FINAL REPORT

National Agro-economic Zoning for Major Crops in Thailand (NAEZ) (Project TCP/THA/3403)

– NAEZ Model Implementation and Results –

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Acknowledgements and citation

Full acknowledgement and citation in any materials or publications derived in part or in whole from NAEZ v4 Thailand data is required and must be cited as follows:

IIASA/FAO, 2016. National Agro-economic Zoning for Major Crops in Thailand (NAEZ v4). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Acronyms and abbreviations

AEZ	Agro-ecological Zones
AR5	IPCC fifth Assessment Report
CGIAR	Consultative Group on International Agricultural Research
CMIP5	Coupled Model Intercomparison Project Phase 5
CROPWAT	Computerized irrigation scheduling programme
CRU	Climate Research Unit of East Anglia University
DEM	Digital elevation model
DSMW	Digital Soil Map of the World
ECMWF	European Centre for Medium-Range Weather Forecasts
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 moisture constraints
fc3	Yield constraint factor due to agro-climatic constraints
fc4	Yield constraint factor due to soil and terrain constraints
Fm	Fournier index
GAEZ v4	Global Agro-ecological Zones, Version 4
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory, United States of America
GPCC	Global Precipitation Climatology Centre
HadGEM3	Headley centre, UK Meteorological Office (global ecosystem model 3)
Hi	Harvest index
HWSD	Harmonized world soil database
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre-Simon Laplace, France
ISI-MIP	Intersectoral Impact Model Intercomparison Project
ISRIC	International soil Research and Information Centre - world soil information
LAI	Leaf areas index
LDD	Land Development Department, Thai Ministry of National Development
LGP	Length of growing period
LGPeq	Equivalent growing period
LGPt	Temperature growing period
LUT	Land utilization types
MIROC	Model for Interdisciplinary Research on Climate, Japan
NorESM	Norwegian Earth System Model
PET	Potential evapotranspiration
SQ1	Soil nutrient availability
SQ2	Soil nutrient retention capacity
SQ3	Rooting conditions
SQ4	Oxygen availability to roots
SQ5	Excess salts
SQ6	Toxicity
SQ7	Workability
SRTM	Shuttle radar topography mission
$Tsum_t$	Accumulated temperatures for period when temperatures exceed t ^{o}C

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 1976a, 1984a 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.

Geo-referenced 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 (crop cycle length, 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 AEZ procedures are applied for rain-fed conditions and for irrigated conditions under different irrigation systems (gravity, sprinkler, drip). 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 the assessment of crop/LUT specific suitability and productivity.

AEZ 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 estimated/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, by administrative units and by major river basins, by land protection status, or by 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. AEZ 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.

In addition, in GAEZ v4 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 of year 2010.

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 2010;

