2	-	-
TEB	SQ1, SQ2	5	3.5	2	-	-	-
CEC (clay)	SQ2 (LOW+INT)	24	16	-	-	-	-
CEC (clay)	SQ2 (HIGH)	16	-	-	-	-	-
Base Saturation (%)	SQ2 (LOW+INT)	80	50	35	0	-	-
Base Saturation (%)	SQ2 (HIGH)	50	35	-	-	-	-
Rooting depth (cm)	SQ 3, SQ 7b	90	70	35	30	-	0
Rooting depth (cm)	SQ 7a	70	35	-	30	-	0
Coarse fragments	SQ 3, SQ 7a, SQ 7b	15	35	55	-	-	100
Electric Conductivity	SQ 5	1	3	5	6	10	100
ESP (%)	SQ 5	15	20	35	45	-	100
$CaCO_3$ (%)	SQ 6	20	30	40	60	-	500
Gypsum (%)	SQ 6	3	5	10	20	-	100
Vertic properties	SQ3	-	x	-	-	-	-
CEC soil	SQ2 (LOW+INT)	10	8	4	2	-	-
CEC soil	SQ2 High	8	4	2	-	-	-
Gelic	SQ3, SQ7a	-	-	-	-	-	X
Vertic properties	SQ7a HIIGH	-	X	-	-	-	-
Vertic properties	SQ7b (LOW+INT)	-	-	-	-	X	-

Soil profile attribute ratings for all crops are provided by the five water supply systems in Appendix 6-2.

6.3.2 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 6-7 presents soil texture ratings for 13 texture classes for the production of rain-fed wheat.

Table 6-7 Soil texture ratings for rain-fed wheat

Soil Texture Ratings for Rain-fed Production of Wheat													
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	100	100	100	100	100	100	100	100	100	100	90	70	30
Nutrient retention capacity, SQ2)	100	100	100	100	100	100	100	100	100	100	90	70	30
Rooting conditions, SQ3	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 by the five water supply systems in the Appendix 6-3.

6.3.3 Soil drainage ratings

Soil drainage is characterized in the Harmonized World Soil Database in 7 classes:

Table 6-8 Soil drainage classes

Code	Drainage level
VP	Very Poor
P	Poor
I	Imperfectly
MW	Moderately well
W	Well
SE	Somewhat excessive
E	Excessive

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

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

Fine, medium and coarse textures							
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 drainage ratings for all crops are provided by the five water supply systems in the Appendix 6-4.

6.3.4 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 five water supply systems (rain-fed, rain-fed with water conservation, gravity irrigation, sprinkler irrigation and drip irrigation systems).

The ratings presented below (Table 6-10) refer to the rain-fed production of wheat. The ratings represent constraints implied by the occurrence of soil phases in percentage (100% rating no consttraint 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: So called *"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.

Table 6-10 Soil phase ratings for rain-fed wheat

Soil Quality	Rating Type*	Soil Phases (HWSD)	INPUT LEVEL HIGH	INT	LOW
SQ3	Full	Stony	75	75	75
		Lithic	50	50	50
	Split	Petric	60	60	60
		Petrocalcic	60	60	60
		Petrogypsic	60	60	60
		Petroferric	60	60	60
		Fragipan	100	95	85
		Duripan	100	95	85
	Full	Anthraquic	85	85	85
	Split	Placic	100	95	85
	Full	Rudic	75	75	75
	Split	Skeletic	60	60	60
	Full	Erosion	100	100	100
SQ3	Split	Gravelly	60	60	60
		Concretionary	60	60	60
	Full	0 No information (ROO= 0)	100	100	100
		1 No obstacle to roots between 0 and 80 cm (ROO=1)	100	100	100
		2 Obstacle to roots between 60 and 80 cm depth (ROO=2)	90	90	90
		3 Obstacle to roots between 40 and 60 cm depth (ROO=3)	80	80	80
		4 Obstacle to roots between 20 and 40 cm depth (ROO=4)	50	50	50
		5 Obstacle to roots between 0 and 80 cm depth (ROO=5)	70	70	70
		6 Obstacle to roots between 0 and 20 cm depth (ROO=6)	0	0	0
		0 No information (IL=0)	100	100	100
		1 No impermeable within 150 cm (IL=1)	100	100	100
		2 Impermeable between 80 and 150 cm (IL=2)	100	100	100
		3 Impermeable between 40 and 80 cm (IL=3)	80	80	80
		4 Impermeable within 40 cm (IL=4)	30	30	30
SQ4	Full	Phreatic	100	100	100
		Anthraquic	100	100	100
		Inundic	100	100	100
	Split	Placic	100	100	100
	Full	Excessively drained	100	100	100
		Flooded	100	100	100
		0 No information (IL=0)	100	100	100
		1 No impermeable within 150 cm (IL=1)	100	100	100
		2 Impermeable between 80 and 150 cm (IL=2)	100	100	100
		3 Impermeable between 40 and 80 cm (IL=3)	100	100	100
		4 Impermeable within 40 cm (IL=4)	100	100	100
		0 No information (WR=0)	100	100	100
		1 Not wet within 80 cm for over 3 months, nor wet within 40 cm for over 1 month (WR=1)	100	100	100
		2 Wet within 80 cm for 3 to 6 months, but not wet within 40 cm for over 1 month (WR=2)	100	100	100
		3 Wet within 80 cm over 6 months, but not wet within 40 cm for over 11 month (WR=3)	100	100	100
		4 Wet within 40 cm depth for over 11 month (WR=4)	100	100	100
SQ5	Split	Saline	20	20	20
		Sodic	35	35	35
		Salic	20	20	20
SQ6		Petrocalcic	50	50	50
		Petrogypsic	35	35	35

Soil Quality	Rating Type	Soil Phases (HWSD)	INPUT LEVEL		
			HIGH	INT	LOW
SQ7	Full	Stony	50	75	75
		Lithic	30	50	75
	Split	Petric	50	50	50
		Petrocalcic	50	50	50
		Petrogypsic	50	50	50
		Petroferric	50	50	50
		Fragipan	100	100	100
		Duripan	100	100	100
		Placic	100	100	100
	Full	Rudic	50	75	75
	Split	Skeletic	50	50	50
	Full	Erosion	100	100	100
		No limitation to agricultural use	100	100	100
	Split	Gravelly	50	50	50
		Concretionary	50	50	50
	Full	No information (ROO= 0)	100	100	100
		No obstacle to roots between 0 and 80 cm (ROO=1)	100	100	100
		Obstacle to roots between 60 and 80 cm depth (ROO=2)	100	100	100
		Obstacle to roots between 40 and 60 cm depth (ROO=3)	50	75	100
		Obstacle to roots between 20 and 40 cm depth (ROO=4)	30	50	75
		Obstacle to roots between 0 and 80 cm depth (ROO=5)	50	75	75
		Obstacle to roots between 0 and 20 cm depth (ROO=6)	0	0	0
		No information (IL=0)	100	100	100
		No impermeable within 150 cm (IL=1)	100	100	100
		Impermeable between 80 and 150 cm (IL=2)	100	100	100
		Impermeable between 40 and 80 cm (IL=3)	50	75	100
		Impermeable within 40 cm (IL=4)	30	50	75

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

Soil phase ratings for all crops are provided by the five water supply systems in the Appendix 6-5.

6.4 Soil quality and soil suitability

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

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

2) Soil qualities are combined in crop specific, input and management level specific and water supply specific soil suitability ratings.

6.4.1 Soil quality

The procedures used to derive the soil qualities[3]: (SQ1-7) from various combinations of soil attributes are described below.

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

[3] The soil qualities are separately estimated for topsoil (0-30 cm) and subsoil (30-100 cm) and combined by weighting fashion according to prevalence of active roots.

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

$\tau(x_{jo}) \leq \tau(x_j)$, j = 1,…,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 input farming and to some extent also for intermediate input levels. Diagnostics related to nutrient availability are manifold. Important soil profile attributes for 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)*

Nutrient retention capacity (SQ2)

Nutrient retention capacity is of particular importance for the effectiveness of fertilizer applications and is in particular 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 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) and effective soil volume (vol. %) accounting for 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 peoperty 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[4] and presence of coarse fragments.

Relevant soil phases considered are:

FAO 74 soil phases: Stony, lithic, petric, petrocalcic, petrogypsic, petroferric, fragipan and duripan.

FAO 90 soil phases: Rudic, lithic, pertroferric, placic, skeletic, fragipan and duripan.

ESB (FAO85) 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 is evaluated separately for topsoil and subsoil attributes.

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

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.

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 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 respectively phreatic, anthraquic, inundic, and placic 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.

Excess salts (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 and is measured as exchangeable sodium percentage (ESP).

[4] Petric Calcisols and Petric Gypsysols

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.

Toxicities (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, 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 petro-calcic and petro-gypsic soil phases is selected. 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, in particular for manual 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 SQ7 is influenced by (i) physical hindrance to cultivation and (ii) limitations to cultivation imposed by texture/clay mineralogy and bulk-density. 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.

6.4.2 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, excess salts, toxicity 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 five 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.

Low input farming:

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

Intermediate input farming:

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

High input farming:

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

The results of soil unit suitability assessment 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.

In module V (see below agro-ecological crop suitability and corresponding agronomically attainable yields is generated for each grid-cell, through assessing all dominant and associated soil component shares of all soil associations as quantified in the Harmonized World Soil Database.

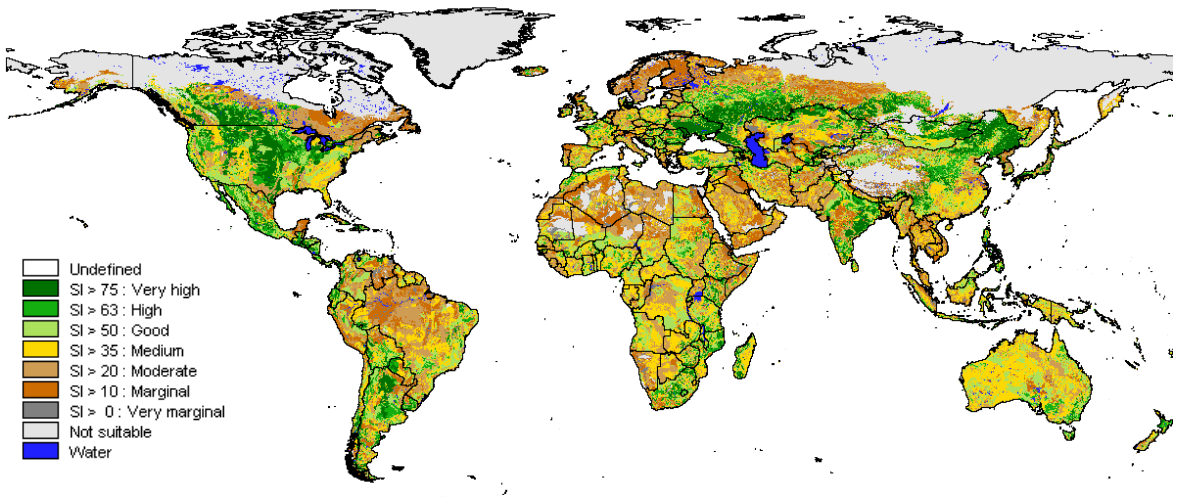

Figure 6-5 Rainfed soil suitability, low input level

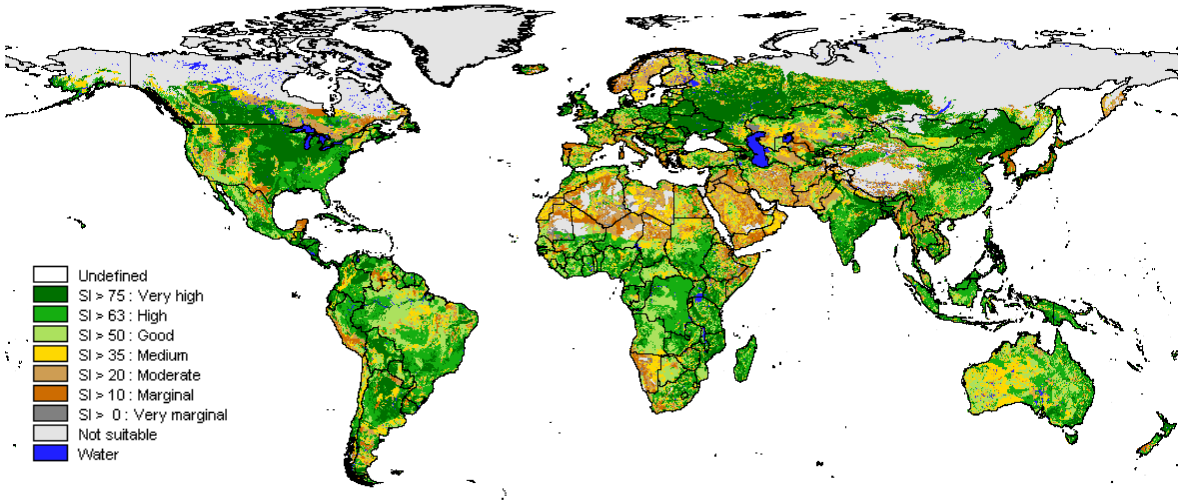

Figure 6-6 Rainfed soil suitability, high input level

6.5 Terrain suitability

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 = 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 climatic inventory. 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 the 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 defined by LGP classes.

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:

S1	-	Optimum conditions
S2	-	Sub-optimum conditions
S1/S2	-	50% optimum and 50% sub-optimum conditions
S2/N	-	50% sub-optimum and 50% not suitable conditions
N	-	Not suitable conditions

Table 6-11 presents terrain-slope ratings for rain-fed conditions for eight crop groups at three levels of inputs and management as used for the lowest class of the Fournier index, i.e., Fm< 1300. Appendix 6-6 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.

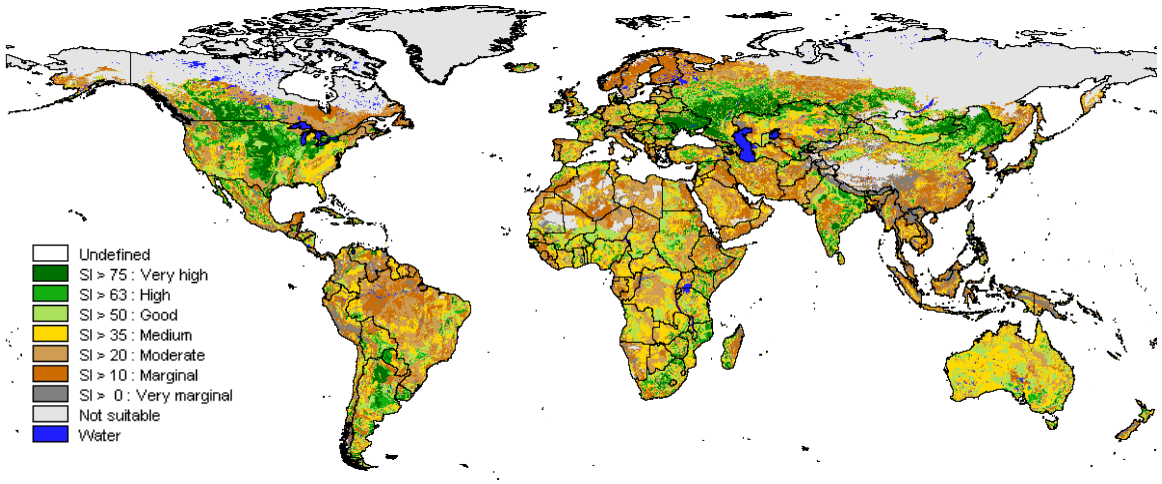

Figure 6-7 Rainfed soil and terrain suitability, low input level

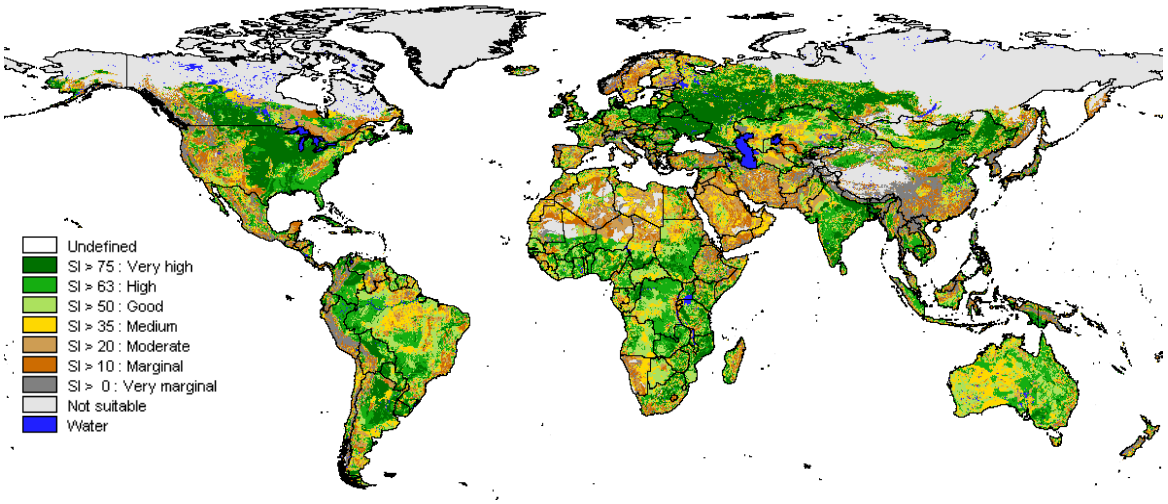

Figure 6-8 Rainfed soil and terrain suitability, high input level

Table 6-11 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	N	N	N
Annuals 2	S1	S1	S1	S1	S1/S2	N	N	N
Annuals 3	S1	S1	S1/S2	S2/N	N	N	N	N
Perennials 1	S1	S1	S1	S1/S2	S2/N	N	N	N
Perennials 2	S1	S1	S1	S1	S1/S22	S2/N	N	N
Perennials 3	S1	S1	S1	S1	S1/S2	S2/N	N	N
Perennials 4	S1	S1	S1	S1	S1	S2	N	N
Perennials 5	S1	S1	S1	S1	S1/S2	N	N	N

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	N	N
Annuals 2	S1	S1	S1	S1	S1/S2	S2	N	N
Annuals 3	S1	S1	S1/S2	S2	S2/N	N	N	N
Perennials 1	S1	S1	S1	S1	S1	S1/S2	N	N
Perennials 2	S1	S1	S1	S1	S1	S1/S2	N	N
Perennials 3	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 4	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 5	S1	S1	S1	S1	S1	S1/S2	S2/N	N

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	N	N
Annuals 2	S1	S1	S1	S1	S1	S1/S2	N	N
Annuals 3	S1	S1	S1	S1/S2	S2	S2/N	N	N
Perennials 1	S1	S1	S1	S1/S2	S2	S2/N	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

Crop Groups:

Annuals 1: wheat, barley, rye, oat, buckwheat

Annuals 2: maize, sorghum, pearl millet, foxtail millet, potato, white potato, sweet potato, beans, phaseolus bean, chickpea, cowpea, gram, dry pea, pigeon pea, rapeseed, soybean and groundnut, sunflower, cotton, sugar beet, rape, flax, white yam, greater yam, tobacco, cabbage, carrot, onion, tomato)

Annuals 3: wetland rice

Perennials 1: sugarcane

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

6.6 Soil and terrain suitability assessment for irrigated conditions

Five water supply systems have been separately evaluated. Apart from evaluating rain-fed and rain-fed with water conservation based crop production systems, specific soil requirements for three major irrigation systems have been established namely for gravity-, sprinkler and drip irrigation.

6.6.1 Soil suitability for irrigated conditions

Evaluation of rain-fed with water conservation systems follows procedures as outlined for rain-fed production. 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 are 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 *et al.*, 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 (1976b), FAO/Unesco (1974), and FAO/Unesco/ISRIC (1990). Details of the application of standard or adapted ratings are presented by water supply system in Table 6-12. Soil profile attribute ratings, soil texture ratings, soil drainage ratings and soil phase ratings for all crops, all relevant levels of inputs and the five water supply systems are presented in the Appendix 6-2.

6.6.2 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 6-6.

Table 6-12 Soil and terrain evaluation ratings by water supply system

SOIL AND TERRAIN EVALUATION						
Water supply systems		**Rain-fed**			**Irrigated**	
		Without Soil Moisture Conservation	**With Soil Moisture Conservation**	**Gravity Irrigation**	**Sprinkler Irrigation**	**Drip Irrigation**
Input Levels		**H, I., L**	**H, I**	**H, I.**	**H, I**	**H**
Deviations from rain-fed soil parameter rating.						
SQ7	Texture/minerarology	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
SQ3	Rooting depth	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)	standard (rainfed)
SQ4	Drainage	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
SQ6	CaCO3	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
SQ6	CaSO4	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
SQ5	Salinity	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	adapted ratings
SQ5	Sodicity	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
Deviations from rain-fed slope parameter rating.						
Other	Slopes	standard (rainfed)	standard (rainfed)	standard (irrigated)	standard (rainfed)	standard (rainfed)
Deviations from rain-fed phase parameter rating						
SQ4	Phreatic	n,a.	n,a.	standard (rainfed)	n,a.	n,a.
	Anthraquic	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	Inundic	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	Placic	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	Excessively drained	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Flooded	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	0 No information (IL=0)	n,a.	n,a.	n,a.	n,a.	n,a.
	1 No impermeable within 150 cm (IL=1)	n,a.	n,a.	n,a.	n,a.	n,a.
	2 Impermeable between 80 and 150 cm (IL=2)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
	3 Impermeable between 40 and 80 cm (IL=3)	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	4 Impermeable within 40 cm (IL=4)	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	0 No information (WR=0)	n,a.	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 (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
	2 Wet within 80 cm for 3 to 6 months, but not wet within 40 cm for over 1 month (WR=2)	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	3 Wet within 80 cm over 6 months, but not wet within 40 cm for over 11 month (WR=3)	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
	4 Wet within 40 cm depth for over 11 month (WR=4)	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
SQ5	Saline	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	adapted ratings
	Sodic	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
	Salic	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	adapted ratings

SOIL AND TERRAIN EVALUATION						
Water supply systems		**Rain-fed**			**Irrigated**	
		Without Soil Moisture Conservation	**With Soil Moisture Conservation**	**Gravity Irrigation**	**Sprinkler Irrigation**	**Drip Irrigation**
Input Levels		**H, I, L**	**H, I**	**H, I**	**H, I.**	**H**
SQ6	Petrocalcic	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)	standard (rainfed)
	Petrogypsic	standard (rainfed)	standard (rainfed)	adapted ratings	standard (rainfed)	standard (rainfed)
SQ7	Stony	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Lithic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Petric	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Petrocalcic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Petrogypsic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Petroferric	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Fragipan	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Duripan	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Placic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Rudic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Skeletic	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Erosion	n.a.	n.a.	n.a.	n.a.	n.a.
	No limitation to agricultural use	n.a.	n.a.	n.a.	n.a.	n.a.
	Gravelly	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Concretionary	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	No information (ROO= 0)	n.a.	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.	n.a.
	Obstacle to roots between 60 and 80 cm depth (ROO=2)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Obstacle to roots between 40 and 60 cm depth (ROO=3)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Obstacle to roots between 20 and 40 cm depth (ROO=4)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Obstacle to roots between 0 and 80 cm depth (ROO=5)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Obstacle to roots between 0 and 20 cm depth (ROO=6)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	No information (IL=0)	n.a.	n.a.	n.a.	n.a.	n.a.
	No impermeable within 150 cm (IL=1)	n.a.	n.a.	n.a.	n.a.	n.a.
	Impermeable between 80 and 150 cm (IL=2)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Impermeable between 40 and 80 cm (IL=3)	standard (rainfed)	adapted ratings	adapted ratings	standard (rainfed)	standard (rainfed)
	Impermeable within 40 cm (IL=4)	**standard (rainfed)**	**adapted ratings**	**adapted ratings**	**standard (rainfed)**	**standard (rainfed)**

6.7 Soil and terrain suitability assessment for rain-fed conditions under water conservation regimes

Selected annual crop/LUTs have separately been evaluated for and rain-fed condition with water conservation management. The waterbalance implications are presented in section 3.4.1-3.4.2. Crop/LUTs for for rain-fed with water-conservation assessments include LUTs of wheat, barley, grain and silage maize, sorghum, millets, chickpea, cowpea, soybean and rape. The assessment has been carried out for arid and semi arid areas, which correspond with LGPs of less than 180 days.