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

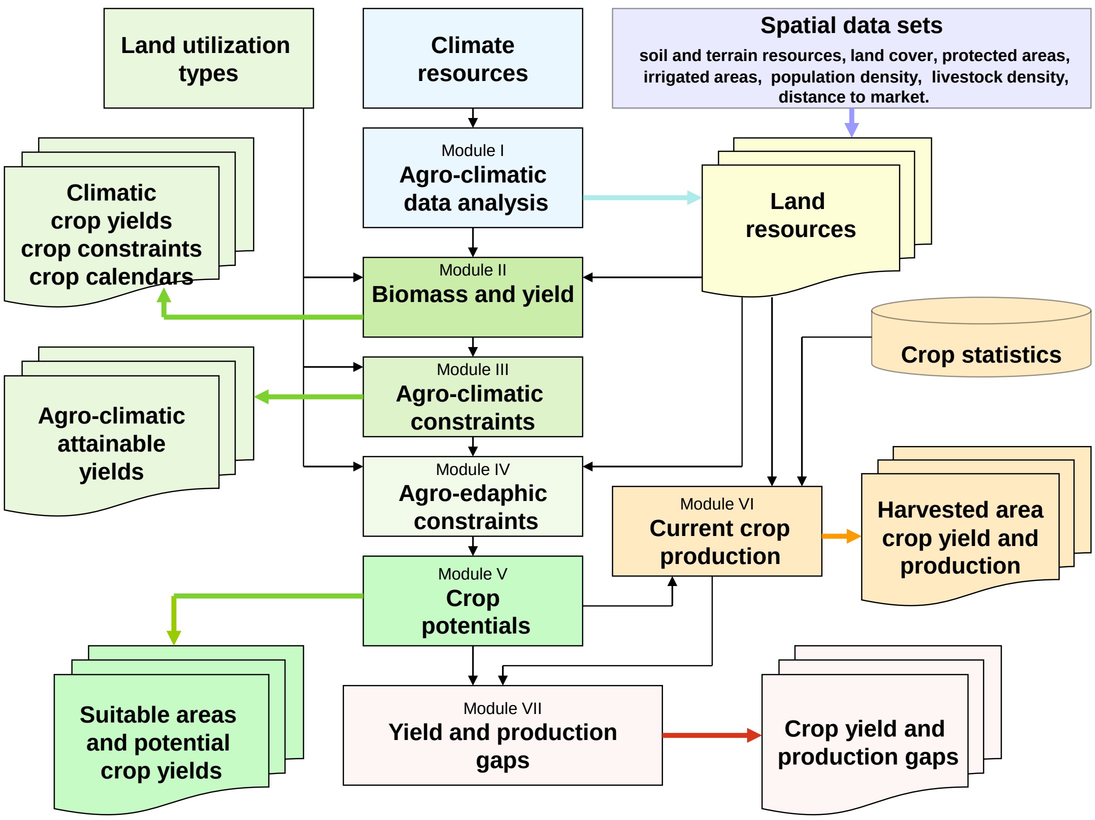


Figure 1-1 Overall structure and data integration of GAEZ v4 (Module I-VII)

The NAEZ system applied in this agro-economic zoning study for Thailand is based on the assessment logic of GAEZ v4 with adaptation to the specific needs and data availability of the project. Like in GAEZ v4, the modules 1-5 of NAEZ Thailand undertake a thorough agro-ecological assessment of major economic crops. Unlike in GAEZ, the actual use and production of crops was derived from district level crop statistics and a detailed spatial land use database of 2009-2012 prepared by the Land Development Department, Thai Ministry of Development. For this reason, there was no need to apply Modules VI and VII of the GAEZ v4 framework, which undertake 'downscaling' to attribute aggregate national crop statistics to physical land units. A new module, here termed Module 6, was added in the NAEZ Thailand system (Figure 1-2) to provide spatial quantification of production costs and attainable net revenue at prevailing prices and attainable agro-ecological yields (Module 6a).