6.8 Fallow period requirements

In their natural state, many soils, in particular in the tropics, 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 and Kassam (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 (FAO/IIASA, 1991).

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 are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow.

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 6-7), 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 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 other soilsthen Fluvosols and Gleysols fallow requirement 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 vs3.0 the fallow requirement factors have been applied for the estimations of average annual potential production.

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 on the basis of prevalence of specific soil types. Fluvisols[5] and to a lesser extent Gleysols[6] are typically representing the flat terrain of alluvial valleys and other water-collecting sites.

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 the 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 water-logging 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, 1978-81a) has been followed. This includes accounting for crop-specific tolerances to excess moisture (high groundwater, water-logging and flooding/inundation) and the use of available estimates of flooding regimes of the Fluvisols. Since Gleysols are mostly, but not necessarily, subjected to water-logging 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

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

[6] 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.

and regular fresh sediment deposits, nor do they suffer from flooding. The moisture regime of Fluvisols under these protected conditions is 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 below:

Table 6-13 Fluvisol and Gleysol suitability ratings

	Fluvisols		Gleysols	
	natural	protected	natural	artificially drained
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%

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, water-logging and flooding. The rating tables are presented in Appendix 6-8.

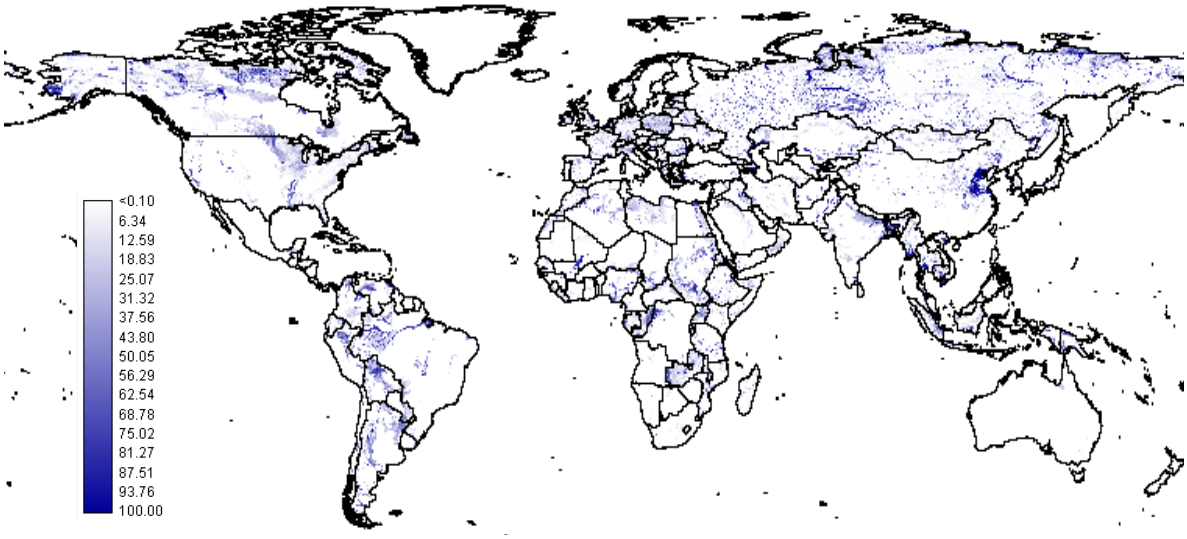

Figure 6-9 Water collecting sites

6.1 Description of Module IV outputs

The main output information provided by Module IV is given in Appendix 6-9 and 6-10.

7 Module V (Integration of climatic and edaphic evaluation)

7.1 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. 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 evaluation and slope rules are applied separately for each water supply systems. The information flow in Module V is summarized in Figure 7-1.

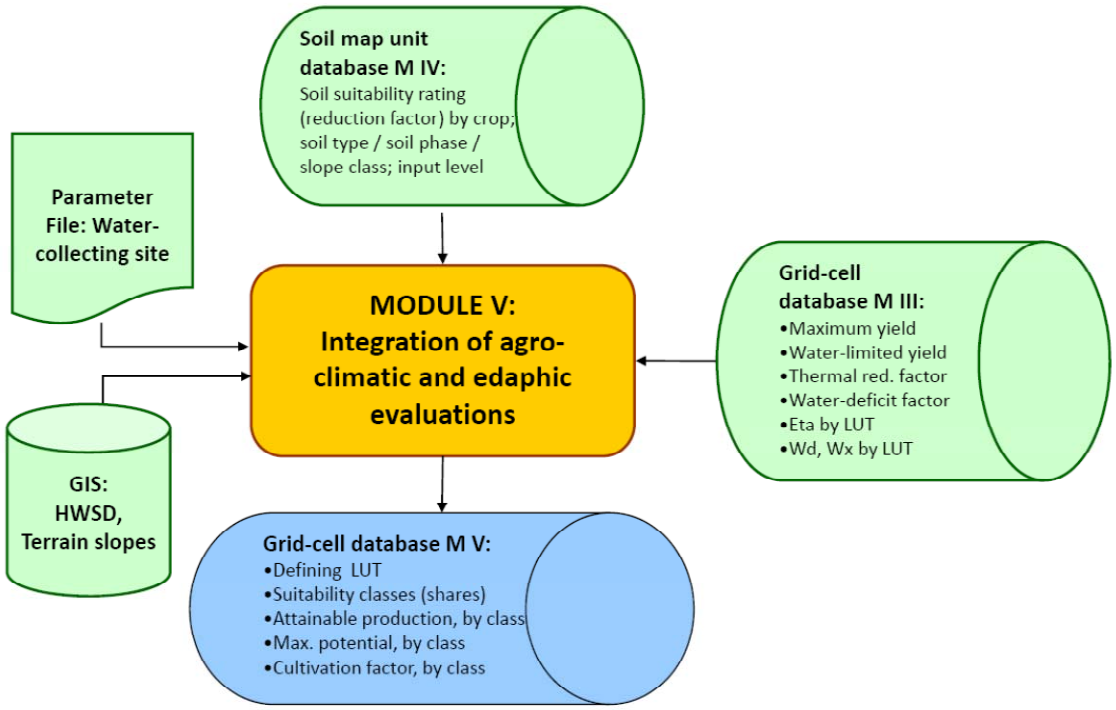

Figure 7-1 Information flow in Module V

7.2 Description of Module V outputs

7.2.1 Main processing steps in Module V

The algorithm in Module V steps through the grid cells of the spatial soil association layer of the Harmonized World Soil Database (HWSD) 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. One hundred of these produce the edaphic characterization at 5 arc-minutes, which is the resolution used for providing GAEZ results. As a result, information stored for 5 arc-minute grid cells contains distributions of the individual sub-grid evaluations.

The main purpose of Module V is to compile a grid-cell database for each crop or crop group storing evaluation results that summarize the processed sub-grid information. Computations include the following steps:

- Reading agro-climatic yields calculated for separate crop water balances of six broad soil AWC classes (from Module II/III);
- applying AEZ rules for water-collecting sites (defined as Fluvisols and Gleysols on flat terrain);
- applying reduction factors due to edaphic evaluation for the specific combinations of soil types/slope classes making up a grid-cell;
- aggregating results over component land units (soil type/slope combinations), and
- calculating applicable fallow requirement factors depending on climate characteristics, soil type and crop group.

7.2.2 Module V output results

The results of crop evaluations in Module V are stored as a large number of separate databases each organized by grid cells. Separate files are generated by crop, input level, water supply system and scenario/time period, each containing sub-grid distribution information in terms of suitable extents and potential production by suitability classes.
A detailed description of the information provided by Module V is given in the Appendix 7-1 and 7-2.

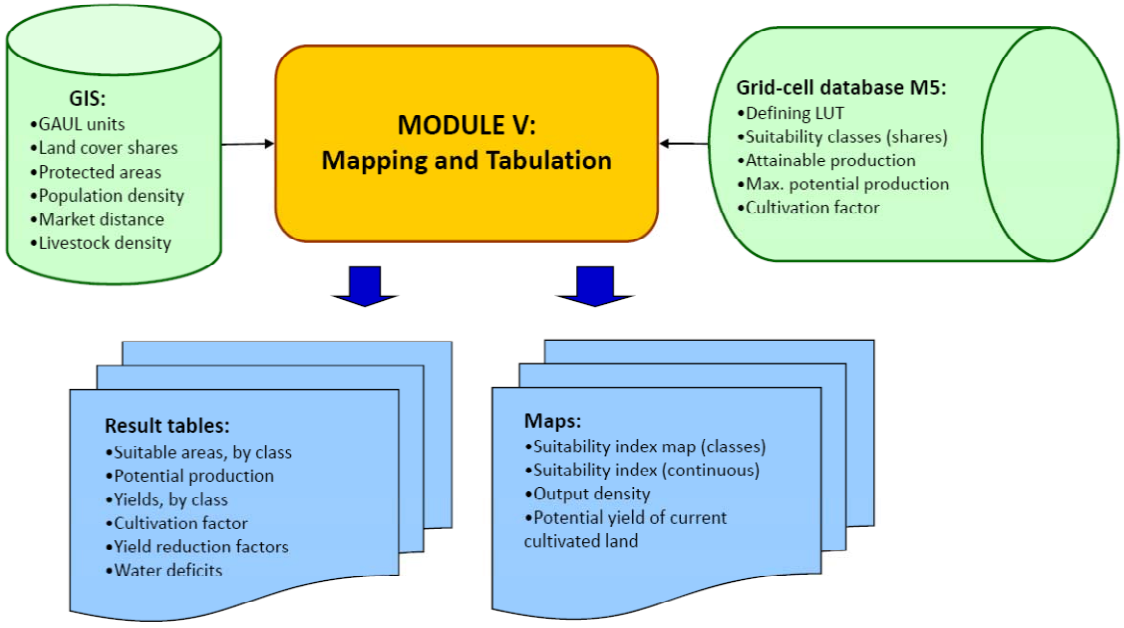

Figure 7-2 Mapping and Tabulation in Module V results

Various utility programs have been developed to aggregate and tabulate results by administrative units or to map the contents of Module V crop databases in terms of suitability index and potential gridcell output. Crop summary tables provide standardized information on distributions of crop suitability and crop yield data, which are discussed at length in Appendix 7-3. Figure 7-3 below shows the agro-ecologically suitable total production of rain-fed, higy-input wheat.

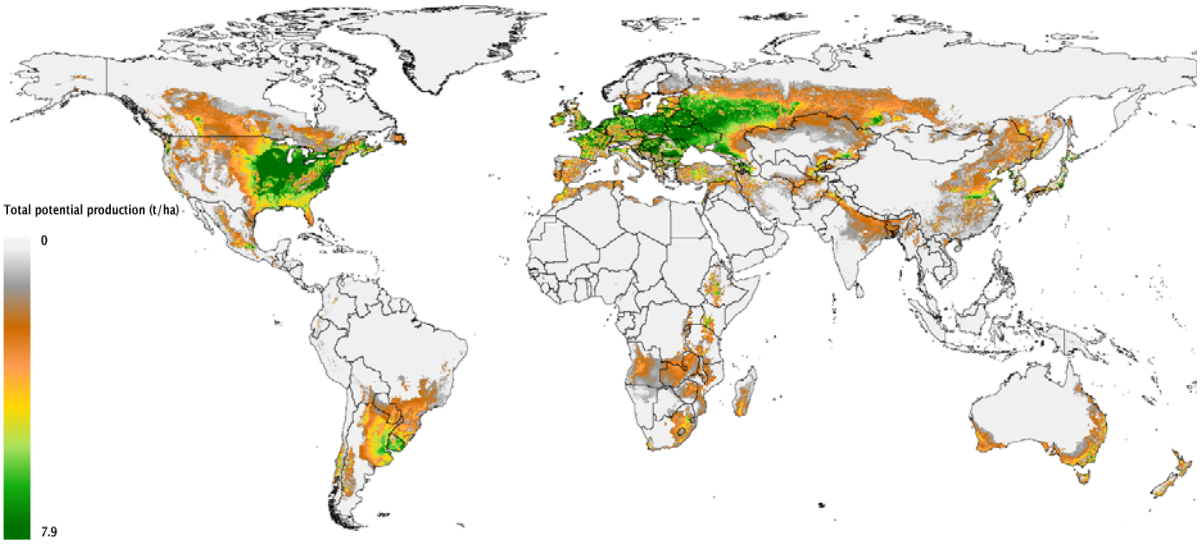

Figure 7-3 Agro-ecological suitability and productivity potential of wheat

8 Module VI (Actual Yield and Production)

8.1 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.

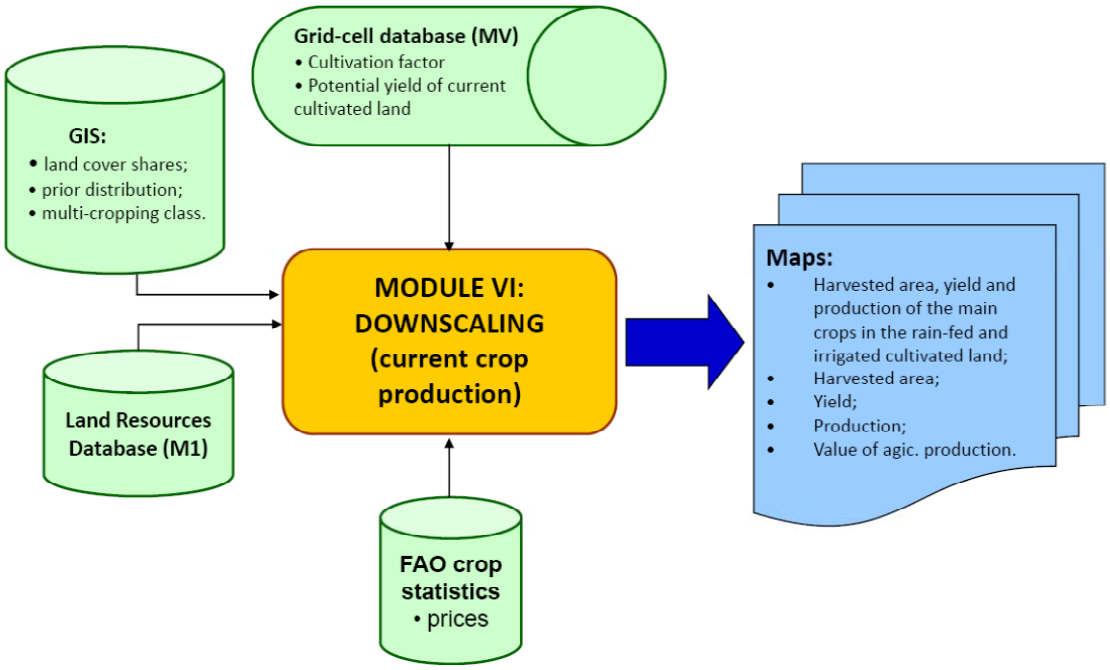

Figure 8-1 Information flow of Module VI

8.2 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 include the spatial heterogeneity of agricultural production at finer resolutions, e.g., grid cells, within country boundaries. In this case a "downscaling" method is needed for allocation of aggregate national production values to individual spatial units (grid-cells) by applying formal methods that accont for land characteristics , assess possible production options and using available evidence from observed or inferred geo-spatial information, e.g. remotely sensed land cover, soil, climate and vegetation distribution, population density and distribution, etc.

Land cover data products contain classifications providing detailed geographical information of the distribution of cultivated land. Besides these 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 or crop suitabilities for specific agricultural activities, farming systems data, human population distribution, locations of markets and

infrastructure etc. Such data in combination with GAEZ crop suitability layers is 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, 2006b) and combine the available statistics with other "prior" hard (accounting identities) and soft (expert opinion) 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 cultivated land 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.,* 2006) based on cross entropy maximization principles, thereby allocating cropping activities to appropriate tracts of rain-fed respectively irrigated land while providing realistic estimates of current yield and production for the cultivated land 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) Estimation of shares of rain-fed or irrigated cultivated land by 5 arc-minute grid cell (for explanations see Appendix 8-1), and

(ii) Estimation of crop specific harvested area, yield and production of crops within the rain-fed and irrigated cultivated land of each grid cell (for details see Appendix 8-2).

Figure 8-2 presents the example results of the estimations of shares of cultivated land by grid cell and Figure 8-3 shows results of harvested area for wheat production in 2000.

8.2.1 Estimation of cultivated land shares

For the estimation of land shares by major land uses in individual 5 arc-minute grid cells, data from several land cover datasets was used. For the year 2000 the database combines (i) the GLC2000 land cover regional and global classifications (http://www-gvm.jrc.it/glc2000), (ii) a global land cover categorization, compiled by IFPRI (IFPRI, 2002), based on a reinterpretation of the Global Land Cover Characteristics Database (GLCC) ver. 2.0, EROS Data Centre (EDC, 2000), and (iii) a special layer of forest land from the Forest Resources Assessment of FAO (FAO, 2001). Furthermore, global 5 arc-minute inventories of irrigated land (GMIA version 4.0; FAO/University of Frankfurt, 2006) were used and an interpretation of the IUCN-WCMC protected areas inventory (WPDA,2009) (along with other convention types of legally protected areas) to distinguish protected land in two categories, namely areas where some restricted agricultural use is permitted and protected areas where cultivation is strictly prohibited. Finally, a population inventory for year 2000 has been used to estimate land required for housing and infrastructure (population density map developed by FAO-SDRN, based on spatial data of LANDSCAN 2003, with calibration to UN 2000 population figures).

In step (i) various land cover interpretations are combined to produce a quantification of each grid-cell in the spatial raster in terms of seven main land use/land cover shares. These shares are: cultivated land, subdivided into (i) rain-fed and (ii) irrigated land; (iii) forest; (iv) pasture and other vegetated land; (v) barren and very sparsely vegetated land; (vi) water, and (vii) urban land and land required for housing and infrastructure.

An iterative calculation procedure was used to estimate land cover class weights, consistent with aggregate FAO land statistics (of arable land and forest land) and spatial land cover patterns

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

The occurrence of cultivated land (share) in 2000 is presented in Figure 8-2.

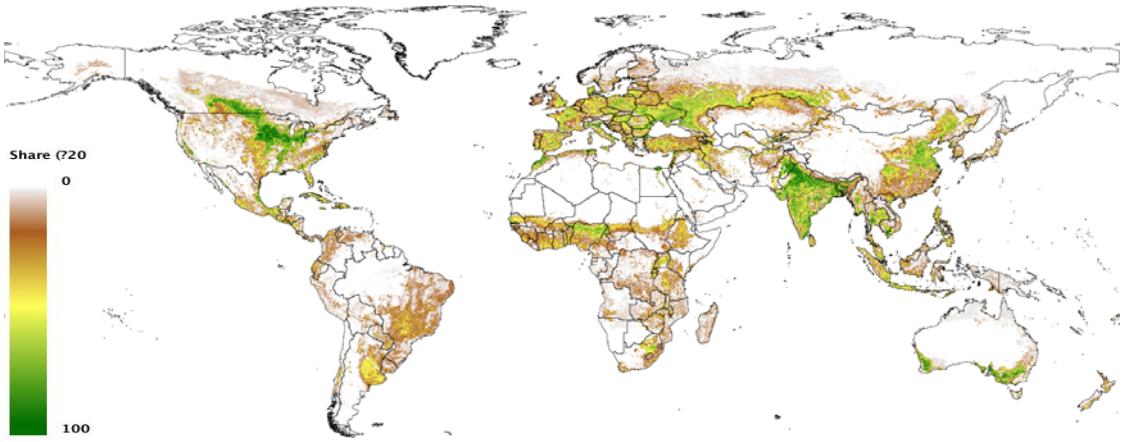

Figure 8-2 Shares of cultivated land by 5 arc-minute grid cell

8.2.2 Allocation of agricultural statistics to cultivated land

Agricultural crop production data are available at national scale from FAO. Sub-national information was collected and compiled by Montfreda *et al.* (2008) and FAO's Agro-MAPS: Global spatial database of agricultural land-use statistics, version 2.5. With spatial occurrence of rain-fed and irrigated cultivated land established in the previous step, the main objective of the second step is to allocate crop production statistics to the respective spatial land 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 cultivated land of each grid cell is available from geographically detailed GAEZ assessments for different input levels and water sources (i.e., rain-fed and irrigated) including estimates of agronomically attainable crop yields. Additional spatially explicit information can be used in estimating crop distributions, for example, spatially explicit farming systems information (including purpose of production in terms of subsistence/market orientation), distance to nearest market, livestock density, population density, etc.

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 to ensure that 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 cultivated land, including its capacity to support multi-cropping, and is in agreement with ancillary sub-national data, in particular selected crop area distribution data (Montfreda *et al.*, 2008) and agronomic suitability of crops as estimated in AEZ.

8.1 Description of Module VI outputs

The downscaling procedures and implementation for the year 2000 respectively 2005 agricultural statistics have resulted in the following data sets:

(i) Global inventory of shares of cultivated land, forest land, grass and other vegetated land, barren and very sparsely vegetated land, infrastructure and built-up urban areas and water by grid-cell. The cultivated land shares are subdivided in rain-fed and irrigated land;

(ii) Area, yield and production for major crops in rain-fed cultivated land, based on year 2000 and 2005 statistics, and

(iii) Area, yield and production for major crops in irrigated land based on year 2000 and 2005 statistics.

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

For illustration, maps of cultivated land, harvested area, yield and production of rain-fed maize are presented in Figure 8-2, Figure 8-3, Figure 8-4 and Figure 8-5 respectively.

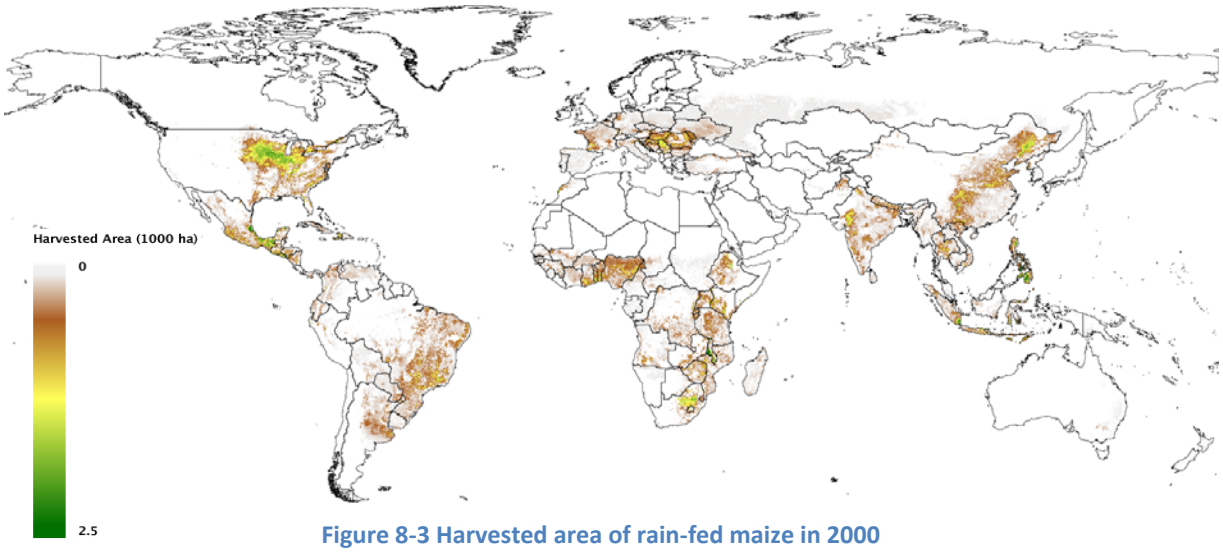

Figure 8-3 Harvested area of rain-fed maize in 2000

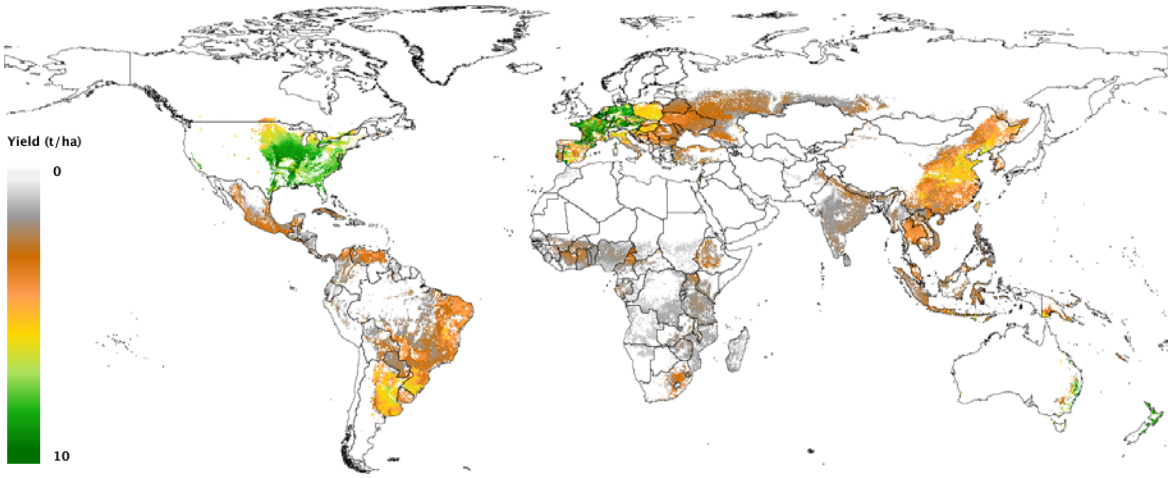

Figure 8-4 Yield of rain-fed maize in 2000

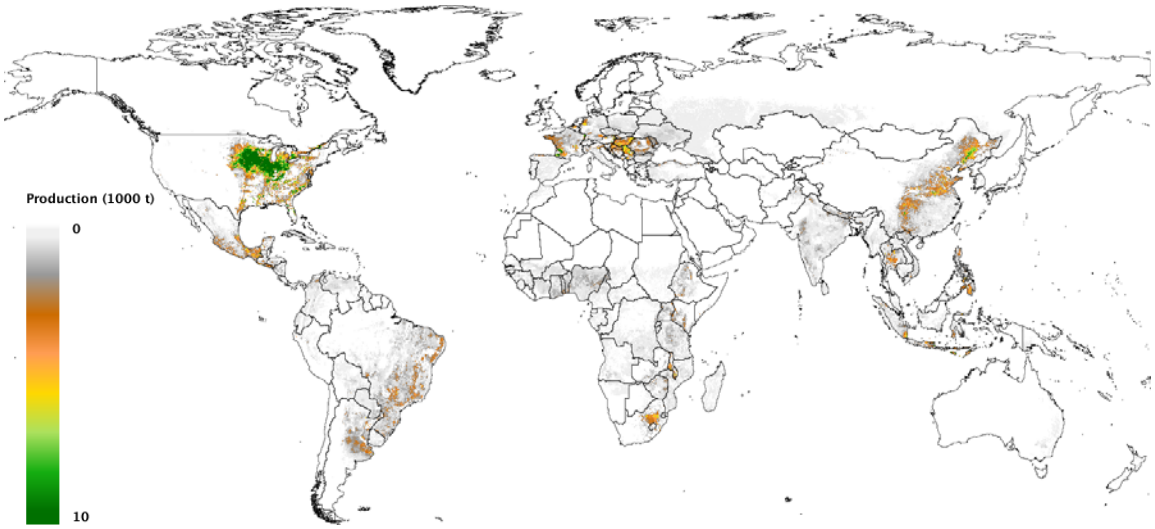

Figure 8-5 Production of rain-fed maize

The results of spatial allocation of crop statistics for the year 2000 and 2005 in Module VI are stored as a large number of separate GIS rasters of 5 arc-minute grid-cells, separately by 23 crops/crop groups, rain-fed and irrigated conditions, for harvested area, production and associated yield.

9 Module VII (Yield and Production Gaps)

9.1 Introduction

Apparent yield and production gaps have been estimated by comparing potential attainable yields and production (estimated in GAEZ v3.0) and actual yields and production from downscaling year 2000 and 2005 statistics of main food and fiber crops (statistics derived from FAOSTAT and AQUASTAT.

Numerical yield gap analysis relies on results of both crop suitability analysis (Module V) and downscaling of base year agricultural statistics (Module VI). A schematic representation of Module VII is presented in Figure 9-1 below.

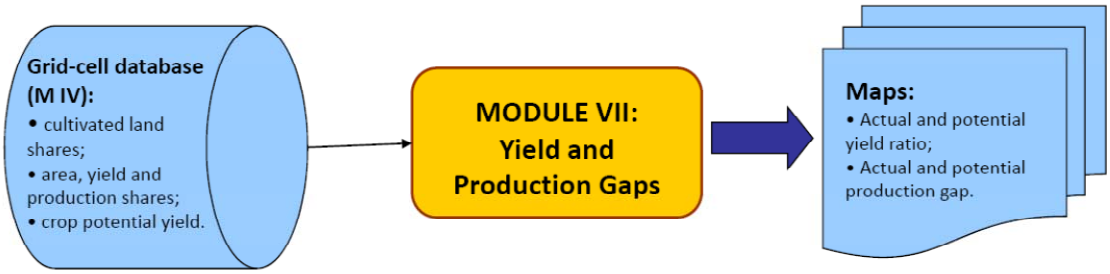

Figure 9-1 Schematic representation of Module VII

Yield and production gaps are estimated by comparing simulated potential and (down-scaled) actual yield and production of main food and fiber crops. The underlying metyhological framework of yield and production gap estimation is presented in Figure 9-2.

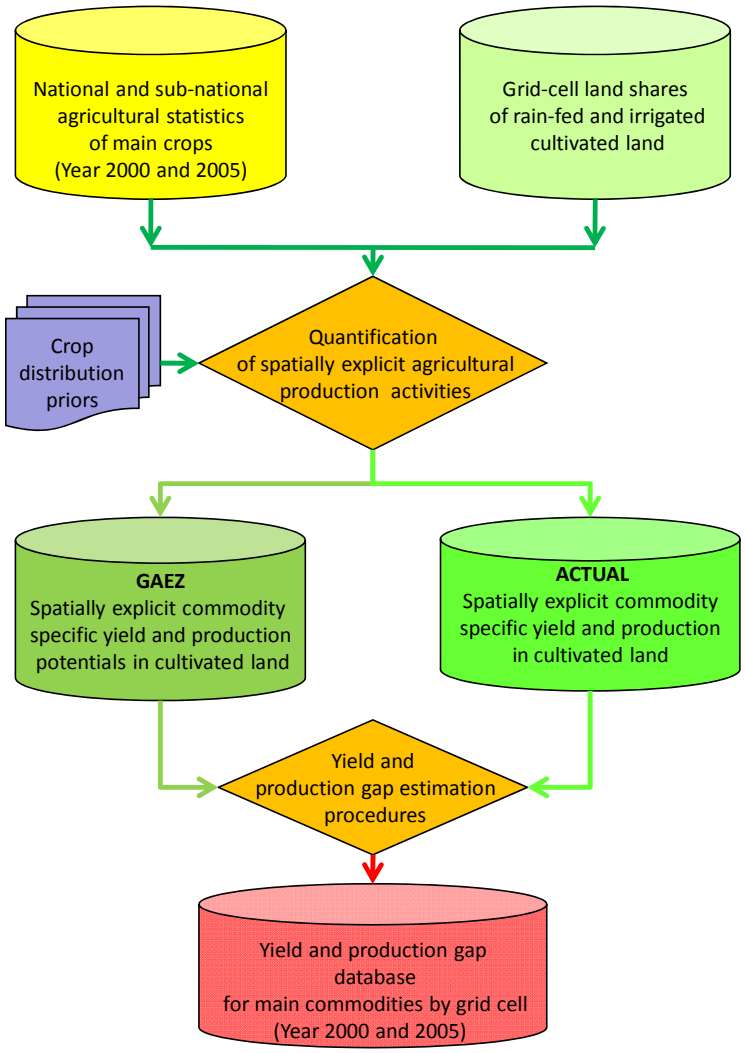

Figure 9-2 Yield-gap estimation procedures

9.2 Yield and production gaps assessment procedures

For 18 of the 23 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 rainfed and irrigated cultivated land. These commodities are presented in Table 9-1 below.

Note that for comparison of FAOSTAT statistical production (usually in harvested area or fresh weight) with GAEZ simulated potential production (yield calculated in dry weight of main produce) an appropriate conversion factor is applied to the GAEZ estimates. Conversion factors between GAEZ and FAOSTAT data are given in Table 9-1.

Table 9-1 Commodities used in the GAEZ yield gap analysis

FAOSTAT Crop/commodity	GAEZ Crop/LUT equivalents
Wheat	Wheat LUTs (20)
Rice	Wetland rice LUTs (8)
Maize	Grain maize LUTs (18)
Sorghum	Sorghum LUTs (18)
Millet	Pearl millet and foxtail millet LUTs (6)
Tuber crops	Potato and sweet potato LUTs (11)
Cassava/other roots	Cassava, yam and cocoyam LUTs (7)
Sugar beet	Sugar beet LUTs (8)
Sugarcane	Sugarcane LUT (1)
Pulses	Phaseolus bean Chickpea, Cowpea, Dry pea, Grams, Pigeon-pea LUTs (35)
Soybean	Soybean LUTs (6)
Rape	Rape LUTs (10)
Sunflower	Sunflower LUTs (6)
Groundnut	Groundnut LUTs (3)
Oil palm	Oil palm LUT (1)
Olive	Olive LUT (1)
Cotton	Cotton LUTs (7)

Comparisons of FAOSTAT compatible GAEZ area, yield and production with downscaled FAOSTAT 2000 respectively 2005 area yield and production statistics is presented in ratios and absolute differences. The comparison is performed on the cultivated land occurring within 5 arc-minute grid cells.

GAEZ potentials respect production potentials from rainfed and irrigated cultivated areas. Two input levels are used for the yield gap analysis low input potentials and mixed input potentials. The definition of mixed input (see section 6.1.1) assumes high agricultural inputs and management on the best land, intermediate inputs moderately suitable land and low inputs on marginal land. This assumption is regarded as a reasonal reflection of actual agricultural input and management circumstances.

Figure 9-3 presents apparent yield gap ratios (actual/potential production) comparing high input level potentials with actual yields.

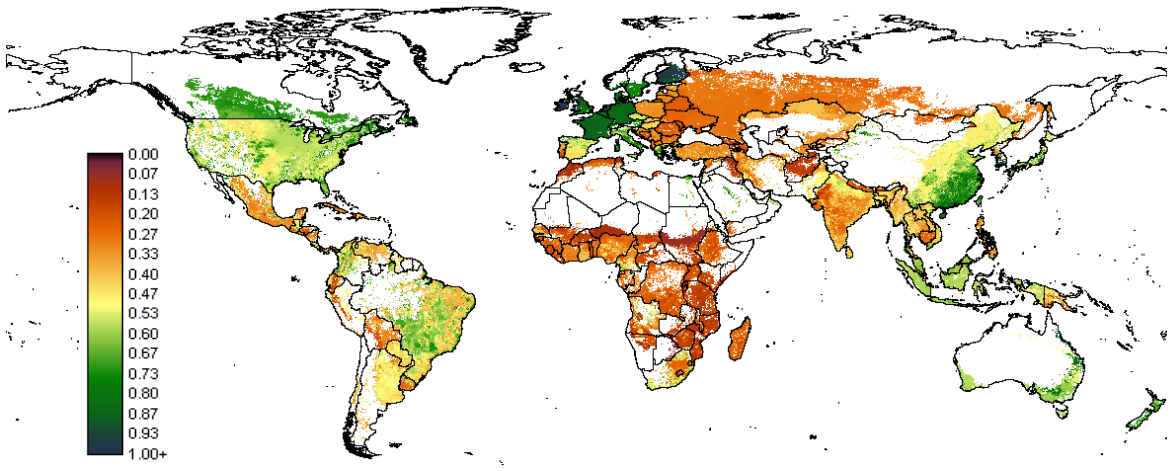

Figure 9-3 Yield gap ratios

9.3 Description of Module VII outputs

Table 9-2 Commodities for Downscaling and yield gap assessments

CROPS		FAOSTAT (HARVESTED WEIGHT)				GAEZ (DRY WEIGHT)			FAOSTAT-GAEZ
Code	**Name**	**Commodities**	**Produce**	**Unit**	**Price (GK$/t)**	**Crop/LUTs**	**Produce**	**Unit**	**Conversion factor**
1	Wheat	Wheat	grain	tons	155	Wheat LUTs	grain	tons	0.875
2	Rice	Rice	grain	tons	200	Wetland rice LUTs	grain	tons	0.875
3	Maize	Maize	grain	tons	125	Grain maize LUTs	grain	tons	0.87
4	Sorghum	Sorghum	grain	tons	130	Sorghum LUTs	grain	tons	0.88
5	Millet	Millet	grain	tons	140, 170	Pearl millet and foxtail millet LUTs	grain	tons	0.9
6	Other cereals	Other cereals	grain	tons	92 - 250	Barley, rye, oat, buckwheat, dry rice LUTs	grain	tons	0.875-0.9
7	Tubers	Potato, Sweet potato	tuber	tons	105, 85	Potato and sweet potato LUTs	tuber	tons	0.25, 0.3
8	Roots	Cassava, Yams, other roots and Plantain	root	tons	75, 95, 120	Cassava, yam, cocoyam and plantain LUTs	root	tons	0.35
9	Sugar beet	Sugar beet	root	tons	32	Sugar beet LUTs	sugar	tons	0.14
10	Sugarcane	Sugarcane	stalk	tons	20	Sugarcane LUT	sugar	tons	0.1
11	Pulses	Pulses	grain	tons	235 - 500	Ph. bean, chickpea, cowpea, dry pea, grams, pigeon-pea LUTs	grain	GK$	1
12	Soybean	Soybean	grain	tons	250	Soybean LUTs	grain	tons	0.9
13	Rape	Rapeseed	seed	tons	330	Rape LUTs	seed	tons	0.9
14	Sunflower	Sunflower	seed	tons	300	Sunflower LUTs	seed	tons	0.9
15	Groundnut	Groundnuts in shells	grain	tons	436	Groundnut LUTs	grain	tons	0.67
16	Oil palm	Oilpalm	fruit	tons	75	Oil palm LUT	oil	tons	0.225
17	Olive	Olive	fruit	tons	500	Olive LUT	oil	tons	0.22
18	Cotton	Cotton	seed + lint	tons	525, 1430	Cotton LUTs	lint	tons	0.35
19	Cash crops 1	Banana, Coconut	fruit	tons	150, 105	Banana & coconut LUTs	fruit, copra	GK$	0.35, 0.175
20	Vegetables	Vegetables	various	tons	100 - 1650	Vegetables LUTs (cabbage, carrot, oinion, tomato)	various	GK$	0.125-0.175
21	Cash crops 2	Coffee, Tea, Cocoa	beans, leaves	tons	1000, 1500, 750	Coffee LUTs, tea LUTs, cocoa LUTs	beans, cd. leaves	GK$	0.35, 0.3, 0.5
22	Fodder	Fodder	AGB	tons	25	Fodder LUTs	AGB	GK$	0.1
23	Residual	Other crops not listed above	various	tons	90 - 4500	n.a.	n.a.	n.a.	n.a.

Crops available in yield and production gap assessments

Pulses in FAOSTAT include: Dry beans, Dry broad beans, Dry peas, Chick-peas, Cow peas, Pigeon peas, Lentils, Bambara beans, other pulses.
AGB = Above ground biomass

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APPENDIXES

Appendix 2-1 Country List (GAUL) and regionalizations

This document is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/GAEZ_Regions.pdf

Appendix 3-1 Calculation of Reference Evapotranspiration

The calculation of reference evapotranspiration (ET_O), i.e., the rate of evapotranspiration from a hypothetic reference crop with an assumed crop height of 12 cm, a fixed 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 $°C^{-1}$)
γ^*	modified psychrometric constant (kPa $°C^{-1}$)
ϑ	slope of vapor pressure curve (kPa $°C^{-1}$)
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):

$$\psi = arc\cos\left(-\tan\varphi \tan\delta\right) \tag{21}$$

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.

Appendix 3-2 Outputs Module I

Outputs calculated in Module I are stored in two separate binary files, one holding variables related to temperature profiles and thermal growing periods and one file storing moisture related characteristics. Each file begins some 18 header records holding a copy of the main control parameters used to run the model. The output variables from Module I are described in the tables below.

Table A-3-1 Content of fixed output records from GAEZ Module I

Variables	Description	Record number	Type of variable	Length of variable (in bytes)
btext	Explanatory text string	1	Character	16
version	Program version string	2	Character	14
datestr	date string (when file was created)	3	Character	9
Mrow	Number of rows of grid	4	Integer	2
Mcol	Number of columns of grid	4	Integer	2
Lenmin	Control parameter LENMIN	4	Integer	2
Itflg	Control parameter ITFLG	4	Integer	2
Rlps	Lapse the applied (degree C perm)	4	Real	4
dRl	Parameter of change in winter use efficiency under elevated CO2	4	Real	4
Sa0	AWC level (mm/m)	4	Real	4
Sdep0	Maximum applicable soil depth (m)	4	Real	4
Rplim1	Water balance control parameter RPLIM1	4	Real	4
Rplim2	Water balance control parameter RPLIM2	4	Real	4
Samin	Water balance control parameter SAMIN	4	Real	4
Kc1	Water balance control parameter KC1	5	Real	4
Kc2	Water balance control parameter Kc2	5	Real	4
Kc3	Water balance control parameter Kc3	5	Real	4
Kc4	Water balance control parameter Kc4	5	Real	4
KC5	Water balance control parameter Kc5	5	Real	4
Kc6	Water balance control parameter Kc6	5	Real	4
Kc7	Water balance control parameter Kc7	5	Real	4
dTx	Climate sensitivity run control parameter dTx	5	Real	4
dTn	Climate sensitivity run control parameter dTn	5	Real	4
dP	Climate sensitivity run control parameter dP	5	Real	4
dS	Climate sensitivity run control parameter dS	5	Real	4
dW	Climate sensitivity run control parameter dW	5	Real	4
flnmap1	Input file name: grid-cell land mask	6	Character	64
flninp	Input file name: land pixel file	7	Character	64
flntc1	Output file name: thermal regime pixel values	8	Character	64
flnlgp	Output file name: moisture regime pixel values	9	Character	64
flntmx	Input file name: average monthly temperature	10	Character	64
flntmn	Input file name: average monthly temperature range	11	Character	64
flnpcp	Input file name: monthly precipitation	12	Character	64
flnwnd	Input file name: monthly wind-run	13	Character	64
flnsol	Input file name: monthly sunshine fraction	14	Character	64
flnrhu	Input file name: monthly relative humidity	15	Character	64
flnwdf	Input file name: monthly wet day frequency	16	Character	64
flngcm	Output file name: climate change distortions from GCM	17	Character	64
EoH	End of header string 'EOH'	18	Character	3

Following the header records, there is one record saved in each file for every grid cell marked as land in the binary land mask file, as listed in Table 3-2 and Table 3-3.