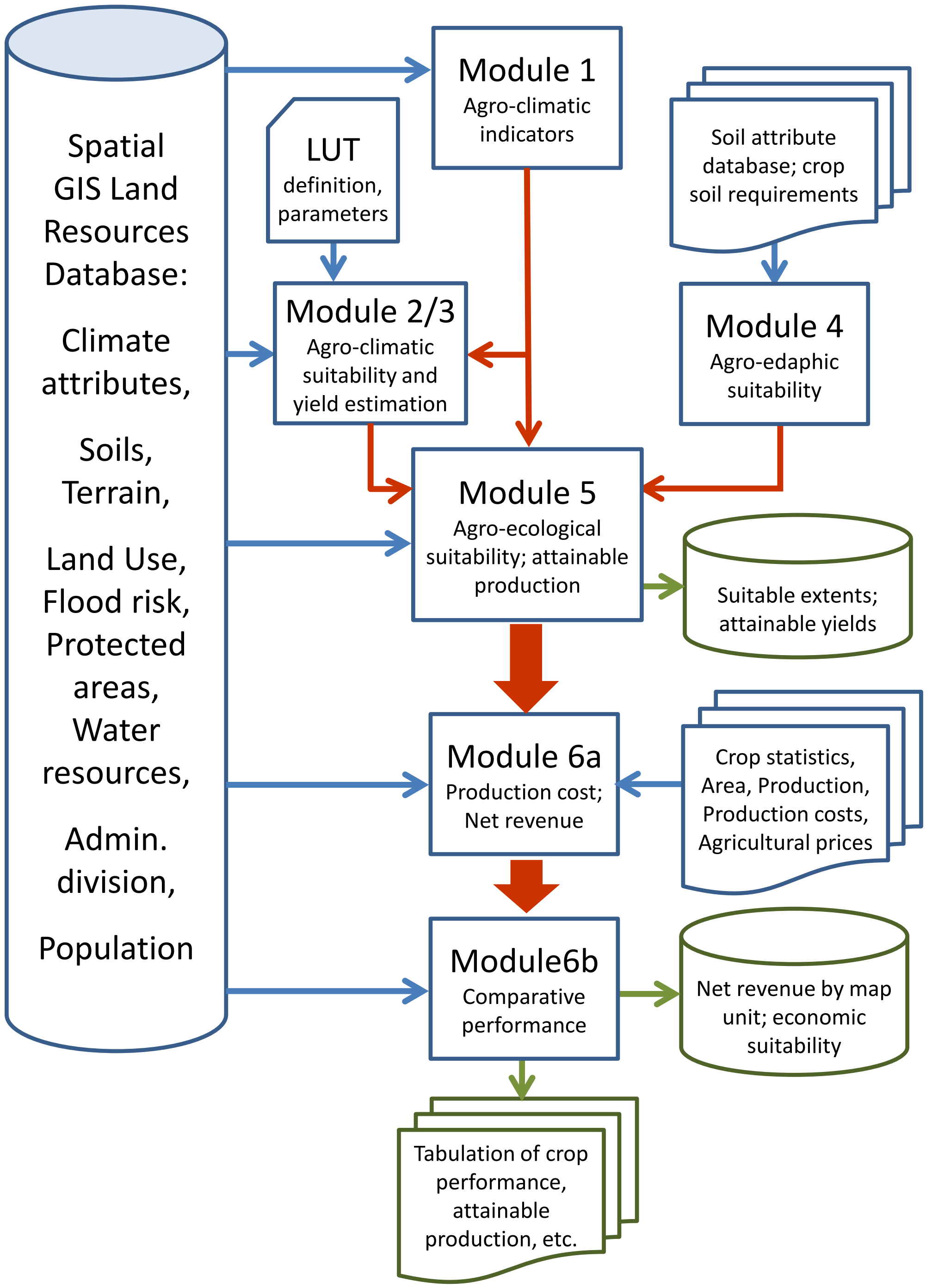


Figure 1-2 Overall structure and data integration of NAEZ Thailand (Module 1-6)

The results where then used to map the comparative advantage of eight major economic crops and to compare their economic performance with regard to current land use patterns (Module 6b). The quantification and mapping of the comparative advantage of each crop was then also repeated for attainable yields under projected future climate conditions. A summary of the information flow in NAEZ Thailand, main types of input data (in blue), information flow between NAEZ modules (in orange) and types of outputs (in green) are shown in Figure 1-2.

1.2.1 Module 1: Agro-climatic data analysis

Climate data analysis and compilation of general agro-climatic indicators

Module 1 of AEZ 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 and daily climate data are read and converted to variables required for subsequent calculations. The latter includes calculation of reference potential and actual evapotranspiration through daily soil water balances.

Thermal regime characterization generated in Module 1 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 2: Biomass and yield calculation

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

In Module 2, all land utilization types (LUT) are assessed for water-limited biomass and yields. Currently about 300 crop and pasture LUTs are processed for each of the assumed input levels. 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 advanced input level, high-yielding varieties are deployed with advanced field management and machinery providing optimum plant densities with high leaf area index.

Module 2 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 2 requires a considerable amount of computer time for its processing and is the most CPU-demanding component in AEZ. Results of Module 2 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 3: Agro-climatic constraints

Yield reduction due to agro-climatic constraints

Module 3 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 3 update for each grid cell the output file of Module 2 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 4: Agro-edaphic constraints

Yield reduction due to soil and terrain limitations

This module evaluates expected crop-specific yield reductions due to limitations imposed by soil and terrain conditions. Soil suitability is determined on the basis of a set of soil attribute data attached to the spatial soil database provided by the Land Development Department, Thai Ministry of Development. Several soil qualities - soil nutrient availability, soil nutrient retention capacity, soil rooting conditions, soil oxygen availability, soil toxicities, soil salinity and sodicity conditions and soil workability - are estimated on crop by crop basis and are combined in a crop-specific soil 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 LDD soil database. Thereby the rating procedures result in a quantification of suitability for all combinations of crop types, soil types and slope classes. Ratings also depend on level of management and input conditions.