Table A-3-2 Module I output file describing thermal conditions during the growing period

Variables	Description	Type of variable	Length of variable (in bytes)
irow	Pixel reference: row number	Integer	2
icol	Pixel reference: column number	Integer	2
alt	Pixel reference: median elevation [m]	Integer	2
itcc	Thermal climate class	Integer	2
Itcc2	Thermal zones class	Integer	2
iscold	Cold-break indicator (i.e. no hibernating crops permitted)	Integer	2
cidx	Index of continentality	Integer	2
tmean	Mean annual temperature [°C*100]	Integer	2
tamin	Mean annual minimum temperature [°C*100]	Integer	2
tamax	Mean annual maximum temperature [°C*100]	Integer	2
cbtlim	Minimum snow-adjusted monthly temperature [°C]	Real	4
tadif	Annual temperature amplitude (= warmest month minus coldest month)	Real	4
ndtr(1-9,1)	Number of days above (30, 25, 20, 15, 10, 5, 0, -5, < -5) °C for period when temperature trend is up	Integer	9*2
ndtr(1-9,2)	Number of days above (30, 25, 20, 15, 10, 5, 0, -5, < -5) °C for period when temperature trend is down	Integer	9*2
Tsum(1-3)	Accumulated temperature sums for periods with average daily temperature above 0, 5, 10 °C (average temperature) [°Cd]	Real	3*4
Tsumh(1-3)	Average temperature for days with average daily temperature above 0, 5, 10 °C [hours]	Real	3*4
lgpt(1-3)	Number of days, beginning day, ending day with average daily temperature > 0, 5, 10 °C [days]	Integer	3*3
ndx 35	Number of days with maximum temperature >35 °C	Integer	2
ndx 30	Number of days with maximum temperature >30 °C	Integer	2
ndx 00	Number of days with minimum temperature >0 °C	Integer	2
ndx a00	Number of days with average temperature >0 °C	Integer	2
ndx a05	Number of days with average temperature >5 °C	Integer	2
ndx a10	Number of days with average temperature >10 °C	Integer	2
frost1	Air frost index	Real	4
frost2	Snow-adjusted air frost index	Real	4
ndtr2 (1-6,1)	Number of days in longest LGP with average daily temperature above (30, 25, 20, 15, 10, 5, 0, -5, else °C) for the period when temperature trend is up	Integer	6*2
ndtr2 (1-6,2)	Number of days in longest LGP with average daily temperature above (30, 25, 20, 15, 10, 5, 0, -5, else °C) for the period when temperature trend is down	Integer	6*2
Tsum2 (1-3)	Accumulated temperature sums in longest LGP for days above 0, 5, 10 °C [°Cd]	Real	3*4
Tsum2h (1-3)	Accumulated temperature sums in longest LGP for days above 0, 5, 10 °C [hours]	Real	3*4

Table A-3-3 Module I output for soil moisture conditions and length of growing period characteristics

Variables	Description	Type of variable	Length of variable (in bytes)
irow	Pixel reference: row number	Integer	2
icol	Pixel reference: column number	Integer	2
sP	Annual rainfall [mm]	Integer	2
sETo	Annual reference potential evapotranspiration [mm]	Integer	2
sETa	Annual (actual) evapotranspiration of reference crops [mm]	Integer	2
sWex	Annual excess moisture in reference water balance [mm]	Integer	2
ridx	Annual aridity index (100*Pcp/ETo)	Integer	2
ridx2	Aridity index during $LGP_{t=5}$	Integer	2
NPP1	Annual net primary production under irrigation conditions	Real	4
NPP2	Annual net primary production under rainfed conditions	Real	4
ishum	Number of months with P>ETo	Integer	2
ishum05	Number of months with P>ETo and Ta>5	Integer	2
nmon05	Number of months with Ta>5	Integer	2
lgptot	Total number of growing period days	Integer	2
ndwtot	Number of growing period days with P>ETo, reference crop	Integer	2
ndhtot	Number of growing period days with ETa≥ETo, reference crop	Integer	2
nlgp	Number of component growing periods	Integer	2
begdrm	Beginning of dormancy period (0, if no dormancy) [day]	Integer	2
enddrm,	End of dormancy period , (0, if no dormancy) [day]	Integer	2
ndw2	Number of days during $LGP_{t=5}$ with ETa≥0'9 ETo	Integer	2
ndw1	Number of days during $LGP_{t=5}$ with ETa≥0'4 ETo	Integer	2
ndw0	Number of days during $LGP_{t=5}$ with Eta<0'4 ETo	Integer	2
ndwb90	Number of days during $LGP_{t=5}$ with water balance $W_b \geq 0'9S_a$	Integer	2
ndwb50	Number of days during $LGP_{t=5}$ with water balance $W_b \geq 0'5S_a$	Integer	2
ndwb10	Number of days during $LGP_{t=5}$ with water balance $W_b \geq 0'1S_a$	Integer	2
ndwb00	Number of days during $LGP_{t=5}$ with water balance $W_b < 0'1S_a$	Integer	2
ridxw	Seasonal acidity index, October-March	Integer	2
ridxs	Seasonal acidity index, April-September	Integer	2
ridq1	Seasonal acidity index, month 1-3	Integer	2
ridq2	Seasonal acidity index, month 4-6	Integer	2
ridq3	Seasonal acidity index, month 7-9	Integer	2
ridq4	Seasonal acidity index, month 10-12	Integer	2
Lgplen, ndpet, ndwet, beglgp, endlgp (1-nact*)		Integer	5*nact*2

*nact … min (nlgp, 5)

Appendix 3-3 Subroutine descriptions of Module I

Module I: Climate data analysis and reference crop assessment

Module I deals with the reading, conversion, interpolation, analysis and classification of climate data and the creation of historical, base line and future gridded climate data layers relevant to agronomic suitability analysis. The main objective in Module I is the compilation of geo-referenced climatic indicators, including agro-climatic indicators and the estimation of year-round soil moisture balance and evapotranspiration for FAO reference crops (similar to grass). A diagram of the functions and routines of Module I is shown in Figure 3-1 shows the subroutines and functions in alphabetical order with a short description of what the routine or function is used for, which file it is contained within, and which other routines or functions it links to. Table 3-4 lists the source files in alphabetical order and which routines and functions are contained within the source file.

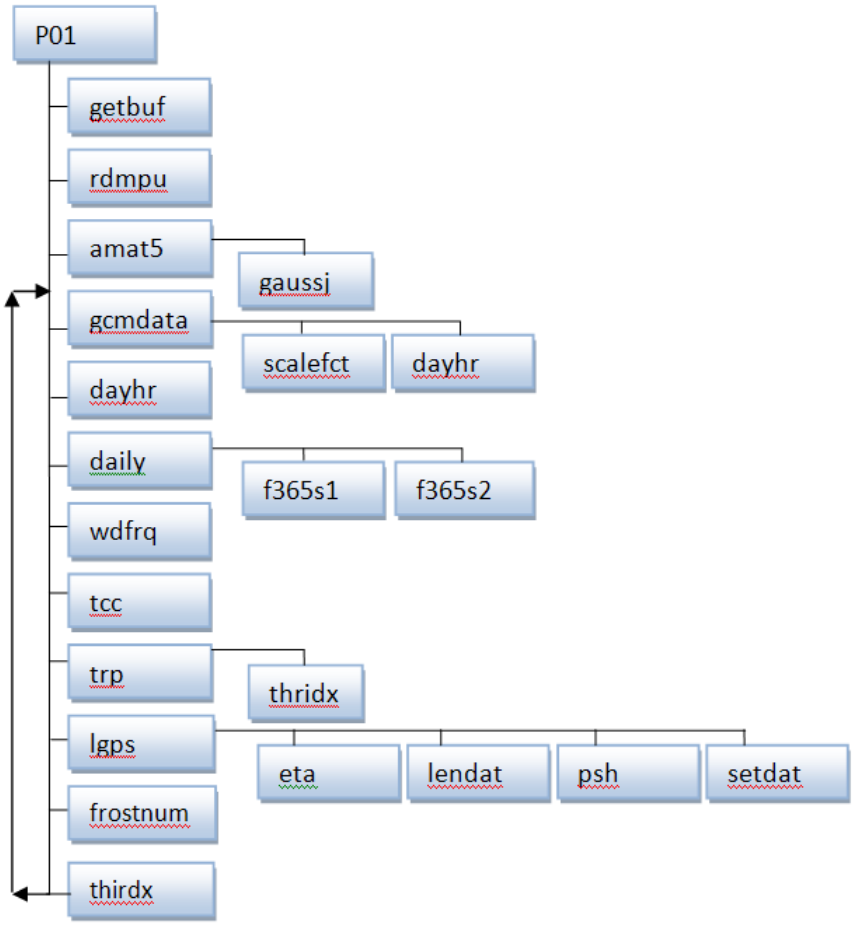

Table A-3-4 Subroutines and functions of Module I

Program	Subroutines	Function	Called from	Calls to
LGPSUB.F	AMAT5	generates coefficients of a system of linear equations for generating daily values by spline interpolation	P01	GAUSSJ
LGPSUB.F	DAILY	converts monthly or decadal data to daily values and calls the next two functions.	P01	F365S1, F365S2
LGPSUB.F	F365S1	fills in daily values by spline interpolation	DAILY	
LGPSUB.F	F365S2	fills in daily values by spline interpolation when the value must be greater or equal to 0	DAILY	
FROST	FROSTNUM	Calculates air frost index and snow-adjusted air-frost index	POI	-

Program	Subroutines	Function	Called from	Calls to
LGPSUB.F	GAUSSJ	Gauss-Jordan elimination with full pivoting	AMAT5	
P01.F	GCMDAT	reads GCM climate change data for correction of current position	P01	DAYHR, SCALEFCT
LGP.F	LGPS	determines the number, length and dates of growing periods	P01	
P01.F	RDMPU	utility routine to read the soil mapping unit available water content data from an input file	GCMDAT	
P01.F	SCALEFCT	algorithm used to calculate a scaling fraction for scaling monthly climatic data variables to match the annual changes from GCM	LGPS	
LGP.F	SETDAT	shifts a calculated day of the year by a multiple of 365 to fit within the range 1-365	P01	
P01.F	TCC	calculates thermal climate class and thermal zone class	P01	THRIDX
P01.F	TRP	calculates temperature growing periods and thermal regime parameters	P01	
P01.F	WDFRQ	distributes rain according to wet day frequency		
LGPSUB.F	CYCSUM	integrates an attribute over growth cycle		
LGPSUB.F	CYCVAL	averages an attribute over growth cycle	P01, GCMDAT	
P01.F	DAYHR	calculates day length for a given latitude and day of the year	P01	
ET0.F	ET0	calculates potential evapotranspiration by the Penman-Monteith method	LGPS	
ETAM.F	ETA	calculates actual evapotranspiration by simulating a daily water balance for an FAO reference crop (similar to grass)	P01	
P01.F	GETBUF	utility function to get next line from an input file, skipping comments	LGPS	
LGP.F	LENDAT	calculates the number of days between two dates including the start and end date.	LPGS	
ETAM.F	PSH	calculates the soil water depletion fraction (p) for a given crop type and level of daily ETo	P01, TRP	
LGPSUB.F	THRIDX	determines temperature profile class index	AMAT5	

Table A-3-5 Fortran source files for Module I and included header files, subroutines and functions

Fortran file	Associated Header Files	Subroutines	Functions
ET0.F			et0
ETAM.F			eta, psh
FROST.F	clim.h, tcc.h	Frostnum	-
LGP.F		lgps, setdat	lendat
LGPSUB.F		amat5, daily, f365s1, f365s2, gaussj	cycval, cycsum, trcidx
P01.F	clim.h, tcc.h	gcmdat, rdmpu, scalefct, tcc, trp, wdfrq	dayhr, getbuf

Appendix 3-4 Example of Module I output at grid-cell level

Example of information generated at grid cell level is given for Ilonga, Tanzania is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Example_grid_cell_output_Module_I.docx

Appendix 4-1 Crops and land utilization types (LUTs)

Suitability and potential yield assessments are available for 11 crop groups (Table 4-1), 49 crops (Table 4-2), 92 crop types (Table 4-3) and 280 Crop/LUTs (Table 4-4). Results for downscaling of crops/commodities are available for 23 crop/commodities and results of yield and production gap analysis are available for 17 crops/commodities (Table 4-5).

Table A-4-1 Crop groups

Code	Crop group
1	Cereals
2	Roots and tubers
3	Sugar crops
4	Pulses
5	Oilcrops
6	Vegetables
7	Fruits
8	Fibre crops
9	Narcotics and stimulants
10	Fodder crops
11	Bioenergy feedstocks

Table A-4-2 Crops

Code	Common name	*Scientific name*	Crop group
1	Wheat	*Triticum spp.*	Cereals
2	Wetland rice	*Oryza sativa*	Cereals
3	Dryland rice	*Oryza sativa*	Cereals
4	Maize	*Zea mays*	Cereals
5	Barley	*Hordeum vulgare*	Cereals
6	Sorghum	*Sorghum bicolor*	Cereals/Sugar crops
7	Rye	*Secale cereale*	Cereals
8	Pearl millet	*Pennisetum glaucum*	Cereals
9	Foxtail millet	*Setaria italica*	Cereals
10	Oat	*Avena sativa*	Cereals
11	Buckwheat	*Fagopyrum esculentum*	Cereals
12	White potato	*Solanum tuberosum*	Roots and tubers
13	Sweet potato	*Ipomoea batatas*	Roots and tubers
14	Cassava	*Manihot esculenta*	Roots and tubers
15	Yam and Cocoyam	*Dioscorea spp. and Colocasia esculenta*	Roots and tubers
16	Sugarcane	*Saccharum spp.*	Sugar crops
17	Sugar beet	*Beta vulgaris L.*	Sugar crops
18	Phaseolus bean	*Phaseolus vulgaris and Ph. lunatus*	Pulses
19	Chickpea	*Cicer arietinum*	Pulses
20	Cowpea	*Vigna unguiculata*	Pulses
21	Dry pea	*Pisum sativum L.*	Pulses
22	Gram	*Vigna radiata*	Pulses
23	Pigeonpea	*Cajanus cajan*	Pulses
24	Soybean	*Glycine max*	Oil crops
25	Sunflower	*Helianthus annuus*	Oil crops
26	Rape	*Brassica napus*	Oil crops
27	Groundnut	*Arachis hypogaea*	Oil crops
28	Oil palm	*Elaeis oleifera*	Oil crops

Code	Common name	*Scientific name*	Crop group
29	Olive	*Olea europaea*	Oil crops
30	Jatropha	*Jatropha curcas.*	Bioenergy feedstocks
31	Cabbage	*Brassica oleracea*	Vegetables
32	Carrot	*Daucus carota*	Vegetables
33	Onion	*Allium cepa*	Vegetables
34	Tomato	*Lycopersicon lycopersicum*	Vegetables
35	Banana/Plantain	*Musa spp.*	Fruits
36	Citrus	*Citrus Sinensis*	Fruits
37	Coconut	*Cocos nucifera*	Fruits
38	Cacao	*Theobroma cacao*	Narcotics and stimulants
39	Cotton	*Gossypium hirsutum.*	Fibre
40	Flax	*Linum usitatissimum*	Fibre crops
41	Coffee	*Coffea arabica*	Narcotics and stimulants
42	Tea	*Camellia Sinenses var. Sinensis*	Narcotics and stimulants
43	Tobacco	*Nicotiana tobacum*	Narcotics and stimulants
44	Alfalfa	*Medicago sativa*	Fodder crops
45	Pasture legume	*various*	Fodder crops
46	Grass	*various*	Fodder crops
47	Miscanthus	*Miscanthus spp*	Bioenergy feedstocks
48	Switchgrass	*Panicum virgatum*	Bioenergy feedstocks
49	Reed canary grass	*Phalaris arundinacea*	Bioenergy feedstocks

Table A-4-3 Crop types

Code	Common name	*Scientific name*	Crop group
1	Winter wheat	*Triticum spp.*	Cereals
2	Spring wheat	*Triticum spp.*	Cereals
3	Wheat (subtropical cultivars)	*Triticum spp.*	Cereals
4	Wheat (tropical cultivars)	*Triticum spp.*	Cereals
5	Japonica wetland rice	*Oryza japonica*	Cereals
6	Indica wetland rice	*Oryza indica*	Cereals
7	Indica dryland rice	*Oryza sativa*	Cereals
8	Maize (tropical lowland cultivars)	*Zea mays*	Cereals
9	Maize (tropical highland cultivars)	*Zea mays*	Cereals
10	Maize (temperate and subtropical cult.)	*Zea mays*	Cereals
11	Silage maize (temperate and subtropical cult.)	*Zea mays*	Fodder crops
12	Winter barley	*Hordeum vulgare*	Cereals
13	Spring Barley	*Hordeum vulgare*	Cereals
14	Barley (subtropical cultivars)	*Hordeum vulgare*	Cereals
15	Barley (tropical cultivars)	*Hordeum vulgare*	Cereals
16	Sorghum (tropical lowland cultivars)	*Sorghum bicolor*	Cereals
17	Sorghum (tropical highland cultivars)	*Sorghum bicolor*	Cereals
18	Sorghum (temperate and subtropical cult.)	*Sorghum bicolor*	Cereals
19	Sweet sorghum (temperate and subtropical cult.)	*Sorghum bicolor*	Sugar crops
20	Winter rye	*Secale cereale*	Cereals
21	Spring rye	*Secale cereale*	Cereals
22	Pearl millet	*Pennisetum glaucum*	Cereals
23	Foxtail millet	*Setaria italica*	Cereals
24	Spring oat	*Avena sativa*	Cereals
25	Buckwheat	*Fagopyrum esculentum*	Cereals
26	White potato	*Solanum tuberosum*	Roots and tubers
27	Sweet potato	*Ipomoea batatas*	Roots and tubers
28	Cassava	*Manihot esculenta*	Roots and tubers
29	White yam	*Dioscorea spp.*	Roots and tubers

Code	Common name	*Scientific name*	Crop group
30	Greater yam	*Dioscorea spp.*	Roots and tubers
31	Yellow yam	*Dioscorea spp.*	Roots and tubers
32	Cocoyam	*Colocasia esculenta*	Roots and tubers
33	Sugarcane	*Saccharum spp.*	Sugar crops
34	Sugar beet	*Beta vulgaris L.*	Sugar crops
35	Phaseolus bean (tropical lowland)	*Phaseolus vulgaris and Ph. lunatus*	Pulses
36	Phaseolus bean (tropical highland)	*Phaseolus vulgaris and Ph. lunatus*	Pulses
37	Phaseolus bean (temperate and subtropical cult.)	*Phaseolus vulgaris and Ph.lunatus*	Pulses
38	Chickpea	*Cicer arietinum*	Pulses
39	Chickpea (cold tolerant)	*Cicer arietinum*	Pulses
40	Cowpea	*Vigna unguiculata*	Pulses
41	Dry pea	*Pisum sativum L.*	Pulses
42	Gram	*Vigna radiate*	Pulses
43	Pigeonpea	*Cajanus cajan*	Pulses
44	Soybean (tropical and subtropical cult.)	*Glycine max*	Oilcrops
45	Soybean (temperate and subtropical cult.)	*Glycine max*	Oilcrops
46	Sunflower (tropical and subtropical cult.)	*Helianthus annuus*	Oilcrops
47	Sunflower (temperate and subtropical cult.)	*Helianthus annuus*	Oilcrops
48	Winter rape	*Brassica napus*	Oilcrops
49	Spring rape	*Brassica napus*	Oilcrops
50	Rabi rape	*Brassica napus*	Oilcrops
51	Groundnut	*Arachis hypogaea*	Oilcrops
52	Oilpalm	*Elaeis oleifera*	Oilcrops
53	Olive	*Olea europaea*	Oilcrops
54	Jatropha	*Jatropha curcas*	Oilcrops
55	Cabbage	*Brassica oleracea*	Vegetables
56	Carrot (temperate and subtropical cultivars)	*Daucus carota*	Vegetables
57	Carrot (temperate and subtropical cultivars)	*Daucus carota*	Vegetables
58	Carrot (tropical cultivars)	*Daucus carota*	Vegetables
59	Onion (temperate and subtropical cultivars)	*Allium cepa*	Vegetables
60	Onion hibernating cultivar	*Allium cepa*	Vegetables
61	Onion (tropical cultivars)	*Allium cepa*	Vegetables
62	Tomato (temperate and subtropical cultivars)	*Lycopersicon lycopersicum*	Vegetables
63	Tomato (tropical and subtropical cultivars)	*Lycopersicon lycopersicum*	Vegetables
64	Banana/Plantain	*Musa spp.*	Fruits
65	Citrus	*Citrus sinensis*	Fruits
66	Coconut 1 (tall)	*Cocos nucifera*	Fruits
67	Coconut 2 (hybrid tall)	*Cocos nucifera*	Fruits
68	Coconut 3 (dwarf)	*Cocos nucifera*	Fruits
69	Cacao (comun)	*Theobroma cacao*	Narcotics and stimulants
70	Cacao (hybrid)	*Theobroma cacao*	Narcotics and stimulants
71	Cotton (tropical cultivars)	*Gossypium spp.*	Fibre crops
72	Cotton (temperate and subtropical cult.)	*Gossypium spp.*	Fibre crops
73	Flax	*Linum usitatissimum*	Fibre crops
74	Coffee arabica	*Coffea arabica*	Narcotics and stimulants
75	Coffee robusta	*Coffea robusta*	Narcotics and stimulants
76	Tea (china tea)	*Camellia Sinenses var. Sinensis*	Narcotics and stimulants
77	Tea (hybrid tea)	*Sinensis and Assamica*	Narcotics and stimulants
78	Tea (assam tea)	*Camellia sinensis* var. *assamica*	Narcotics and stimulants
79	Tobacco (tropical cultivars)	*Nicotiana tobacum*	Narcotics and stimulants
80	Tobacco (temperate and subtropical cult.)	*Nicotiana tobacum*	Narcotics and stimulants
81	Alfalfa (temperate and subtropical cult.)	*Medicago sativa*	Fodder crops
82	Alfalfa (tropical cultivars)	*Medicago sativa*	Fodder crops
83	Pasture legumes (temp. and subtropical cult.)	*various*	Fodder crops

Code	Common name	*Scientific name*	Crop group
84	Pasture legumes (tropical and subtropical cult.)	*various*	Fodder crops
85	Pasture grasses (C3/I cultivars)	*various*	Fodder crops
86	Pasture grasses (C3/II cultivars)	*various*	Fodder crops
87	Pasture grasses (C4/II cultivars)	*various*	Fodder crops
88	Pasture grasses (C4/I cultivars)	*various*	Fodder crops
89	Miscanthus (C4/II)	*Miscanthus spp*	Bioenergy feedstocks
90	Miscanthus (C4/I)	*Miscanthus spp*	Bioenergy feedstocks
91	Switchgrass	*Panicum virgatum*	Bioenergy feedstocks
92	Reed canary grass	*Phalaris arundinacea*	Bioenergy feedstocks

Table A-4-4 Crop/LUTs

Code	Crop type	Growth cycle	Harvested part
1	Winter wheat	35+105 days	Grain
2	Winter wheat	40+120 days	Grain
3	Winter wheat	45+135 days	Grain
4	Winter wheat	50+150 days	Grain
5	Spring wheat	90 days	Grain
6	Spring wheat	105 days	Grain
7	Spring wheat	120 days	Grain
8	Spring wheat	135 days	Grain
9	Spring wheat	150 days	Grain
10	Wheat (subtropical cultivars)	105 days	Grain
11	Wheat (subtropical cultivars)	120 days	Grain
12	Wheat (subtropical cultivars)	135 days	Grain
13	Wheat (subtropical cultivars)	150 days	Grain
14	Wheat (tropical highland cultivars)	100 days	Grain
15	Wheat (tropical highland cultivars)	115 days	Grain
16	Wheat (tropical highland cultivars)	130 days	Grain
17	Wheat (tropical highland cultivars)	145 days	Grain
18	Wheat (tropical highland cultivars)	160 days	Grain
19	Wheat (tropical highland cultivars)	175 days	Grain
20	Wheat (tropical highland cultivars)	190 days	Grain
21	Japonica wetland rice	105 days	Grain
22	Japonica wetland rice	120 days	Grain
23	Japonica wetland rice	135 days	Grain
24	Japonica wetland rice	150 days	Grain
25	Indica wetland rice	105 days	Grain
26	Indica wetland rice	120 days	Grain
27	Indica wetland rice	135 days	Grain
28	Indica wetland rice	150 days	Grain
29	Indica dryland rice	105 days	Grain
30	Indica dryland rice	120 days	Grain
31	Indica dryland rice	135 days	Grain
32	Maize (tropical lowland cultivars)	90 days	Grain
33	Maize (tropical lowland cultivars)	105 days	Grain
34	Maize (tropical lowland cultivars)	120 days	Grain
35	Maize (tropical lowland cultivars)	135 days	Grain
36	Maize(tropical highland cultivars)	120 days	Grain
37	Maize (tropical highland cultivars)	150 days	Grain
38	Maize (tropical highland cultivars)	180 days	Grain
39	Maize (tropical highland cultivars)	210 days	Grain
40	Maize (tropical highland cultivars)	240 days	Grain
41	Maize (tropical highland cultivars)	270 days	Grain
42	Maize (tropical highland cultivars)	300 days	Grain