1.2.5 Module 5: Integration of climatic and edaphic evaluation

Module 5 executes the final step in the AEZ crop suitability and land productivity assessment. It retrieves the LUT specific results of the agro-climatic evaluation for biomass and yield calculated in Module 2/3 for different soil classes and it uses the edaphic rating produced for each soil/slope combination in Module 4. 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 5 steps through the grid cells of the spatial soil association layer of the 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 information takes place at 3 arc-second grid cells. Ten thousand of these produce the edaphic characterization at 5 arc-minutes, the resolution used for providing agro-climatic 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 AEZ 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 AEZ by means of the Fournier index.

Application of the procedures in the modules 1-5 result for each grid-cell in an expected yield and suitability distribution regarding rain-fed and irrigation conditions for each 3-arcsec 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 6: Economic evaluation and comparative advantage of major crops

Module 6 builds on the results of the NAEZ Thailand crop suitability and land productivity assessment. First, LUT specific production cost functions representative for the year 2014 are used and evaluated with respect to the estimated agro-ecological attainable crop yields to estimate for each of the economic crops considered in the study the grid-cell specific production cost. Average farm gate prices of 2010-2014 were then applied to determine the respective attainable net revenues per unit area.

The various crop-specific results were then used to construct a spatial database showing a surface of best attainable net revenues by choosing in each grid cell the best performing crop of the eight economic crops considered – rice, maize, cassava, soybean, sugarcane, oil palm, para rubber and coffee. Each of the economic crops was then compared to this umbrella surface in order to indicate and map out its comparative advantage in terms of attainable net revenue relative to the best available option.

2 Description of AEZ input datasets

2.1 Climate data

2.1.1 Observed climate

For the global agro-ecological zones historical assessment time series data are used from the Climate Research Unit (CRU) at the University of East Anglia, the Global Precipitation Climatology Centre (GPCC), and the EU WATCH Integrated Project.

Climatic Research Unit (CRU) TS v3.21 (time-series) datasets were obtained from British Atmospheric Data Centre (BADC). These are month-by-month variations in climate over the last century covering the period January 1901 to December 2012. CRU TS v3.21 data are calculated on 0.5x0.5 degree grids, which are based on an archive of monthly average daily data provided by more than 4000 weather stations distributed around the world. CRU TS v3.21 variables used in GAEZ v4 are daily mean temperature, diurnal temperature range, cloud cover, vapor pressure and wind speed.

For monthly precipitation the GPCC Full Data Reanalysis Product Version 6 is used. It covers the period from 1901 to 2010. This new extended product version using the new GPCC climatology as analysis background was generated in December 2011. The data coverage per month varies from 10,700 to more than 47,000 stations.

New global sub-daily (3 hours) meteorological forcing data were provided in WATCH[1] for use with land surface- and hydrological-models. The data are derived from the ERA-40 and ERA-Interim reanalysis products via sequential interpolation to half-degree resolution, elevation correction and monthly-scale adjustments based on CRU (corrected-temperature, diurnal temperature range, cloud-cover) and GPCC (precipitation) monthly observations combined with new corrections for varying atmospheric aerosol-loading and separate precipitation gauge corrections for rainfall and snowfall. The ERA-40 and ERA-Interim products include all the key near-surface meteorological variables required. However, in order to remove model biases, the ERA data require adjustment (usually called “bias-correction”) based on monthly observational data using recent versions of respectively CRU-TS and GPCC v5/v6 time series data.

For the global agro-ecological zones assessment time series data are used from the Climate Research Unit (CRU) at the University of East Anglia, a 30 arc-minute latitude/longitude gridded monthly climate data time series for the period 1901-2012, version CRU TS 3.2. Six monthly and three daily climatic variables are required for AEZ climate analysis as shown in Table 2-1.

For precipitation, an alternative data product was obtained from Global Precipitation Climatology Centre (GPCC v6). Original monthly CRU and GPCC 30 arc-minute latitude/longitude climatic surfaces were interpolated at IIASA to a 5 arc-minute grid for all years between 1960 and 2010. Monthly climatic variables used include: precipitation; number of rainy days; mean minimum, mean maximum temperature; diurnal temperature range; cloudiness; wind speed; 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

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

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 Base period climatic input variables for the GAEZ assessment

Variable	Symbol	Units	Source[2]
Average Temperature	T_a	^oC	CRU TS 3.21
Diurnal Temperature range	T_{range}	^oC	CRU TS 3.21
Sunshine fraction	n/N	%	CRU TS 3.21
Wind speed at 10 m height	U_{10}	m/s	CRU TS 3.21
Relative humidity	RH	%	CRU TS 3.21
Precipitation	P	mm	GPCC v6
Daily deviation of Tmax from monthly mean	dT_x	^oC	WATCH
Daily deviation of Tmin from monthly mean	dT_n	^oC	WATCH
Daily share of monthly precipitation	P_d	%	WATCH

[2]See text for details

As an example of the gridded climate data, Figure 2-1 shows the average annual precipitation for the reference period (1981-2010) and the ensemble mean of projected precipitation in 2041-2070 of five climate models (see below) for emission pathway RCP 6.0.