Code	Crop type	Growth cycle	Harvested part
43	Maize (temperate and subtropical cultivars)	90 days	Grain
44	Maize (temperate and subtropical cultivars)	105 days	Grain
45	Maize (temperate and subtropical cultivars)	120 days	Grain
46	Maize (temperate and subtropical cultivars)	135 days	Grain
47	Maize (temperate and subtropical cultivars)	150 days	Grain
48	Maize (temperate and subtropical cultivars)	165 days	Grain
49	Maize (temperate and subtropical cultivars)	180 days	Grain
50	Silage maize (temperate and subtropical cultivars)	105 days	Fodder
51	Silage maize (temperate and subtropical cultivars)	120 days	Fodder
52	Silage maize (temperate and subtropical cultivars)	135 days	Fodder
53	Silage maize (temperate and subtropical cultivars)	150 days	Fodder
54	Silage maize (temperate and subtropical cultivars)	165 days	Fodder
55	Silage maize (temperate and subtropical cultivars)	180 days	Fodder
56	Winter barley	35+105 days	Grain
57	Winter barley	40+120 days	Grain
58	Winter barley	45+135 days	Grain
59	Winter barley	50+150 days	Grain
60	Spring barley	90 days	Grain
61	Spring barley	105 days	Grain
62	Spring barley	120 days	Grain
63	Spring barley	135 days	Grain
64	Barley (subtropical cultivars)	90 days	Grain
65	Barley (subtropical cultivars)	105 days	Grain
66	Barley (subtropical cultivars)	120 days	Grain
67	Barley (subtropical cultivars)	135 days	Grain
68	Barley (tropical highland cultivars)	100 days	Grain
69	Barley (tropical highland cultivars)	115 days	Grain
70	Barley (tropical highland cultivars)	130 days	Grain
71	Barley (tropical highland cultivars)	145 days	Grain
72	Barley (tropical highland cultivars)	160 day)	Grain
73	Barley (tropical highland cultivars)	175 days	Grain
74	Barley (tropical highland cultivars)	190 days	Grain
75	Sorghum (tropical lowland cultivars)	90 days	Grain
76	Sorghum (tropical lowland cultivars)	105 days	Grain
77	Sorghum (tropical lowland cultivars)	120 days	Grain
78	Sorghum (tropical lowland cultivars)	135 days	Grain
79	Sorghum (tropical highland cultivars)	120 days	Grain
80	Sorghum (tropical highland cultivars)	150 days	Grain
81	Sorghum (tropical highland cultivars)	180 days	Grain
82	Sorghum (tropical highland cultivars)	210 days	Grain
83	Sorghum(tropical highland cultivars)	240 days)	Grain
84	Sorghum (tropical highland cultivars)	270 days	Grain
85	Sorghum (tropical highland cultivars)	300 days	Grain
86	Sorghum (temperate and subtropical cultivars)	90 days	Grain
87	Sorghum (temperate and subtropical cultivars)	105 days	Grain
88	Sorghum (temperate and subtropical cultivars)	120 days	Grain
89	Sorghum (temperate and subtropical cultivars)	135 days	Grain
90	Sorghum (temperate and subtropical cultivars)	150 days	Grain
91	Sorghum (temperate and subtropical cultivars)	165 days	Grain
92	Sorghum (temperate and subtropical cultivars)	180 days	Grain
93	Sweet sorghum (temperate and subtropical cultivars)	90 days	Supra
94	Sweet sorghum (temperate and subtropical cultivars)	105 days	Supra
95	Sweet sorghum (temperate and subtropical cultivars)	120 days	Supra
96	Sweet sorghum (temperate and subtropical cultivars)	135 days	Supra
97	Sweet sorghum (temperate and subtropical cultivars)	150 days	Supra
98	Sweet sorghum (temperate and subtropical cultivars)	165 days	Supra
99	Sweet sorghum (temperate and subtropical cultivars)	180 days	Supra

Code	Crop type	Growth cycle	Harvested part
100	Winter rye	30+90 days	Grain
101	Winter rye	35+105 days	Grain
102	Winter rye	40+120 days	Grain
103	Winter rye	45+135 days	Grain
104	Spring rye	90 days	Grain
105	Spring rye	105 days	Grain
106	Spring rye	120 days	Grain
107	Spring rye	135 days	Grain
108	Pearl millet	70 days	Grain
109	Pearl millet	90 days	Grain
110	Foxtail millet	75 days	Grain
111	Foxtail millet	90 days	Grain
112	Foxtail millet	105 days	Grain
113	Foxtail millet	120 days	Grain
114	Spring oat	90 days	Grain
115	Spring oat)	105 days	Grain
116	Spring oat	120 days	Grain
117	Buckwheat	75 days	Grain
118	Buckwheat	90 days	Grain
119	White potato	90 days	Tuber
120	White potato	105 days	Tuber
121	White potato	120 days	Tuber
122	White potato	135 days	Tuber
123	White potato	150 days	Tuber
124	White potato	165 days	Tuber
125	White potato	180 days)	Tuber
126	Sweet potato	120 days	Tuber
127	Sweet potato	135 days	Tuber
128	Sweet potato	150 days	Tuber
129	Sweet potato	165 days	Tuber
130	Cassava	perennial	Root
131	White yam	195 days	Tuber
132	White yam	225 days	Tuber
133	Greater yam	240 days	Tuber
134	Greater yam	270 days	Tuber
135	Yellow yam	330 days	Tuber
136	Cocoyam	330 days	Tuber
137	Sugarcane	330 days	Sugar
138	Sugar beet	120 days	Sugar
139	Sugar beet	135 days	Sugar
140	Sugar beet	150 days	Sugar
141	Sugar beet	165 days	Sugar
142	Sugar beet	180 days	Sugar
143	Sugar beet	195 days	Sugar
144	Sugar beet	210 days	Sugar
145	Phaseolus bean (tropical lowland cultivars)	90 days	Grain
146	Phaseolus bean (tropical lowland cultivars)	105 days	Grain
147	Phaseolus bean (tropical lowland cultivars)	120 days	Grain
148	Phaseolus bean (tropical lowland cultivars)	135 days	Grain
149	Phaseolus bean (tropical lowland cultivars)	150 days	Grain
150	Phaseolus bean (tropical highland cultivars)	120 days	Grain
151	Phaseolus bean (tropical highland cultivars)	135 days	Grain
152	Phaseolus bean (tropical highland cultivars)	150 days	Grain
153	Phaseolus bean (tropical highland cultivars)	165 days	Grain
154	Phaseolus bean (tropical highland cultivars)	180 days	Grain
155	Phaseolus bean (temperate and subtropical cultivars)	90 days	Grain
156	Phaseolus bean (temperate and subtropical cultivars)	105 days	Grain

Code	Crop type	Growth cycle	Harvested part
157	Phaseolus bean (temperate and subtropical cultivars)	120 days	Grain
158	Phaseolus bean (temperate and subtropical cultivars)	135 days	Grain
159	Phaseolus bean (temperate and subtropical cultivars)	150 days	Grain
160	Chickpea	90 days	Grain
161	Chickpea	105 days	Grain
162	Chickpea	120 days	Grain
163	Chickpea (cold tolerant)	150 days	Grain
164	Chickpea (cold tolerant)	165 days	Grain
165	Chickpea (cold tolerant)	180 days	Grain
166	Cowpea	80 days	Grain
167	Cowpea	100 days	Grain
168	Cowpea	120 days	Grain
169	Dry pea	90 days	Grain
170	Dry pea	105 days	Grain
171	Dry pea	120 days	Grain
172	Green gram	60 days	Grain
173	Green gram	80 days	Grain
174	Green gram	100 days	Grain
175	Pigeon pea	135 days	Grain
176	Pigeon pea	150 days	Grain
177	Pigeon pea	165 days	Grain
178	Pigeon pea	180 days	Grain
179	Pigeon pea	195 days	Grain
180	Soybean (tropical and subtropical cultivars)	105 days	Grain
181	Soybean (tropical and subtropical cultivars)	120 days	Grain
182	Soybean (tropical and subtropical cultivars)	135 days	Grain
183	Soybean (temperate and subtropical cultivars)	105 days	Grain
184	Soybean (temperate and subtropical cultivars)	120 days	Grain
185	Soybean (temperate and subtropical cultivars)	135 days	Grain
186	Sunflower (tropical and subtropical cultivars)	135 days	Seed
187	Sunflower (tropical and subtropical cultivars)	150 days	Seed
188	Sunflower (temperate and subtropical cultivars)	105 days	Seed
189	Sunflower (temperate and subtropical cultivars)	120 days	Seed
190	Sunflower (temperate and subtropical cultivars)	135 days	Seed
191	Sunflower (temperate and subtropical cultivars)	150 days	Seed
192	Winter rape	35+105 days	Seed
193	Winter rape	40+120 days	Seed
194	Winter rape	45+135 days	Seed
195	Winter rape	45+150 days	Seed
196	Spring rape	105 days	Seed
197	Spring rape	120 days	Seed
198	Spring rape	135 days	Seed
199	Spring rape	150 days	Seed
200	Rabi rape	135 days	Seed
201	Rabi rape	150 days	Seed
202	Groundnut	90 days	Kernel
203	Groundnut	105 days	Kernel
204	Groundnut	120 days	Kernel
205	Oil palm	perennial	Oil
206	Olive	perennial	Oil
207	Jatropha	perennial	Oil
208	Cabbage	90 days	Head
209	Cabbage	105 days	Head
210	Cabbage	120 days	Head
211	Cabbage	135 days	Head
212	Cabbage	150 days	Head
213	Cabbage	165 days	Head

Code	Crop type	Growth cycle	Harvested part
214	Carrot (fresh-early) (temperate and subtropical cultivars)	60 days	Root
215	Carrot (fresh-early) (temperate and subtropical cultivars)	75 days	Root
216	Carrot (fresh-early) (temperate and subtropical cultivars)	90 days	Root
217	Carrot (storage-late) (temperate and subtropical cultivars)	135 days	Root
218	Carrot (storage-late) (temperate and subtropical cultivars)	165 days	Root
219	Carrot (storage-late) (temperate and subtropical cultivars)	195 days	Root
220	Carrot (fresh) (tropical cultivars)	75 days	Root
221	Carrot (fresh) (tropical cultivars)	90 days	Root
222	Carrot (fresh) (tropical cultivars)	105 days	Root
223	Onion (temperate and subtropical cultivars)	120 days	Bulb
224	Onion (temperate and subtropical cultivars)	135 days	Bulb
225	Onion (temperate and subtropical cultivars)	150 days	Bulb
226	Onion (temperate and subtropical cultivars)	165 days	Bulb
227	Onion (temperate and subtropical cultivars)	180 days	Bulb
228	Onion (hybernating) (temperate and subtropical cultivars)	45+105 days	Bulb
229	Onion (hybernating) (temperate and subtropical cultivars)	60+120 days	Bulb
230	Onion hybernating) (temperate and subtropical cultivars)	75+135 days	Bulb
231	Onion (tropical cultivars)	90 days	Bulb
232	Onion (tropical cultivars)	105 days	Bulb
233	Onion) (tropical cultivars)	120 days	Bulb
234	Onion (tropical cultivars)	135 days	Bulb
235	Tomato (temperate and subtropical cultivars)	90 days	Fruit
236	Tomato (temperate and subtropical cultivars)	105 days	Fruit
237	Tomato (temperate and subtropical cultivars)	120 days	Fruit
238	Tomato (temperate and subtropical cultivars)	135 days	Fruit
239	Tomato (tropical and subtropical cultivars)	105 days	Fruit
240	Tomato (tropical and subtropical cultivars)	120 days	Fruit
241	Tomato (tropical and subtropical cultivars)	135 days	Fruit
242	Banana/Plantain	perennial	Fruit
243	Citrus	perennial	Fruit
244	Coconut 1 (tall)	perennial)	Copra
245	Coconut 2 (hybrid tall)	perennial	Copra
246	Coconut 3 (dwarf)	perennial	Copra
247	Cacao (comun)	perennial	Beans
248	Cacao (hybrid)	perennial	Beans
249	Cotton (tropical cultivars)	135 days	Fiber
250	Cotton (tropical cultivars)	150 days	Fiber
251	Cotton (tropical cultivars)	165 days	Fiber
252	Cotton (tropical cultivars)	180 days	Fiber
253	Cotton (temperate and subtropical cultivars)	135 days	Fiber
254	Cotton (temperate and subtropical cultivars)	150 days	Fiber
255	Cotton (temperate and subtropical cultivars)	165 days	Fiber
256	Flax	90 days	Fiber
257	Flax	105 days	Fiber
258	Flax	120 days	Fiber
259	Coffee arabica	perennial	Green beans
260	Coffee robusta	perennial	Green beans
261	Tea china tea (*camelia sinenses*)	perennial	Leaves
262	Tea hybrid (*sinensis and assamica*)	perennial	Leaves
263	Tea assam tea (*camelia sinenses var. assamica*)	perennial	Leaves
264	Tobacco (tropical cultivars)	105 days	Leaves
265	Tobacco (tropical cultivars)	120 days	Leaves
266	Tobacco (tropical cultivars)	135 days	Leaves
267	Tobacco (temperate and subtropical cultivars)	150 days	Leaves
268	Tobacco (temperate and subtropical cultivars)	165 day)	Leaves
269	Alfalfa (temperate and subtropical cultivars)	perennial	AGB
270	Alfalfa (tropical cultivars)	perennial	AGB

Code	Crop type	Growth cycle	Harvested part
271	Pasture legumes (C3/I species)	perennial	AGB
272	Pasture legumes (C3/II species)	perennial	AGB
273	Pasture grasses (C3/I species)	perennial	AGB
274	Pasture grasses (C3/II species)	perennial	AGB
275	Pasture grasses (C4/II species)	perennial	AGB
276	Pasture grasses (C4/I species)	perennial	AGB
277	Miscanthus (C4/II type)	perennial	AGB
278	Miscanthus (C4/I type)	perennial	AGB
279	Switchgrass	perennial	AGB
280	Reed canary grass	perennial	AGB

ABG: Above ground biomass.

Table A-4-5 Crops/commodities

Code	Crop/commodity	Crops
1	Wheat	**Wheat**
2	Rice	**Rice**
3	Maize	**Maize**
4	Sorghum	**Sorghum**
5	Millet	**Millet**
6	Other cereals	**Barley, Rye, Oat and minor other cereals**
7	Tubers	**Potato, Sweet potato**
8	Roots	**Cassava, Yams, other Roots and Plantain**
9	Sugar beet	**Sugar beet**
10	Sugarcane	**Sugarcane**
11	Pulses	**Pulses**
12	Soybean	**Soybean**
13	Rape	**Rapeseed**
14	Sunflower	**Sunflower**
15	Groundnut	**Groundnuts in shells**
16	Oil palm	**Oil palm**
17	Olive	**Olive**
18	Cotton	**Cotton**
19	Cash crops 1	**Banana, Coconut**
20	Vegetables	**Vegetables**
21	Cash crops 2	**Coffee, Tea, Cocoa**
22	Fodder	**Fodder**
23	Residual	**Other crops not listed above: mainly fruit, nuts, spices, tobacco, fiber crops, other oil crops**
	Color code indicates crops/commodities available in yield and production gap assessments	

Appendix 4-2 Parameters for calculation of water-limited yields

Table A-4-6 Water-limited yield parameters

	Length of Crop Stage (% of growth cycle)				Crop water requirements relative to reference evapotranspiration				Yield loss factors				
NAME	**d1**	**d2**	**d3**	**d4**	**K1c**	**K3c**	**K5c**	**KTc**	**Ky1**	**Ky2**	**Ky3**	**Ky4**	**KyT**
Wheat (winter)	10.00	30.00	35.00	25.00	0.40	1.10	0.30	0.85	0.20	0.60	0.75	0.50	1.05
Wheat (spring)	10.00	20.00	45.00	25.00	0.40	1.10	0.30	0.85	0.20	0.65	0.80	0.55	1.15
Rice (wetland)	10.00	30.00	30.00	30.00	1.10	1.20	0.90	1.10	1.00	2.00	2.50	1.00	2.00
Rice (dryland)	10.00	30.00	30.00	30.00	0.50	1.20	0.60	0.90	0.40	0.90	1.50	0.50	1.25
Maize /grain)	15.00	30.00	35.00	20.00	0.40	1.10	0.60	0.85	0.40	0.90	1.50	0.50	1.25
Barley (winter)	10.00	30.00	35.00	25.00	0.40	1.10	0.25	0.85	0.20	0.60	0.75	0.50	1.05
Barley (spring)	10.00	20.00	45.00	25.00	0.40	1.10	0.25	0.85	0.20	0.65	0.80	0.55	1.15
Sorghum	10.00	25.00	40.00	25.00	0.40	1.05	0.55	0.80	0.20	0.60	0.90	0.50	0.90
Sweet sorghum	10.00	25.00	40.00	25.00	0.40	1.05	1.00	0.95	0.20	0.60	0.90	0.50	0.90
Winter rye	10.00	30.00	35.00	25.00	0.40	1.10	0.25	0.85	0.20	0.60	0.75	0.50	1.05
Spring rye	10.00	20.00	45.00	25.00	0.40	1.10	0.25	0.85	0.20	0.65	0.80	0.55	1.15
Pearl Millet	10.00	25.00	40.00	25.00	0.35	1.05	0.30	0.80	0.20	0.60	0.80	0.50	0.90
Foxtail Millet	10.00	25.00	40.00	25.00	0.40	1.10	0.55	0.85	0.20	0.60	0.80	0.50	1.00
Spring oat	10.00	20.00	45.00	25.00	0.40	1.10	0.25	0.85	0.20	0.65	0.80	0.55	1.15
Buckwheat	15.00	20.00	40.00	25.00	0.40	1.05	0.30	0.80	0.20	0.60	0.80	0.50	0.90
White Potato	20.00	25.00	35.00	20.00	0.50	1.10	0.75	0.85	0.50	0.80	0.80	0.70	1.10
Sweet Potato	20.00	25.00	35.00	20.00	0.50	1.10	0.65	0.85	0.50	0.80	0.80	0.70	1.10
Sugarbeet	15.00	30.00	35.00	20.00	0.50	1.10	0.70	0.85	1.00	1.00	1.00	0.50	1.10
Phaseolous Bean	20.00	33.00	33.00	14.00	0.40	1.10	0.90	0.85	0.20	0.60	1.10	0.75	1.15
Chickpea	20.00	33.00	33.00	14.00	0.40	1.00	0.60	0.85	0.20	0.60	1.10	0.75	1.15
Cowpea	20.00	33.00	33.00	14.00	0.40	1.05	0.60	0.85	0.20	0.60	1.10	0.75	1.15
Green gram	20.00	33.00	33.00	14.00	0.40	1.05	0.60	0.85	0.20	0.60	1.10	0.75	1.15
Pigeonpea	20.00	30.00	30.00	20.00	0.40	1.00	0.60	0.85	0.20	0.60	1.10	0.75	1.15

	Length of Crop Stage (% of growth cycle)				Crop water requirements relative to reference evapotranspiration				Yield loss factors				
NAME	**d1**	**d2**	**d3**	**d4**	**K1c**	**K3c**	**K5c**	**KTc**	**Ky1**	**Ky2**	**Ky3**	**Ky4**	**KyT**
Groundnut	20.00	30.00	30.00	20.00	0.50	1.05	0.60	0.80	0.20	0.80	0.80	0.60	0.70
Soybean	15.00	20.00	45.00	20.00	0.40	1.10	0.50	0.85	0.20	0.80	1.00	0.80	0.85
Sunflower	17.00	28.00	35.00	20.00	0.40	1.10	0.40	0.80	0.25	0.60	1.00	0.80	0.95
Rape	15.00	25.00	40.00	20.00	0.50	1.10	0.40	0.80	0.20	0.80	1.00	0.80	0.85
Cotton	15.00	30.00	30.00	25.00	0.40	1.15	0.70	0.85	0.20	0.50	0.75	0.50	0.85
Flax	15.00	25.00	35.00	25.00	0.40	1.10	0.30	0.80	0.20	0.60	0.80	0.50	0.95
White yam	20.00	25.00	35.00	20.00	0.50	1.05	0.65	0.85	0.50	0.80	0.80	0.70	1.10
Greater yam	20.00	30.00	30.00	20.00	0.50	1.10	0.65	0.85	0.50	0.85	0.85	0.70	1.10
Tombacco	10.00	25.00	30.00	35.00	0.35	1.10	0.80	0.90	0.20	1.00	0.80	0.50	0.90
Onion	15.00	25.00	30.00	30.00	0.60	1.05	0.80	0.80	0.45	0.45	0.80	0.30	1.10
Tomato	15.00	25.00	30.00	30.00	0.50	1.15	0.80	0.85	0.40	0.40	1.10	0.40	1.05
Cabbage	25.00	35.00	25.00	15.00	0.60	1.05	0.90	0.80	0.20	0.35	0.45	0.60	0.95
Carrot	20.00	25.00	40.00	15.00	0.70	1.05	0.95	0.90	0.40	0.40	0.80	0.30	1.10
Onion	15.00	25.00	30.00	30.00	0.60	1.05	0.80	0.80	0.45	0.45	0.80	0.30	1.10

Notes: 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, vegetative stage, reproductive stage, and maturation stage. Parameters $k1^c$, $k2^c$, and $k3^c$ define crop water requirements respectively for the initial stage, the reproductive phase, and the end of the maturation stage. Coefficient $k0^c$ 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.

Appendix 4-3 Temperature Profile Requirements

This document is available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Temperature_profile_requirements.pdf

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 fulfill 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°C and vernalization processes continue. The parameters used for *fvn* calculation in GAEZ are shown in Table A-4.

Table A-4-7 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_o 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 vernalization days required for full vernalization (VD_{100}).

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 (B_n) of a crop, an estimation of the gross biomass production (B_g) and respiration loss (R) is required:

$$B_n = B_g - R \quad (1)$$

The equation relating the rate of net biomass production (b_n) to the rate of gross biomass production (b_g) and the respiration rate (r) is:

$$b_n = b_g - r \quad (2)$$

The maximum rate of net biomass production (b_{nm}) 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 (b_{na}) over the entire growth cycle is half the maximum growth rate, i.e., b_{na} = 0.5 b_{nm}. The net biomass production for a crop of N days (B_n) is then:

$$B_n = 0.5\, b_{nm} \times N \quad (3)$$

The maximum rate of gross biomass production (b_{gm}) is related to the maximum net rate of CO_2 exchange of leaves (P_m) 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 P_m = 20 kg ha^{-1} hr^{-1} and a leaf area index of LAI = 5, the rate of gross biomass production b_{gm} is calculated from the equation:

$$b_{gm} = F \times b_o + (1 - F)\, b_c \quad (4)$$

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})
- 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)
- 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 ha^{-1} hr^{-1}, b_{gm} is given by the equation:

$$b_{gm} = F\,(0.8 + 0.01 P_m)\, b_o + (1 - F)\,(0.5 + 0.025\, P_m)\, b_c \quad (5)$$

When P_m is less than 20 kg ha^{-1} hr^{-1}, b_{gm} is calculated according to:

$$b_{gm} = F\,(0.5 + 0.025\, P_m)\, b_o + (1 - F)\,(0.05\, P_m)\, b_c \quad (6)$$

To calculate the maximum rate of net biomass production (b_{nm}), the maximum rate of gross biomass production (b_{gm}) and the rate of respiration (r_m) 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 (B_m) When the rate of gross biomass production is b_{gm}, the respiration rate r_m is:

$$r_m = k\, b_{gm} + c\, B_m \quad (7)$$

where k and c are the proportionality constants for growth respiration and maintenance respiration respectively, and B_m 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 ^{o}C, factor c_{30} for a legume crop equals 0.0283 and for a non-legume crop 0.0108. The temperature dependence of c_t for both crop groups is modelled with a quadratic function:

$$c_t = c_{30}\,(0.0044+0.0019\,T+0.0010\,T^2). \quad (8)$$

It is assumed that the cumulative net biomass B_m 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 B_m = 0.5 B_n, and using (3), B_m for a crop of N days is determined according to:

$$B_m = 0.25\, b_{nm}\, x\, N \quad (9)$$

By combining the respiration equation with the equation for the rate of gross photosynthesis, the maximum rate of net biomass production (b_{nm}) or the rate of net dry matter production at full cover for a crop of N days becomes:

$$b_{nm} = 0.72\, b_{gm} / (1 + 0.25\, c_t\, N) \quad (10)$$

Finally, the net biomass production (B_n) for a crop of N days, where 0.5 b_{nm} is the seasonal average rate of net biomass production, can be derived as:

$$B_n = (0.36\, b_{gm}\, x\, L) / (1/N + 0.25\, c_t) \quad (11)$$

where:

- 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
- 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:

$$Y_p = H_i\, x\, B_n \quad (12)$$

where:

- 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 P_m, (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

This document is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Biomass_yield_parameters.xls

Appendix 4-7 Output of Module II

Table A-4-8 Content of fixed output records from GAEZ Module II

Variable	Parameter	Record number	Type of variable	Length of variable (in bytes)
btext	Explanatory text string	1	Character	**16**
version	Program version string	2	Character	**24**
datestr	Date string when file was created	3	Character	**9**
Mrow	Number of rows of grid	4	Integer	**2**
Mcol	Number of columns of grid		Integer	**2**
CR1SEL	Index of first crop in output file		Integer	**2**
CR2SEL	Index of last crop in output file		Integer	**2**
irow0	Row number of upper left corner of sub-window (if used, 0 else)		Integer	**2**
icol0	Column number of upper left corner of sub-window		Integer	**2**
irow1	Row number of lower right corner of sub-window		Integer	**2**
icol1	Column number of lower right corner of sub-window		Integer	**2**
Admsel	Code of administrative unit selected for running (if used, else 0)		Integer	**2**
itech	Input level		Integer	**2**
iflmst	Control parameter IFLMST		Integer	**2**
iagclc	Control parameter IAGCLC		Integer	**2**
irtawc	Control parameter IRTAWC		Integer	**2**
daymin	Control parameter DAYMIN		Integer	**2**
lenmin	Control parameter LENMIN		Integer	**2**
itflg	Control parameter ITFLG		Integer	**2**
Rlps	Lapse rate applied (degree C per 1m)	5	Real	**4**
Ppm	Atmospheric CO2 concentration (ppm)		Real	**4**
dRl	Parameter for change in water use efficiency under elevated CO2		Real	**4**
Sa0	AWC level (mm/m)		Real	**4**
Sdep0	Maximum applicable soil depth (m)		Real	**4**
Rplim1	Water balance control parameter RPLIM1		Real	**4**
Rplim2	Water balance control parameter RPLIM2		Real	**4**
Samin	Water balance control parameter SAMIN		Real	**4**
Tastr	Temperature threshold TASTRT (usually 5 deg C)		Real	**4**
Kc1	Water balance control parameter Kc1		Real	**4**
Kc2	Water balance control parameter Kc2		Real	**4**
Kc3	Water balance control parameter Kc3		Real	**4**
KC4	Water balance control parameter Kc4		Real	**4**
KC5	Water balance control parameter Kc5		Real	**4**
Kc6	Water balance control parameter Kc6		Real	**4**
Kc7	Water balance control parameter Kc7		Real	**4**
dTx	Climate sensitivity run control parameter dT1		Real	**4**
dTn	Climate sensitivity run control parameter dT2		Real	**4**
dP	Climate sensitivity run control parameter dP1		Real	**4**
dS	Climate sensitivity run control parameter dS1		Real	**4**
dW	Climate sensitivity run control parameter dW1		Real	**4**
Idxok	Indicator of LUTs used in simulation (0=off, 1=on)	6	Integer	**2 * ncrp**
Midx	Reference harvest index (kg produce/kg biomass)	7	Real	**4 * ncrp**
flnmap1	Input file name of grid-cell land mask used	8	Character	**50**
flninp	Input file name of land pixel file	9	Character	**50**
flncl1	Input file name: average monthly temperature	10	Character	**50**
flncl2	Input file name: average monthly temperature range	11	Character	**50**
flncl3	Input file name: monthly precipitation	12	Character	**50**
flncl4	Input file name: monthly wind-run	13	Character	**50**

Variable	Parameter	Record number	Type of variable	Length of variable (in bytes)
flncl5	Input file name: average monthly sunshine fraction	14	Character	**50**
flncl6	Input file name: average monthly relative humidity	15	Character	**50**
flncl7	Input file name: monthly wet-day frequency	16	Character	**50**
flngem	Input file name: climate change from GCM	17	Character	**50**
EoH	**End of header string 'EOH'**	**18**	**Character**	**3**

*ncrp … number of crops = index last crop – index first crop + 1

Table A-4-9 Information contained in each pixel data record of Module II

Variable	Description	Length of variable (in bytes)	Type of variable
irow	Pixel reference: row number	2	**Integer**
icol	Pixel reference: column number	2	**Integer**
alt	Pixel reference: median elevation [m]	2	**Integer**
lgpt2	Length of LGPt=5	2	**Integer**
lgpt3	Length of LGPt=10	2	**Integer**
lgptot	Total number of growing period days	2	**Integer**
ndwtot	Number of days when estimated ETa of reference crop equals reference ETo	2	**Integer**
ndhtot	Number of days when precipitation exceeds reference to Eto	2	**Integer**
nlgp	Number of distinct component growing periods	2	**Integer**
begdrm	Beginning of dormancy period (day of year)	2	**Integer**
enddrm	End of dormancy period (day of year)	2	**Integer**
Ym0	Maximum radiation/temperature limited yield (kg per hectare)	4 * ncrp	**Real**
fc1	Crop-specific yield reduction factor obtained by thermal profile evaluation; index ranging 0 – 10000.	2 * ncrp	**Integer**
fc2	Crop-specific yield reduction factor due to water deficit (CROPWAT method); index ranging 0 – 10000.	2 * ncrp	**Integer**
fc3	Crop-specific yield reduction factor due to agro-climatic constraints; index ranging 0 – 10000.	2 * ncrp	**Integer**
cdef	Crop water deficit by LUT (= crop-specific ETa – ETa, mm)	2 * ncrp	**Integer**
ceta	Crop/LUT-specific ETa (mm)	2 * ncrp	**Integer**
ctsum	Crop/LUT-specific accumulated temperature during growth cycle (degree-days) [°Cd]	2 * ncrp	**Integer**
ccyl	Crop/LUT-specific growth cycle length [days]	2 * ncrp	**Integer**
ccbd	**Crop/LUT-specific beginning of growth cycle [day of year]**		

ncrp … number of crops = index last crop – index first crop + 1

Appendix 4-8 Sub routine descriptions of Module II

Module II processes the gridded databases of the AEZ study area to estimate LGP(s) and calculate maximum attainable yields. This includes:

1. crop cycle thermal suitability evaluation
2. pseudo-daily water balance calculation
3. biomass and yield calculation

Application of these rules yields an average suitability factor relative to the maximum temperature limited attainable yield of a particular crop/LUT.

Figure 4-1 is a diagram illustrating the linkages listed in Table 4-10. The subroutines and functions are listed in alphabetical order and with a short description of their use within Module II and which routines call them and which are called by them. Table 4-11 lists the fortran files belonging to Module II, and lists the header files associated with each fortran file and the subroutines and functions included in each file.

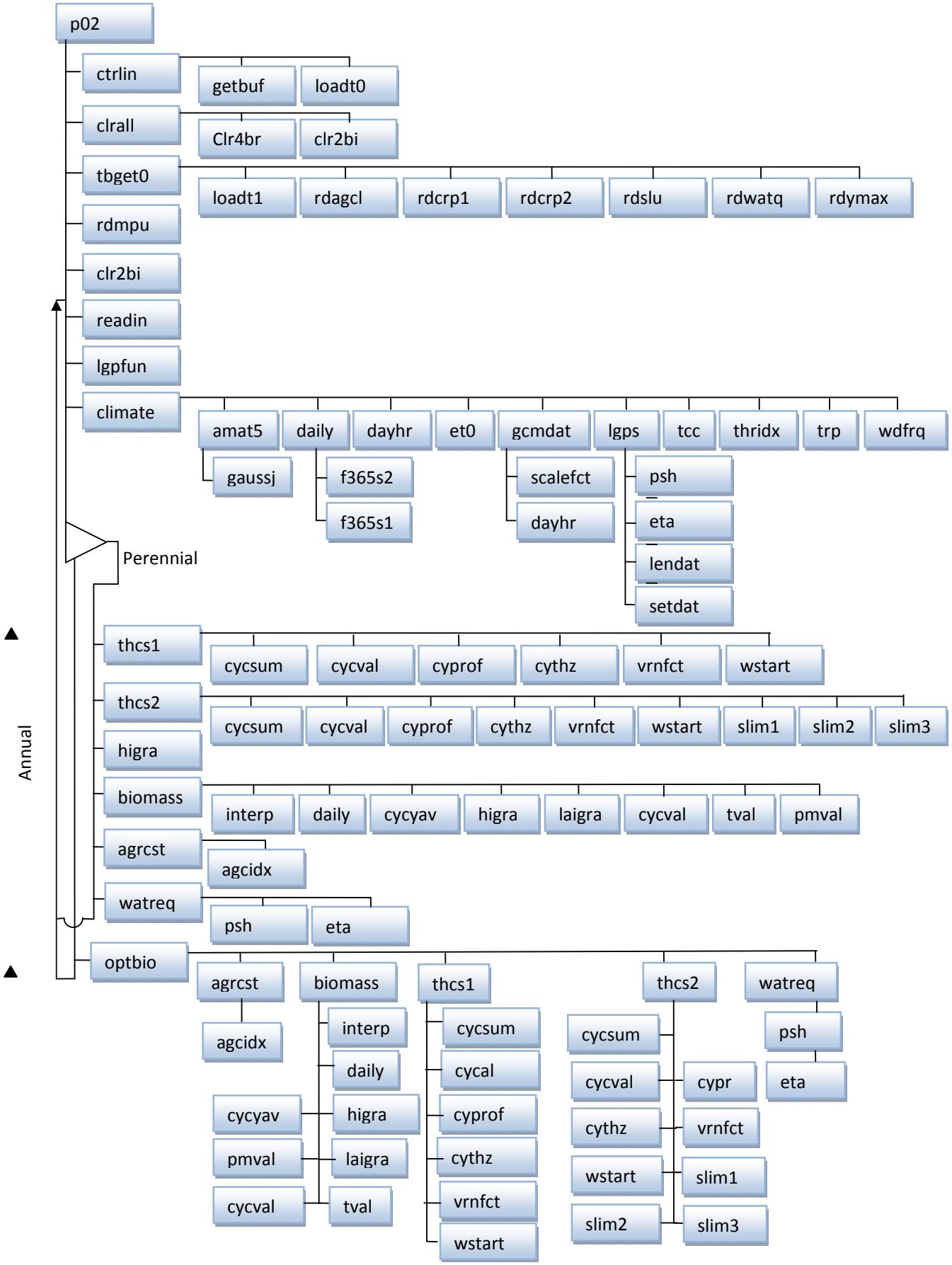

Figure 4-1 Diagram of the subroutines and functions of GAEZ Module II

Table A-4-10 Subroutines and functions of Module II

File Name	Subroutine	Description	Called from	Calls to
BIO.F	AGCIDX	determines lgp index and multiplier fraction depending on length of growing period	AGRCST	
BIO.F	AGRCST	evaluates agroclimatic constraints	P02 (MAIN), OPTBIO	AGCIDX
LGPSUB.F	AMAT5	generates coefficients of a system of linear equations for generating daily values by spline interpolation	CLIMATE	GAUSSJ
BIO.F	BIOMASS	calculates unconstrained crop biomass and yield based on methods set out in FAO's World Soil Resources Report No 48/1 of the Agro-Ecological Project, FAO 1978, but incorporating many enhancements to the original procedure.	P02, OPTBIO	CYCVAL, CYCYAV, DAILY, HIGRA, INTERP, LAIGRA, PMVAL, TVAL
CLIM_GCM.F	CLIMATE	reads climate data for the current position and determine LGPs	P02	AMAT5, DAILY, DAYHR, ET0, GCMDAT, LGPS, TCC, THRIDX, TRP, WDFRQ
CLR.F	CLR2BI	utility procedure which initializes n elements of a 2-byte integer array x to val	CLRALL, P02	
CLR.F	CLR4BI	utility procedure which initializes n elements of a 4-byte integer array x to val		
CLR.F	CLR4BR	utility procedure which initializes n elements of a 4-byte real array x to val	CLRALL, CLRPIX, CLRLNV	
CLR.F	CLR8BR	utility procedure which initializes n elements of a 8-byte real array x to val		
CLR.F	CLRALL	utility procedure which initializes variables and arrays used by P02	P02	CLR2BI, CLR4BR
CLR.F	CLRCH1	utility procedure which initializes n elements of a 1-byte character array x to val	CLRPIX, CLRLNV	
CLR.F	CLRLNV	clears variables, arrays before processing next land inventory entry		CLR4BR, CLRCH1
CLR.F	CLRPIX	clears variables, arrays before processing next raster point	P02	CLR2BI, CLR4BR, CLRCH1
P02.F	CTRLIN	reads control information and opens I/O files	P02	ERROR, GETBUF, LOADT0
THCS1.F	CYPROF	calculates daily temperature profile	THCS1, THCS2	
LGPSUB.F	DAILY	converts monthly or decadal data to daily values and calls the next two functions.	BIOMASS, CLIMATE	F365S1, F365S2
ERROR.F	ERROR	writes out error messages	LOADT0, LOADT1, CTRLIN, TBGET0	
LGPSUB.F	F365S1	fills in daily values by spline interpolation	DAILY	
LGPSUB.F	F365S2	fills in daily values by spline interpolation when the value must be greater or equal to 0	DAILY	
LGPSUB.F	GAUSSJ	performs gauss-jordan elimination with full pivoting	AMAT5	
CLIM_GCM.F	GCMDAT	reads GCM climate change data for current pixel	CLIMATE	DAYHR, SCALEFCT
BIO.F	INTERP	produces weighted average of two series	BIOMASS	
LGP.F	LGPS	determines the length of growing period	CLIMATE	ETA, LENDAT, PSH, SETDAT
LOADTB.F	LOADT0	reads district or province codes	CTRLIN	ERROR

FILE NAME	Subroutine	Function	CALLED FROM	CALLS TO
LOADTB.F	LOADT1	reads additional crop specific information	TBGET0	ERROR
P02.F	OPTBIO	determines optimal crop calendar for given LUT to maximize attainable agro-climatic yield	P02	AGRCST, BIOMASS, THCS1, THCS2, WATREQ
TBGET0.F	RDCRP1	reads crop parameters from PAR.CN file	TBGET0	
TBGET0.F	RDCRP2	reads crop parameters from PAR.BI files	TBGET0	
TBGET0.F	RDMPU	reads the optimal soil mapping unit available water content data from an input file (par.mpu)	P02	
TBGET0.F	RDSLU	reads soil unit codes from par.slu	TBGET0	
TBGET0.F	RDWATQ	reads crop water requirement coefficients from par.wq	TBGET0	
TBGET0.F	RDYMAX	reads maximum yields per input level from par.ym	TBGET0	
READIN.F	READIN	reads in the land information for current pixel	P02	
CLIM_GCM.F	SCALEFCT	algorithm used to calculate a scaling fraction for scaling monthly climatic data variables to match the annual changes from GCM	GCMDAT	
LGP.F	SETDAT	shifts a calculated day of the year by a multiple of 365 to fit within the range 0-365	LGPS	
TBGET0.F	TBGET0	sets up various 'in core' tables which are independent of individual land inventory entries	P02	ERROR, LOADT1, RDAGCL, TDCRP1, RDCRP2, RDSLU, RDWATQ, RDYMAX
CLIM_GCM.F	TCC	calculates thermal climate class and thermal zone class	CLIMATE	
CLIM_GCM.F	TRP	calculates temperature growing periods and thermal regime parameters	CLIMATE	THRIDX
BIO.F	TVAL	utility routine to look up a value in a table	BIOMASS, PMVAL	
WATREQ.F	WATREQ	estimates the impact of water stress on rain-fed attainable crop yields	P02, OPTBIO	ETA, PSH
CLIM_GCM.F	WDFRQ	distributes rain according to wet day frequency	CLIMATE	
	Functions			
LGPSUB.F	CYCSUM	integrates an attribute over growth cycle	THCS1, THCS2	
LGPSUB.F	CYCVAL	averages an attribute over growth cycle	BIOMASS, THCS1, THCS2	
BIO.F	CYCYAV	averages attributes over the year for grass and permanent crops	BIOMASS	
THCS1.F	CYTHZ	calculates cycle component in thermal range	THCS1, THCS2	
DAYHR.F	DAYHR	calculates day length for a given latitude and day of the year	CLIMATE, GCMDAT	
ET0.F	ET0	calculates potential evapotranspiration by the Penman-Monteith method	CLIMATE	
ETAM.F	ETA	calculates actual evapotranspiration by simulating a daily water balance for a FAO reference crop (similar to grass)	LPGS, WATREQ	
BIO.F	HIGRA	calculates the harvest index for grass (i.e. the consumable fraction)	BIOMASS, P02	
P02.F	ISRFED	deprecated function: checks if land can be used for rainfed production		

FILE NAME	Subroutine	Function	CALLED FROM	CALLS TO
BIO.F	LAIGRA	calculates the leaf area index of a grass/legume mixture	BIOMASS	
LGP.F	LENDAT	calculates the number of days between two dates including the start and end date.	LGPS	
BIO.F	PMVAL	calculates photosynthesis rate as a function of temperature and C02 concentration	BIOMASS	TVAL
ETAM.F	PSH	calculates the soil water depletion fraction (p) for a given crop type and level of daily ETo	LGPS, WATREQ	
THCS2.F	SLIM	interpolates a multiplier for values between range and optimum conditions and applied in case of cycle constraints	THCS2	
THCS2.F	SLIM2	Interpolates a multiplier for values between range and optimum conditions, applied in case of temperature sum and LGPT constraints	THCS2	
THCS2.F	SLIM3	Interpolates a multiplier for values between range and optimum conditions, applied in case of wetland rice start-up	THCS2	
THCS1.F	THCS1	evaluates for a given LUT and crop calendar the criteria for optimum growing condition	P02, OPTBIO	CYCSUM, CYCVAL, CYPROF, CYTHZ, VRNFCT, WSTART
THCS2.F	THCS2	evaluates for a given for a given LUT and crop calendar the criteria for range condition	P02, OPTBIO	CYCSUM, CYCVAL, CYPROF, CYTHZ, SLIM, SLIM2, SLIM3, VRNFCT, WSTART
CLIM_GCM.F	THRIDX	determines temperature profile class index	CLIMATE, TRP	
THCS1.F	VRNFCT	calculates vernalization factor	THCS1, THCS2	
THCS2.F	WSTART	calculates accumulated water for rice start-up	THCS1, THCS2	

Table A-4-11 Header and fortran source files subroutines and functions for GAEZ Module II

Fortran file	Associated Header Files	Subroutines	Functions
BIO.F	aezdef.h, bio.h, clim.h, control.h, iounit.h, tcc.h	AGCIDX, AGRCST, BIOMASS, INTERP, TVAL	PMVAL, HIGRA, LAIGRA, CYCYAV
BLKAEZ02.F	aezdef.h, aez02.h, clim.h, iounit.h, lnvrec.h, tabdef.h		
CLIM_GCM.F	aez02.h, aezdef.h, clim.h, control.h, iounit.h, tcc.h	CLIMATE, LGPFUN, GCMDAT, SCALEFCT, TCC, TRP, WDFRQ	THRIDX
CLR.F	aezdef.h, aez02.h, bio.h, clim.h, control.h, iounit.h, lnvrec.h, tabdef.h	CLRALL, CLRPIX, CLRLNV, CLR8BR, CLR4BR, CLR4BI, CLR2BI, CLRCH1	
DAYHR.F			DAYHR
ERROR.F		ERROR	
ET0.F			ET0
ETAM.F			ETA, PSH
LGP.F		LGPS, SETDAT	LENDAT
LGPSUB.F		AMAT5, DAILY, F365S1, F365S2, GAUSSJ	CYCVAL, CYCSUM, TRCIDX
LOADTB.F	aezdef.h, aez02.h, clim.h, control.h, iounit.h	LOADT0, LOADT1	
P02.F	aezdef.h, aez02.h, bio.h, clim.h, control.h, filter.h, iounit.h, lnvrec.h, tabdef.h, tcc.h	CTRLIN, OPTBIO	ISRFED, GETBUF
READIN.F	aezdef.h, aez02.h, clim.h, control.h, iounit.h, lnvrec.h	READIN	
TBGET0.F	aezdef.h, aez02.h, bio.h, clim.h, control.h, iounit.h, lnvrec.h, tabdef.h, usle.h	RDAGC1, RDCRP1, RDCRP2, RDMPU, RDSLU, RDWATQ, RDYMAX, TBGET0	
THCS1.F	aezdef.h, bio.h, clim.h, control.h, tcc.h	CYPROF	THCS1, CYTHZ, VRNFCT
THCS2.F	aezdef.h, bio.h, clim.h, control.h, tcc.h		SLIM, SLIM2, SLIM3, THCS2, WSTART
WATREQ.F	aezdef.h, bio.h, clim.h	WATREQ	

Appendix 4-9 Example of Module II output at grid-cell level

Example of information generated at grid cell level is given for Ilonga, Tanzania is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Example_grid_cell_output_Module_II.docx

Appendix 5-1 Agroclimatic constraints for individual crop/LUTs and input levels for rain-fed conditions

This document is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Agroclimatic_constraints.xls

Appendix 5-2 Outputs Module III

The output format of Module III is identical to output produced in Module II and described above. Note, the main purpose of Module III is to compute and update the LUT-specific agro-climatic constraint factors stored in the result file.