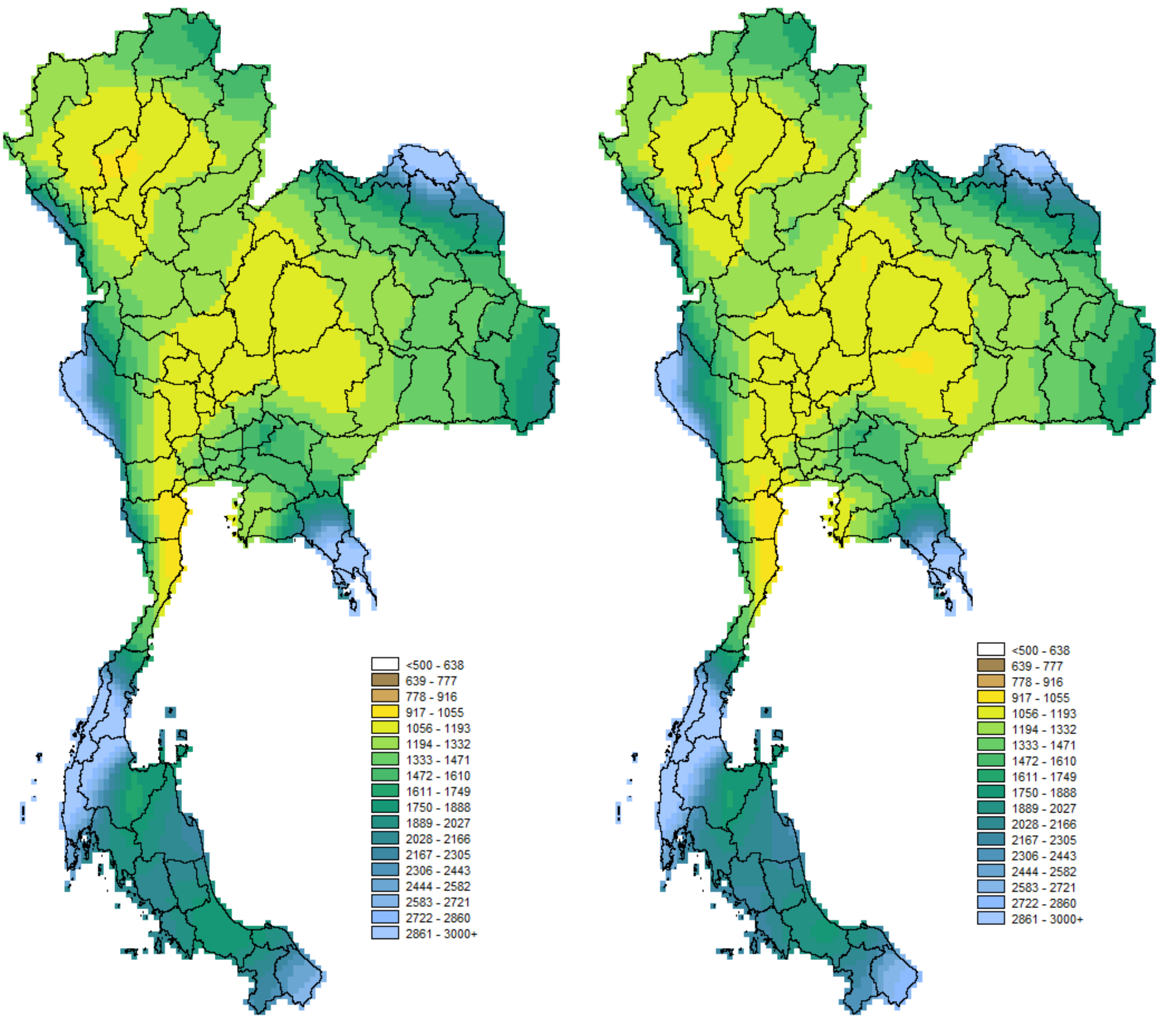


Figure 2-1. Average annual precipitation (mm) in 1981-2010 and 2041-2070 (ensemble mean)

Climate Scenarios

IPCC AR5 (IPCC, 2013) climate model outputs for four Representative Concentration Pathways (RCPs) are used to characterize a range of possible future climate distortions for agro-climatic resources inventories and crop potential assessments for the 2020's, the 2050's and the 2080's.

RCPs are a set of four greenhouse gas concentration (not emissions) trajectories developed for the climate modeling community as a basis for long-term and near-term modeling experiments adopted by the IPCC for its fifth Assessment Report (AR5). The four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 W/m^2 under stringent emission mitigation measures to 8.5 W/m^2 associated by-and-large with 'business as usual' development assumptions. The four RCPs – RCP2.6, RCP4.5, RCP6, and RCP8.5 – are named after a possible level of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m2, respectively). Development of RCPs has been completed and these pathways are documented in a special issue of Climatic Change (van Vuuren et al., 2011), and climate model simulations based on them were undertaken as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012).

Multi-model ensembles for each of the climate forcing levels of the RCPs were analyzed based on spatial data from the IPCC's AR5 CMIP5 process, data bias-corrected and downscaled to 0.5 degree as used in the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013). ISI-MIP data at 0.5 degree resolution of five climate models (GFDL-ESM2M, HadGEM3-ES, IPSL-CM5A-LR, MIROC-ESM, NorESM1-M) and for four RCPs (RCP 2.6, 4.5, 6.0 and 8.5) - totaling 20 combinations of respectively RCPs and climate models - were used for generating climate input data in GAEZ v4 for the 2020s, 2050s and the 2080s.

2.1.2 Use of climate data in AEZ

The average climate and year-by-year historical databases were applied 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 monthly average climate (1961-1990; 1971-2000; 1981-2010) and year-by-year climate attributes for the six 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 AEZ simulation programs.

In a similar way, binary (random access) attribute files were generated from daily precipitation and temperature data to hold (1) daily distributions of monthly rainfall, and (2) daily deviations from monthly means of respectively minimum and maximum temperatures derived from historical data and from GCM outputs. Together with the monthly means these are used to generate daily temperature and precipitation data for each 5 arc-min grid cell in the AEZ agro-climatic assessment.

2.2 Soil data

The NAEZ Thailand system uses a soil series group map prepared by the Land Development Department (LDD). A soil series group is the soil classification unit prepared by combining soils according to the soil series classification in Soil Taxonomy System that have similar physical and chemical characteristics and have similar utilization potential. 62 soil series groups were classified (consisting of 59 soil series groups and 3 other units). This classification system was first applied in about 1987. Subsequently, the Soil Survey and Classification Division had projects to improve 1:50,000 soil provincial maps and to undertake the map preparation and reporting of the provincial land utilization for the cultivated economic plants throughout the country (see http://www.ldd.go.th/ldd_en/en-US/classification-and-kinds-of-soil/).

The LDD map containing associations of 62 soil groups (Figure 2-) is composed of a geographical layer containing reference to some 1,320 unique soil map units, each combining 1 to 3 soil groups. This information is stored as a 3 arc-second raster in a GIS, which is linked to an attribute database containing representative soil profile data for a top-soil (assumed 0-30 cm) and a sub-soil layer (30-100cm or less). The 3 arcsec raster applied in the analysis has 17,900 rows and 10,000 columns, of which about 61 million grid-cells cover Thailand's territory.