Appendix 5-3 Subroutine descriptions of Module III

In Module III, yield losses caused by agro-climatic constraints are quantified for each LUT and location. The result is stored as reduction factor to be applied to this yield calculated in Module II. Five different yield constraints (i.e. yield-reducing factors) are taken into account:

a. Long-term limitation to crop performance due to year-to-year soil moisture balance variability
b. Pests, diseases and weeds damage on plant growth
c. Pests, diseases and weeds damage on quality of produce
d. Climatic factors affecting the efficiency of farming operations
e. Frost hazard and extreme temperature events

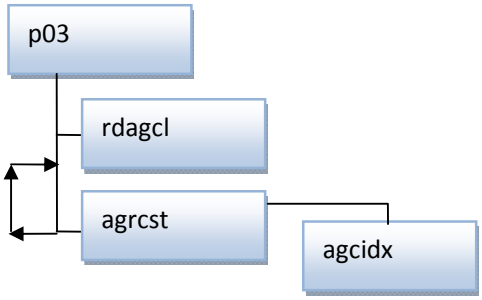

Figure A-5-1 Diagram of the subroutines and functions of GAEZ Module III

Table A-5-1 Subroutines and functions of Module III

Filename	Subroutine	Function	Called from	Calls to
P03.F	AGCIDX	determines lgp index and weight factor for linear interpolation of agro-climatic constraint values	AGCIDX	
P03.F	AGRCST	calculates reduction factor for yield losses caused by agro-climatic constraints	P03	AGCIDX
P03.F	RDAGCL	reads agro-climatic constraint parameters from data files	P03	

Fortran file	Associated Header Files	Subroutines	Functions
P03.F	AEZDEF.H, CLIM.H, TCC.H, BIO.H, CONTROL.H, IOUNIT.H	AGCIDX, AGRCST, RDAGCL	

Appendix 6-1 Soil drainage classes

Soil drainage classes are based on the "Guidelines to 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 and results have been distributed over GAEZ slope classes. The results of the soil drainage evaluation for the FAO 1974 and the FAO 1990 soil classification are available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/GAEZ_Soil_Drainage_Characteristics.xls

Appendix 6-2 Soil profile attribute suitability ratings

Related documents are available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/soil_evaluation.html

Appendix 6-3 Soil texture suitability ratings

Related documents are available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/soil_evaluation.html

Appendix 6-4 Soil drainage suitability ratings

Related documents are available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/soil_evaluation.html

Appendix 6-5 Soil phase suitability ratings

Related documents are available for download at:

http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/soil_evaluation.html

Appendix 6-6 Terrain slope suitability ratings

This document is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Terrain_slope_suitability_ratings.xls

Appendix 6-7 Fallow period requirements

This document is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Fallow_requirements.xls

Appendix 6-8 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 the basis of prevalence of specific soil types. Fluvisols[7] and to a lesser extent Gleysols[8] are typically representing the flat terrain of alluvial valleys and other water-collecting sites. 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, water-logging 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 to 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

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 for 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

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

[8] 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.

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 water-logging) 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 crops.

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, sugarbeet) are all sensitive to high groundwater levels and water-logging. Cotton and groundnut, cabbage, flax, 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. In particular the 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, yam and cocoyam 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

Sugarcane, miscanthus and switch grass (VII)

Sugarcane, miscanthus and switch grass are fairly tolerant to flooding and water-logging (e.g., see FAO, 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, coconut and tea (VIII)

Banana/plantain, oil palm, cocoa, coconut and tea prefer humid conditions. Banana is somewhat tolerant to water-logging, 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

Olives (IX)

Olives tolerate neither high groundwater tables nor water-logging and 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

Natural pastures and reed canary grass (X)

Natural pastures 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 water-logging, 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

Appendix 6-9 Outputs of Module IV

The main purpose of Module IV is to provide for each crop/LUT a comprehensive soil suitability evaluation for all the soil units contained in the Harmonized World Soil Database (HWSD). This is done by the use of individual soil quality ratings (SQ). Seven different SQs are calculated and are combined in a soil unit suitability rating (SR, %). The SR represents the percentage of potential yield expected for a given crop/LUT with respect to the soil characteristics present in a soil map unit of the HWSD and is depending on input/management level.

Module IV produces a separate output file with soil evaluation results for each crop/LUT. A subset of information contained in these files is later on used in Module V when agro-ecological potential yields are estimated, accounting for yield reductions due to constraining soil and terrain-slope conditions. The output file is as a large matrix (in plain ASCII), with rows organized by soil map unit and individual component soil type and columns representing relevant soil unit characteristics followed by the estimated values of different soil qualities and the computed soil suitability ratings for each input/management level and terrain-slope class (see Table 6-1).

Table A-6-1 Content of output file from GAEZ Module IV

Name	Description	Type of variable	Field width
MU_GLOBAL	HWSD global mapping unit identifier	Integer	8
COV	Coverage code indicating source of soil polygon and database	Integer	4
SEQ	Component sequence number within mapping unit	Integer	4
SOIL_SYM	FAO soil unit symbol	Character	9
SOIL_NUM	FAO soil unit numeric code	Integer	9
TOPTEX	Topsoil texture	Integer	7
PH1	Soil phase code 1	Integer	4
PH2	Soil phase code 2	Integer	4
ROO	Class code for 'obstacles to roots'	Integer	4
IL	Class code for 'impermeable layer'	Integer	3
SWR	Class code for 'soil water regime'	Integer	4
SHARE	Percentage of mapping unit	Integer	6
AWC	Available soil water storage capacity	Integer	5
AC	Available soil water storage capacity class	Integer	3
DEPTH	Reference soil depth	Integer	6
Q1	Soil quality rating for SQ1; all input level	Integer	5
Q2I	Soil quality rating for SQ2; low/intermediate input level	Integer	5
Q2H	Soil quality rating for SQ2; high input level	Integer	6
Q3	Soil quality rating for SQ3; all input level	Integer	6
Q4L1	Soil quality rating for SQ4; low input level; slope class 1	Integer	5
Q4L2	Soil quality rating for SQ4; low input level; slope class 2	Integer	5
Q4L3	Soil quality rating for SQ4; low input level; slope class 3	Integer	5
Q4L4	Soil quality rating for SQ4; low input level; slope class 4	Integer	5
Q4L5	Soil quality rating for SQ4; low input level; slope class 5	Integer	5
Q4L6	Soil quality rating for SQ4; low input level; slope class 6	Integer	5
Q4L7	Soil quality rating for SQ4; low input level; slope class 7	Integer	5
Q4L8	Soil quality rating for SQ4; low input level; slope class 8	Integer	5
Q4I1	Soil quality rating for SQ4; intermediate input level; slope class 1	Integer	5
Q4I2	Soil quality rating for SQ4; intermediate input level; slope class 2	Integer	5
Q4I3	Soil quality rating for SQ4; intermediate input level; slope class 3	Integer	5
Q4I4	Soil quality rating for SQ4; intermediate input level; slope class 4	Integer	5
Q4I5	Soil quality rating for SQ4; intermediate input level; slope class 5	Integer	5
Q4I6	Soil quality rating for SQ4; intermediate input level; slope class 6	Integer	5
Q4I7	Soil quality rating for SQ4; intermediate input level; slope class 7	Integer	5
Q4I8	Soil quality rating for SQ4; intermediate input level; slope class 8	Integer	5
Q4H1	Soil quality rating for SQ4; low input level; slope class 1	Integer	5
Q4H2	Soil quality rating for SQ4; low input level; slope class 2	Integer	5
Q4H3	Soil quality rating for SQ4; low input level; slope class 3	Integer	5
Q4H4	Soil quality rating for SQ4; low input level; slope class 4	Integer	5
Q4H5	Soil quality rating for SQ4; low input level; slope class 5	Integer	5
Q4H6	Soil quality rating for SQ4; low input level; slope class 6	Integer	5

Name	Description	Type of variable	Field width
Q4H7	Soil quality rating for SQ4; low input level; slope class 7	Integer	5
Q4H8	Soil quality rating for SQ4; low input level; slope class 8	Integer	5
Q5	Soil quality rating for SQ5; all input level	Integer	6
Q6	Soil quality rating for SQ6; all input level	Integer	6
Q7L	Soil quality rating for SQ7; low input level	Integer	6
Q7I	Soil quality rating for SQ7; intermediate input level	Integer	6
Q7H	Soil quality rating for SQ7; high input level	Integer	6
SiL1	Soil suitability rating; low input level; slope class 1 (0-0.5%)	Integer	5
SiL2	Soil suitability rating; low input level; slope class 2 (0.5-2%)	Integer	5
SiL3	Soil suitability rating; low input level; slope class 3 (2-5%)	Integer	5
SiL4	Soil suitability rating; low input level; slope class 4 (5-8%)	Integer	5
SiL5	Soil suitability rating; low input level; slope class 5 (8-16%)	Integer	5
SiL6	Soil suitability rating; low input level; slope class 6 (16-30%)	Integer	5
SiL7	Soil suitability rating; low input level; slope class 7 (30-45%)	Integer	5
SiL8	Soil suitability rating; low input level; slope class 8 (>45%)	Integer	5
SiI1	Soil suitability rating; intermediate input level; slope class 1 (0-0.5%)	Integer	5
SiI2	Soil suitability rating; intermediate input level; slope class 2 (0.5-2%)	Integer	5
SiI3	Soil suitability rating; intermediate input level; slope class 3 (2-5%)	Integer	5
SiI4	Soil suitability rating; intermediate input level; slope class 4 (5-8%)	Integer	5
SiI5	Soil suitability rating; intermediate input level; slope class 5 (8-16%)	Integer	5
SiI6	Soil suitability rating; intermediate input level; slope class 6 (16-30%)	Integer	5
SiI7	Soil suitability rating; intermediate input level; slope class 7 (30-45%)	Integer	5
SiI8	Soil suitability rating; intermediate input level; slope class 8 (>45%)	Integer	5
SiH1	Soil suitability rating; high input level; slope class 1 (0-0.5%)	Integer	5
SiH2	Soil suitability rating; high input level; slope class 2 (0.5-2%)	Integer	5
SiH3	Soil suitability rating; high input level; slope class 3 (2-5%)	Integer	5
SiH4	Soil suitability rating; high input level; slope class 4 (5-8%)	Integer	5
SiH5	Soil suitability rating; high input level; slope class 5 (8-16%)	Integer	5
SiH6	Soil suitability rating; high input level; slope class 6 (16-30%)	Integer	5
SiH7	Soil suitability rating; high input level; slope class 7 (30-45%)	Integer	5
SiH8	Soil suitability rating; high input level; slope class 8 (>45%)	Integer	5

Appendix 6-10 Subroutine descriptions of Module IV

In terms of computer implementation, the soil evaluation tool is different from the other Modules. It is written using Borland Delphi 7.2SE, so the interface object is the main procedure. Soil attributes of different soil map units are retrieved directly from the HWSD attribute database stored in MS Access format. Figure 6-1 shows the structure and relationships of the main procedures and functions of Module IV coded in Pascal.

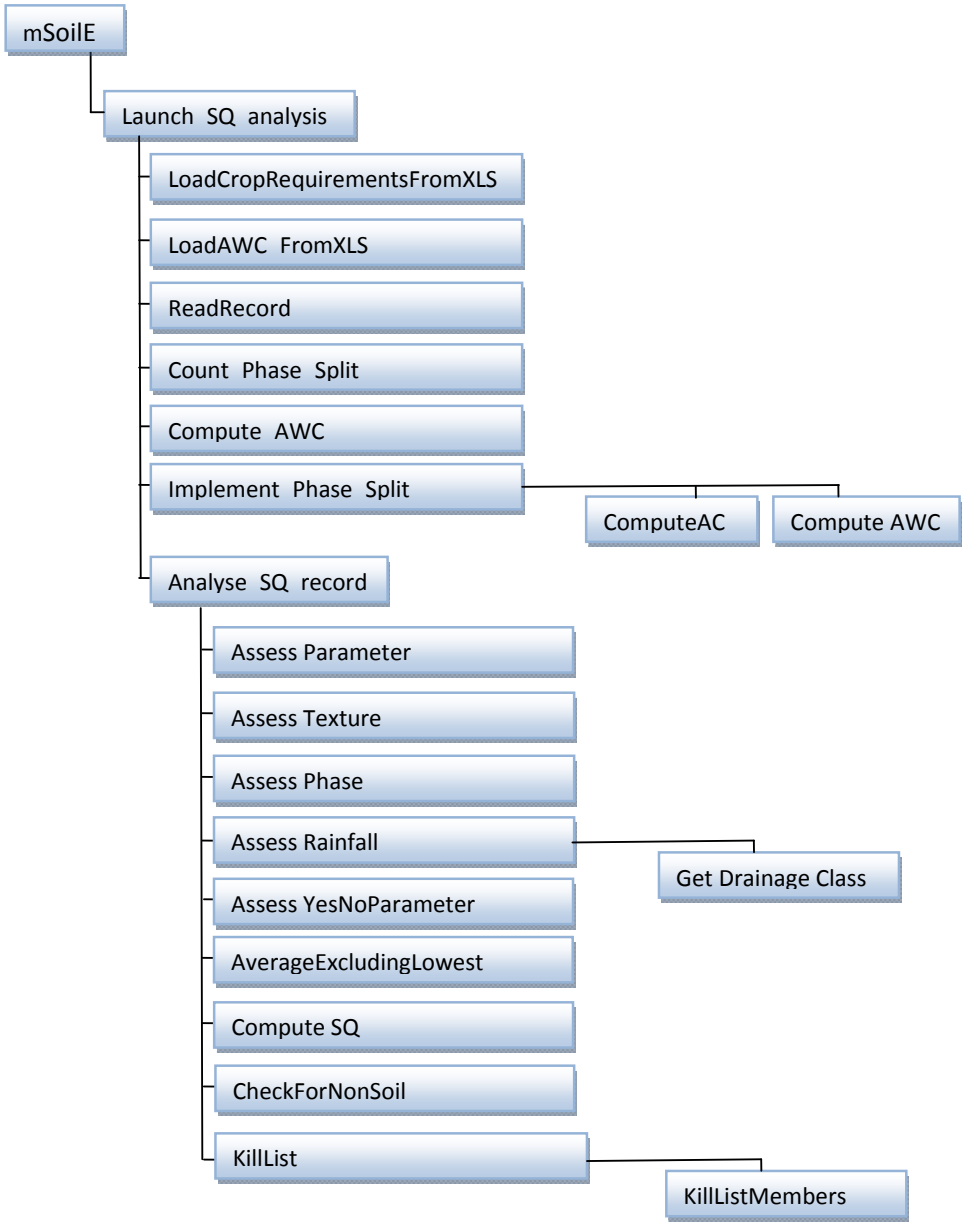

Figure A-6-1 Diagram of the subroutines and functions of GAEZ Module IV

Table A-6-2 Subroutines and functions of GAEZ Module IV

File Name	Procedure	Description	Called from	Calls to
EVALUATION.pas	Analyse_SQ_record	For given crop, soil record and terrain slope classes, computes soil qualities SQ1 to SQ7 and compiles respective soil suitability ratings	Launch_SQ_analysis	Assess_Parameter, Assess_Texture, Assess_Phase, Assess_Drainage, Assess_YesNoParameter, AverageExcludingLowest, Compute_SQ, CheckForNonSoil, minimum, frm, frmV, KillList
ROUTINES.pas	Assess_Drainage	For given crop and input level, rate drainage class as part of SQ4 assessment	Analyse_SQ_record	Get_Drainage_Class
ROUTINES.pas	CheckForNonSoil	Detects non-soil units	Analyse_SQ_record	
ROUTINES.pas	ComputeAC	Computes soil water class number	Implement_Phase_Split	
ROUTINES.pas	EvalAWC	Adjusts soil AWC according to soil phases	Implement_Phase_Split	
ROUTINES.pas	Implement_Phase_Split	Applies splitting rules to soil record due to the presence of certain soil phases	Launch_SQ_analysis	ComputeAC, EvalAWC
FUNCTIONS.pas	KillList	Releases memory not anymore needed for holding lists of soil evaluation data	Analyse_SQ_record	KillListMembers
FUNCTIONS.pas	KillListMembers	Releases memory for a specific list of data	KillList	
EVALUATION.pas	Launch_SQ_analysis	Main function used to carry out for all crops the evaluation of all soil units contained in the HWSD.	SoilEv	Analyse_SQ_record, ComputeAWC, Count_Phase_Split, LoadAWCFromXLS, LoadCropRequirementsFromXLS, Implement_Phase_Split, ReadRecord
READ_SOIL_REC.pas	ReadRecord	Retrieves a data record in MS Access format from the HWSD	Launch_SQ_analysis	
File Name	Function	Description	Called from	Calls to
ROUTINES.pas	Assess_Parameter	Evaluates rating function for given crop and soil attribute value	Analyse_SQ_record	
ROUTINES.pas	Assess_Phase	Applies soil phase adjustment to SQ rating	Analyse_SQ_record	
ROUTINES.pas	Assess_Texture	Applies soil texture rating	Analyse_SQ_record	
ROUTINES.pas	Assess_YesNoParameter	Tests for presence of special soil properties	Analyse_SQ_record	

File Name	Procedure	Description	Called from	Calls to
FUNCTIONS.pas	AverageExcludingLowest	Computes the average over its arguments excluding the lowest value.	Analyse_SQ_record	
ROUTINES.pas	ComputeAWC	Retrieves and assigns soil specific water holding capacity value	Launch_SQ_analysis	
ROUTINES.pas	Compute_SQ	Combines results of topsoil and subsoil evaluation into aggregate SQ rating	Analyse_SQ_record	
ROUTINES.pas	Count_Phase_Split	Checks if soil record must be split due to presence of soil phases	Launch_SQ_analysis	
FUNCTIONS.pas	frm	Formats output	Analyse_SQ_record	
FUNCTIONS.pas	frmV	Formats output	Analyse_SQ_record	
ROUTINES.pas	Get_Drainage_Class	Determines FAO drainage class for given soil, texture, soil phase and slope class	Assess_Drainage	
READ_PARAMS.pas	LoadAWCFromXLS	Retrieves certain soil data from spreadsheet in MS Excel format	Launch_SQ_analysis	
READ_PARAMS.pas	LoadCropRequirementsFromXLS	Retrieves various soil evaluation parameters from spreadsheet in MS Excel format	Launch_SQ_analysis	
FUNCTIONS.pas	minimum	Calculates minimum value of up to eight input parameters	Analyse_SQ_record	

Appendix 7-1 Outputs of Module V

Each run of Module V - typically executed for combinations of selected crops/crop groups, water source (rain-fed or irrigated), input level, and time period or future climate change scenario - generates a binary random access file holding computed results. These output files are organized by grid-cell. Pixels are numbered consecutively, starting from upper left corner of the global 5 arc-minute latitude/longitude raster and counting along pixels in rows down to the lower right corner. A record is stored for each land pixel, i.e. grid-cells not included in the GAEZ land mask are ignored. The information stored for each pixel includes a reference to the specific LUT selected, a distribution of the grid-cell area in terms of crop suitability classes, potential attainable production for each suitability class, agro-climatic potential production (i.e., excluding soil/terrain constraints) for extents in each suitability class, and calculated cultivation factors (= 1 – fallow requirement factor). Two sets of distribution parameters are stored: one for soils in a grid-cell subjected to rules for water-collecting sites, and one summing up results for all other soils in the grid-cell. Results are stored in random access data records as described in Table 7-1.

Table A-7-1 Information contained in each pixel data record of Module V

Variable	Description	Type of variable	Length of variable (in bytes)
af1	Crop indicator to identify LUT and input level defining results stored in grid-cell record for soils not subject to rules for water-collecting sites.	Integer	**2**
af2	Crop indicator to identify LUT and input level defining results stored in grid-cell record for soils which are subject to rules for water-collecting sites (Fluvisols and Gleysols on flat terrain under low or intermediate input level).	Integer	**2**
acut1	Shares of grid-cell by suitability class (VS, S, MS, mS, vmS, NS) calculated for soils not subject to rules for water-collecting sites. (Note: shares over suitability classes and all soils for total grid-cell add to 10000).	Real	**4*6**
acut2	Shares of grid-cell by suitability class (VS, S, MS, mS, vmS, NS) calculated for soils which are subject to rules for water-collecting sites. (Fluvisols and Gleysols on flat terrain under low and intermediate input level).	Real	**4*6**
aqu1	Attainable production by suitability class (VS, S, MS, mS, vmS, NS) calculated for soils not subject to rules for water-collecting sites.	Real	**4*6**
aqu2	Attainable production by suitability class (VS, S, MS, mS, vmS, NS) calculated for soils which are subject to rules for water-collecting sites (Fluvisols and Gleysols on flat terrain under low and intermediate input level).	Real	**4*6**
aqx1	Agro-climatic potential production (i.e. without considering soil and terrain constraints) by extent in different suitability classes (VS, S, MS, mS, vmS, NS) calculated for soils not subject to rules for water-collecting sites.	Real	**4*6**
aqx2	Agro-climatic potential production (i.e. without considering soil and terrain constraints) by extent in different suitability classes (VS, S, MS, mS, vmS, NS) calculated for soils which are subject to rules for water-collecting sites (Fluvisols and Gleysols on flat terrain under low and intermediate input level).	Real	**4*6**
acf1	Cultivation factor by different suitability classes (VS, S, MS, mS, vmS, NS) calculated for soils not subject to rules for water-collecting sites. The calculation of cultivation factors depends on crop, climate characteristics and input level.	Real	**4*6**
acf2	**Cultivation factor by different suitability classes (VS, S, MS, mS, vmS, NS) calculated for soils which are subject to rules for water-collecting sites.**	**Real**	**4*6**

Appendix 7-2 Subroutine descriptions of Module V

This main program of Module V has a simple structure and uses only a small number of subroutines and functions. Calculations are essentially organized in a four-fold nested loop over blocks of 30 arcsec rows and columns being aggregated to 5 arcmin results. Within each grid cell, calculations step through respective combinations of relevant soil types and slope classes. Results are stored in random access data records as described in Table 7-1. Relationships among routines are summarized in Table 7-1. Relationships among routines are summarized in Table 7-2 and Table 7-3. Figure 7-1 provides a simple diagram of the subroutines and functions in GAEZ Module V.

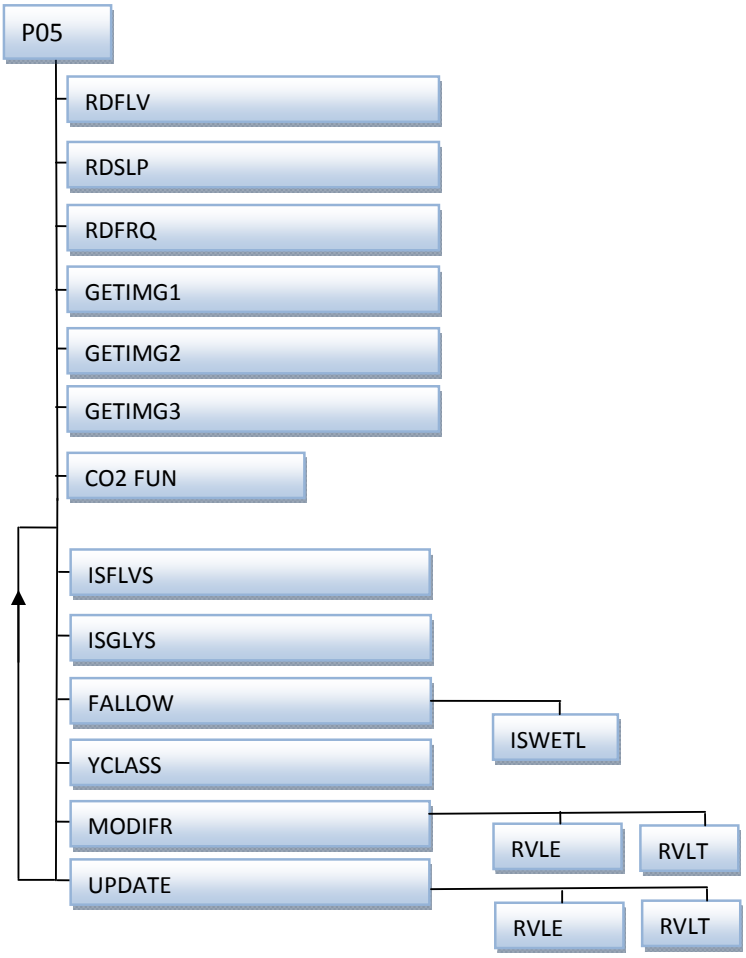

Figure A-7-1 Diagram of the subroutines and functions of GAEZ Module V

Table A-7-2 Subroutines and functions of Module V

Filename	Subroutines/ functions	Description	Called from	Calls to
P05.F	BESTCROP	Determine best component yield for a range suitability classes	UPDATE	
P05.F	CO2FUN	Calculate applicable CO2 fertilization yield increase factor	P05.F	
FALLOW.F	FALLOW	Calculate cultivation factor according to crop, input level, temperature and LGP	P05.F	
P05.F	GETIMG1	Read 1-byte thematic raster	P05.F	
P05.F	GETIMG2	Read 2-byte thematic raster	P05.F	
P05.F	GETIMG3	Read 4-byte thematic raster	P05.F	
P05.F	ISFLVS	Return 'true' for Fluvisoils, else 'false'	P05.F	
P05.F	ISGLYS	Return 'true' for Gleysols, else 'false'	P05.F	
FALLOW.F	ISWETL	Return 'true' for wetland rice, else 'false'	FALLOW	
RULE_G.F	MODIFR	Shifts extents and production among suitability classes according to suitability rule (e.g. rules for water collecting sites, slope rules, permafrost zones, etc.)	P05.F	RULE, RULT
P05.F	RDFLV	Read suitability rules for water collecting sites (PAR.FLV)	P05.F	
P05.F	RDFRQ	Read factors for low input condition (PAR.FRQ)	P05.F	
P05.F	RDSLP	Read slope rules (PAR.SLP)	P05.F	
RULE_G.F	RULE	Apply 2-way suitability rule	MODIFR	
RULE_G.F	RULE	Apply 3-way suitability rule	MODIFR	
P05.F	UPDATE	Update grid cell results of suitable land and potential production	P05.F	YIELD, BESTCROP
P05.F	YCLASS	Determine suitability class for given yield	P05.F	
P05.F	YIELD	Calculate yield from production and harvested area	UPDATE	

Table A-7-3 FORTRAN source files for Module V and included header files, subroutines and functions

Fortran file	Associated heading files	Subroutines	Functions
FALLOW.F	aezdef.h		FALLOW, ISWETL
P05.F	aezdef.h	BESTCROP, GETIMG1, GETIMG2, GETIMG4, RDFLV, RDFLQ, RDSLP, UPDATE	CO2FUN, ISFLVS, ISGLYS, YCLASS, YIELD
RULE_G.F		MODIFR, RULE, RULT	

Appendix 7-3 Crop summary table description

Crop summary tables provide standardized information on distributions of crop suitability and crop yield data. The data is based on aggregations of sub-grid cells distributions and it provides data by predefined land cover and protection classes. Crop summary tables provide detailed data by predefined land cover and protection classes of crop area yield and production potentials. The tables are further organized by crop (49), water supply type (5), input level (4) and time period i.e., historical (1961-2000 individual years), baseline (1961-1990) and future climates (2020s, 2050s and 2080s). The summary tables are available under the Suitability and Potential Yield theme in the GAEZ v3.0 data Portal. An example table for high input rain-fed maize with detailed column heading explanations is available for download at:
http://www.iiasa.ac.at/Research/LUC/GAEZv3.0/docs/Crop_summ_table_description.xlsx

Appendix 8-1 Estimation of shares of cultivated land by grid-cell

The estimation of shares of rain-fed cultivated land by 5 arcmin grid cell presents 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, as well as various environmental assessments requiring spatial detail. The procedure involves a sequence of steps, as follows:

- Collection of national (and possibly sub-national) statistics on cultivated land;
- Integration of available high-resolution global land cover data sets;
- Aggregation of geographical land cover data sets to obtain distributions of land cover classes for national and sub-national administrative units;
- Cross-sectional regressions of statistical cultivated land 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, and application to a spatially detailed population density dataset at 30 arc-sec. Aggregation of results to 5 arcmin 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 cultivated land as reported in the statistical data.

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 are adjusted. The ranges of permissible class weights for each land cover category were defined by (i) where possible, quantitative information contained in the GLC2000 legend class description, and (ii) expert judgment on the plausibility of the presence of cultivated land in a land cover class.

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 cultivated land.

Appendix 8-2 Estimation of area yield and production 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 plausible allocation of aggregate national land and production statistics to individual spatial 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 v3.0 proceeds iteratively. It starts with constructing or retrieving an initial prior allocation to individual crops based on the available geographical and statistical information. 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., 2006).

In the following we list the input data required at the level of spatial units (countries or sub-national administrative units), the geographical layers used at 5 arcmin spatial resolution, and the equations and accounting constraints imposed.

Input data used at administrative unit level:

Total cultivated land (annual and permanent crops)	(TC)	FAOSTAT
Total cultivated land equipped with 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	(δ_j)	AQUASTAT
Share of irrigated production in total crop *j* production	(δ_j)	FAO

GIS data (5 min):

Administrative boundaries and codes	(*adm*)	FAO
Grid-cell area extent	(*TA*)	IIASA
Grid-cell share of cultivated land	(c^T)	IIASA
Grid-cell share of cultivated land equipped with irrigation	(c^I)	AQUASTAT
Cultivation intensity class factor, rain-fed cultivation of annual crops	($\overline{m}^R$)	IIASA AEZ
Cultivation intensity class factor, irrigated cultivation of annual crops	($\overline{m}^I$)	IIASA AEZ
Farming system zone	(*z*)	FAO
Potential crop yield, rain-fed, high input level, by crops	($\overline{Y}_{ij}^{R,high}$)	GAEZ v3.0
Potential crop yield, rain-fed, low input level, by crops	($\overline{Y}_{ij}^{R,low}$)	GAEZ v3.0

Potential crop yield, irrigated, high input level, by crops	($\bar{Y}_{ij}^{I,high}$)	GAEZ v3.0
Distance to market	(*d*)	FAO/IIASA
Population density	(*pd*)	FAO
Ruminant livestock density	(*rum*)	FAO
Location crop priority factor for rain-fed crops	(φ_{jz}^{R})	FAO/IIASA
Location crop priority factor for irrigated crops	(φ_{jz}^{I})	FAO/IIASA
Crop distribution layers, selected crops[9]	(ε_j)	Monfreda et al.

Main equations and constraints:

Total irrigated production of allocation unit, by crops

$$TQ_j^I = \beta_j^I \, TQ_j \qquad j \in \text{crops}$$

Total rain-fed production of allocation unit, by crops

$$TQ_j^R = (1 - \beta_j^I) \, TQ_j \qquad j \in \text{crops}$$

Total irrigated harvested area of allocation unit, by crops

$$TH_j^I = \alpha_j^I \, TH_j \qquad j \in \text{crops}$$

Total rain-fed harvested area of allocation unit, by crops

$$TH_j^R = (1 - \alpha_j^I) \, TH_j \qquad j \in \text{crops}$$

Grid-cell cultivated land

$$TC_i = c_i^T \, TA_i \qquad i \in \text{grid cells}$$

Grid-cell irrigated cultivated land

$$TC_i^I = c_i^I \, TA_i \qquad i \in \text{grid cells}$$

Grid-cell share of rain-fed cultivated land

$$c_i^R = c_i^T - c_i^I \qquad i \in \text{grid cells}$$

Grid-cell rain-fed cultivated land

$$TC_i^R = c_i^R \, TA_i \qquad i \in \text{grid cells}$$

Grid-cell rain-fed cropping intensity applicable for annual crops[10]

$$m_i^R = \rho^R \, \overline{m}_i^R \qquad i \in \text{grid cells}$$

Grid-cell irrigated cropping intensity applicable for annual crops

$$m_i^I = \rho^I \, \overline{m}_i^I \qquad i \in \text{grid cells}$$

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

[9] In the current downscaling application for year 2000, information from the study by Monfreda et al. (2008) was used for selected crops in countries where more than 50% was covered by sub-national statistics.

[10] 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.

$$H_i^I = m_i^I \; TC_i^I \qquad i \in \text{grid cells}$$

Grid-cell rain-fed harvested area, by crops[11]

$$AH_{ij}^R = \begin{cases} m_i^R s_{ij}^R TC_i^R & j \in annual\ crops \\ m^P s_{ij}^R TC_i^R & j \in perennial\ crops \end{cases} \qquad i \in \text{grid cells}$$

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

$$Y_{ij}^I = \mu_j^I \overline{Y}_{ij}^{I,high} \qquad j \in \text{crops}, i \in \text{grid cells}$$

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

$$\varphi_{ij}^I = \overline{Y}_{ij}^{I,high} / \max_{k \in grid\ cells} (\overline{Y}_{kj}^{I,high}) \qquad j \in \text{crops}, i \in \text{grid cells}$$

[11] The cropping intensity of perennial crops in both rain-fed and irrigated cultivated land is kept constant at a value of 0.95.

Grid-cell crop share allocation:

Allocation of land to cropping 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 cultivated land allocation to crops in index set I_1

$$S_{1i}^{R} = \frac{\sum_{j \in I_1^R} m_i^R Y_{ij}^R P_j \lambda_j^R \varphi_{ij}^R}{\sum_{j \in I_1^R \cup I_2^R} m_i^R Y_{ij}^R P_j \lambda_j^R \varphi_{ij}^R} \qquad \text{i} \in \text{grid cells}$$

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 cultivated land allocation to crops in index set I_1 is

$$S_{1i}^{I} = \frac{\sum_{j \in I_1^I} m_i^I Y_{ij}^I P_j \lambda_j^I \varphi_{ij}^I}{\sum_{j \in I_1^I \cup I_2^I} m_i^I Y_{ij}^I P_j \lambda_j^I \varphi_{ij}^I} \qquad \text{i} \in \text{grid cells}$$

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:

$$s_{ij}^{R} = \begin{cases} 0 & j \in I_1 \wedge j \notin I_1^R \\ S_{1i}^{R} \dfrac{\varepsilon_{ij}^{R} \lambda_j^{R}}{\sum_{k \in I_1^R} \varepsilon_{ik}^{R} \lambda_k^{R}} & j \in I_1 \wedge j \in I_1^R \\ & \\ 0 & j \in I_2 \wedge j \notin I_2^R \\ S_{2i}^{R} \dfrac{m_{ij}^{R} Y_{ij}^{R} P_j \lambda_j^{R} \varphi_{ij}^{R}}{\sum_{k \in I_2^R} m_{ik}^{R} Y_{ik}^{R} P_k \lambda_k^{R} \varphi_{ik}^{R}} & j \in I_2 \wedge j \in I_2^R \end{cases} \qquad i \in \text{grid cells}$$

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 multipliers λ_j^R and λ_j^I for area, ρ^R and ρ^I for cropping intensity, and μ_j^R and μ_j^I for yield and production such that all conditions and accounting constraints are met. As a result it produces a grid-cell specific allocation of crop harvested area and production for rain-fed and irrigated cultivated land (i.e. the physical land). In the process, respective cropping intensity factors m_i^R and m_i^I are estimated. The multipliers ρ^R and ρ^I provide a measure of actual cropping intensity compared to potential multi-cropping. The multipliers μ_j^R and μ_j^I represent the ratios of actual achieved to applicable potential crop yields, i.e. an indication of yield gaps for the estimated cropping pattern and historical observed production.

Appendix 9 Global terrain slope and aspect data documentation

The NASA Shuttle Radar Topographic Mission (SRTM) has provided digital elevation data (DEMs) for over 80% of the globe. The SRTM data is publicly available as 3 arc second (approximately 90 meters resolution at the equator) DEMs (CGIAR-CSI, 2006).

For latitudes over 60 degrees north elevation data from GTOPO30 (USGS, 2002) with a resolution of 30 arc-seconds (depending on latitude this is approximately a 1 by 1 km cell size) were used.

Data creation date and version

Creation date: December 2006 (Version 1.0)

Processing Steps

Under an agreement with the National Aeronautics and Space Administration (NASA) and the Department of Defense's National Geospatial Intelligence Agency (NGA), the U.S. Geological Survey (USGS) is now distributing elevation data from the Shuttle Radar Topography Mission (SRTM). The SRTM is a joint project between NASA and NGA to map the Earth's land surface in three dimensions at a level of detail unprecedented for such a large area. Flown aboard the NASA Space Shuttle Endeavour February 11-22, 2000, the SRTM successfully collected data from over 80 percent of the Earth's land surface, for most of the area between 60o N. and 56o S. latitude.

The data currently being distributed by NASA/USGS (finished product) contains "no-data" holes where water or heavy shadow prevented the quantification of elevation. These are generally small holes, which nevertheless render the data less useful, especially in fields of hydrological modelling. Dr. Andrew Jarvis of the CIAT Land Use project, in collaboration with Dr. Robert Hijmans and Dr. Andy Nelson, have further processed the original DEMs to fill in these no-data voids. This involved the production of vector contours, and the re-interpolation of these derived contours back into a raster DEM. These interpolated DEM values were then used to fill in the original no-data holes within the SRTM data.

The DEM files have been mosaiced into a seamless global coverage, and are available for download as 5° x 5° tiles, in geographic coordinate system - WGS84 datum. The available data cover a raster of 24 rows by 72 columns of 5° x 5° latitude/longitude tiles, from north 60 degree latitude to 56 degree south.

These processed SRTM data, with a resolution of 3 arc second (approximately 90m at the equator), i.e. 6000 rows by 6000 columns for each 5° x 5° tile, have been used for calculating: (i) terrain slope 1

gradients for each 3 arc-sec grid cell; (ii) aspect of terrain slopes for each 3 arc-sec grid cell; (iii) terrain slope class by 3 arc-sec grid cell; and (iv) aspect class of terrain slope by 3 arc-sec grid cell. Products (iii) and (iv) were then aggregated to provide distributions of slope gradient and slope aspect classes by 30 arc-sec grid cell and for a 5'x5' latitude/longitude grid used in global AEZ.

The computer algorithm used to calculate slope gradient and slope aspect operates on sub-grids of 3 by 3 grid cells, say grid cells A to I:

A B C
D E F
G H I

SRTM data are stored in 5°x5° tiles[12]. When E falls on a border row or column (i.e., rows or columns 1 or 6000 of a tile) the required values falling outside the current tile are filled in from the neighboring tiles.

[12] For the globe the computer program processes 36 million sub-grids, in total 32.4 billion sub-grids are considered.

To calculate terrain slope for grid cell E, the algorithm proceeds as follows:

1) If the altitude value at E is 'no data' then both slope gradient and slope aspect are set to 'no data'.

2) Replace any 'no data' values in A to D and F to I by the altitude value at E.

Let Px, Py and Pz denote respectively coordinates of grid point P in x direction (i.e. longitude in our case), y direction (i.e. latitude in our application), and z in vertical direction (i.e., altitude), then calculate partial derivatives (dz/dx) and (dz/dy) from:

(dz/dx) = - ((Az-Cz) + 2· (Dz-Fz) + (Gz-Iz)) / (8·size_x)

(dz/dy) = ((Az-Gz) + 2· (Bz-Hz) + (Cz-Iz)) / (8·size_y)

When working with a grid in latitude and longitude, then size_y is constant for all grid cells. However, size_x depends on latitude and is calculated separately for each row of a tile.

The slope gradient (in degrees) at E is:

slgE = arctan$\sqrt{(dz/dx)^2 + (dz/dy)^2}$

and in percent is given by

slpE = 100 $\sqrt{(dz/dx)^2 + (dz/dy)^2}$

The slope aspect, i.e. the orientation of the slope gradient, starting from north (0 degrees) and going clock-wise, is calculated using the variables from above, as follows:

aspE = arctan $\sqrt{(dz/dx) \quad + (dz/dy)}$

The above expression can be evaluated for (dz/dy) ≠ 0. Otherwise aspE = 45° (for (dz/dx) < 0) or aspE = 270° (for (dz/dx) > 0)

3) To produce distributions of slope gradients and aspects for grids at 30 arc-sec or 5 min latitude/longitude, slope gradients are groups into 9 classes:

C1: 0 % ≤ slope ≤ 0.5 %
C2: 0.5 % ≤ slope ≤ 2 %
C3: 2 % ≤ slope ≤ 5 %
C4: 5 % ≤ slope ≤ 10 %
C5: 10 % ≤ slope ≤ 15 %
C6: 15 % ≤ slope ≤ 30 %
C7: 30 % ≤ slope ≤ 45 %
C8: Slope > 45 %
C9: Slope gradient undefined (i.e., outside land mask)

Slope aspects are classified in 5 classes:

N: 0° < aspect ≤ 45° or 315° < aspect ≤ 360°
E: 45° < aspect ≤ 135°
S: 135° < aspect ≤ 225°
W: 225° < aspect ≤ 315°
U: Slope aspect undefined; this value is used for grids where slope gradient is undefined or slope gradient is less than 2 %.

Detailed data description

Data Format:

The data are provided as ASCII files in a grid format. They consist of header information containing a set of keywords, followed by cell values in row-major order. The file format is:

NCOLS xxx
NROWS xxx XLLCENTER xxx | xllcorner xxx>

YLLCENTER xxx | yllcorner xxx>

CELLSIZE xxx

NODATA_VALUE xxx

row 1

row 2

…

row n

where xxx is a number. Row 1 of the data is at the top of the grid, row 2 is just under row 1 and so on. The end of each row of data from the grid is terminated with a carriage return in the file. The grid is defined in the header information with the following keywords:

NCOLS: number of columns
NROWS: number of rows
XLLCENTER: x-coordinate of lower left centre
YLLCENTER: y-coordinate of lower left centre
CELLSIZE: grid cell size
NODATA_VALUE: The value assigned to nodata information

Geographical details

Spatial coverage:	Global
Grid cell size:	5 minutes and 30 arc seconds
Projection:	Geographic coordinate system (Longitude, latitude) Units: Decimal degrees , Datum: WGS84

Data content

The data comprise one elevation map describing median elevation in each grid cell, eight slope and four aspect maps describing percentage distributions of the respective slope or aspect classes. The sum of all classes for slopes and aspects respectively is 100 percentages.

Units:

Elevation data:	meters
Slope and aspect classes:	percentage * 1000

Land mask:

In addition a land mask has been provided. The land mask shows the number of 3 arc second grid cells in the SRTM data that fall into a 5 minutes or 30 arc second grid cell. Along coastlines 5 minutes or 30 arcsecond grid cells usually only contain a fraction of the higher resolution 3 arc second grid cells, which were used for the slope and aspect calculations. In the 5 minutes and 30 arc second grids the slopes and aspect distributions always sum up to 100 percent. Thus if the real percentage distribution of a particular 5 minutes or 30 arc second is required it can be calculated using the land mask.

Table A-11-1 Description of file names of the IIASA-LUC Global Terrain Slopes and Aspect Database

FILE NAMES		Description
grid cell size: 5x5 minutes	grid cell size: 30 arc seconds	
LAND MASK		
GloLand_5min	GloLand_30as	Number of 3 arc second grid cells that belong to the land mask and fall into respective 5 minutes or 30 arc second grid cells
ELEVATION		
GloElev_5min	GloElev_30as	Median elevation (meters)
SLOPES		**Slope class**
GloSlopesCl1_5min	GloSlopesCl1_30as	0 % ≤ slope ≤ 0.5 %
GloSlopesCl2_5min	GloSlopesCl2_30as	0.5 % ≤ slope ≤ 2 %
GloSlopesCl3_5min	GloSlopesCl3_30as	2 % ≤ slope ≤ 5 %
GloSlopesCl4_5min	GloSlopesCl4_30as	5 % ≤ slope ≤ 10 %
GloSlopesCl5_5min	GloSlopesCl5_30as	10 % ≤ slope ≤ 15 %
GloSlopesCl6_5min	GloSlopesCl6_30as	15 % ≤ slope ≤ 30 %
GloSlopesCl7_5min	GloSlopesCl7_30as	30 % ≤ slope ≤ 45 %
GloSlopesCl8_5min	GloSlopesCl8_30as	Slope > 45 %
ASPECT		**Aspect class**
GloAspectClN_5min	GloAspectClN_30as	North: 0°< aspect ≤45° or 315°< aspect ≤360°
GloAspectClE_5min	GloAspectClE_30as	East: 45° < aspect ≤ 135°
GloAspectClS_5min	GloAspectClS_30as	South: 135° < aspect ≤ 225°
GloAspectClW_5min	GloAspectClW_30as	West: 225° < aspect ≤ 315°
GloAspectClU_5min	GloAspectClU_30as	Undefined: Slope aspect undefined; this value is used for grids where slope gradient is undefined or slope gradient is less than 2%.

Global Agro-Ecological Zones (GAEZ v3.0)

– Model Documentation –

Food and Agriculture Organization of the United Nations

International Institute for Applied Systems Analysis