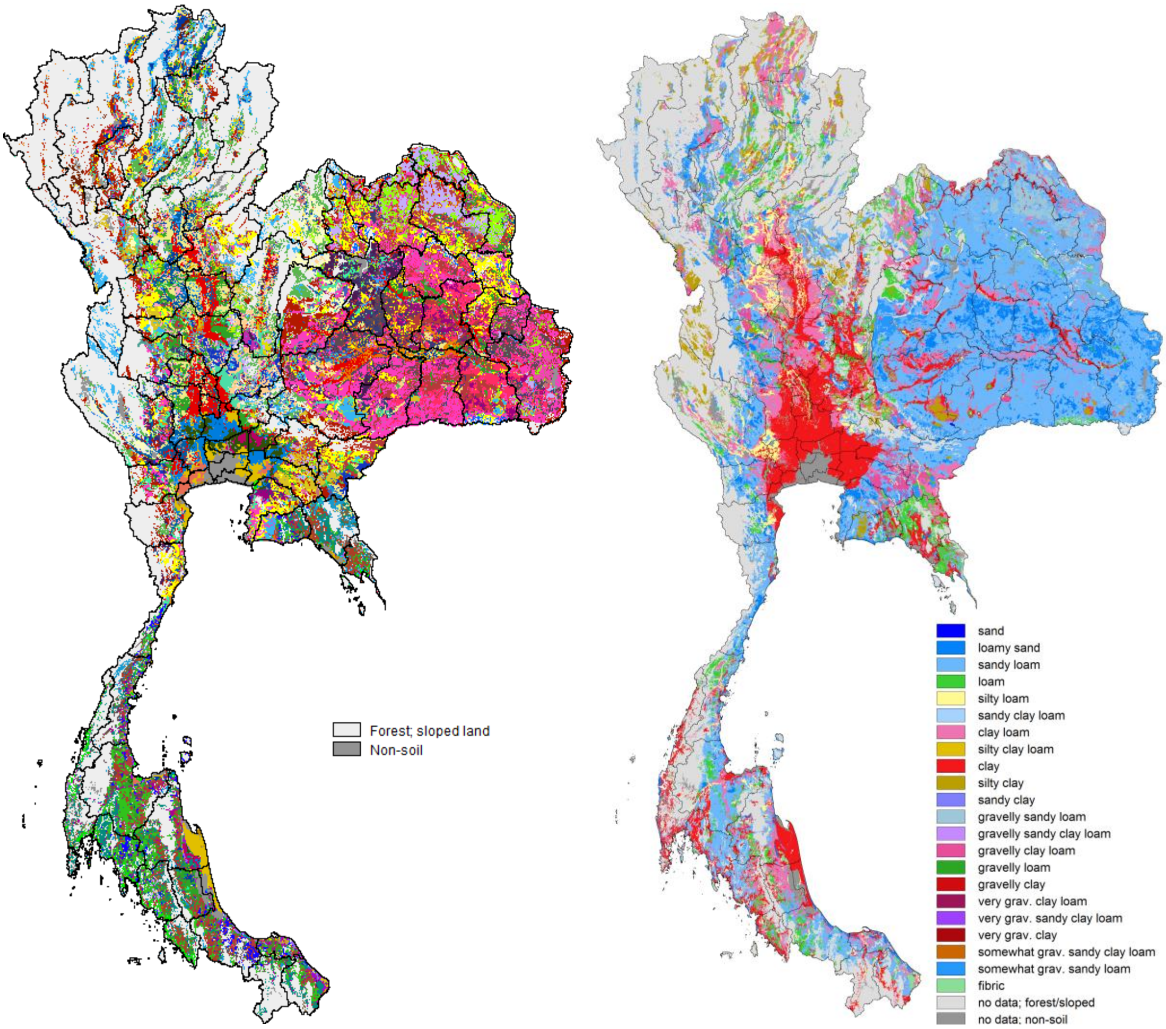


Figure 2-2. LDD map of soil series group associations (left) and soil texture class (right)

The raster of soil map units is linked to attribute data regarding the composition of soil mapping units and their characterization in terms of selected soil parameters (texture class, pH, drainage, effective soil depth, soil water holding capacity, soil depth, cation exchange capacity, base saturation, total exchangeable nutrients, salinity, fertility status, slope class, presence of jarosite).

2.3 Elevation data and derived terrain slope and aspect data

The altitude and terrain slope database (Figure 2-) has been compiled using elevation data from the Shuttle Radar Topography Mission (SRTM). The SRTM data is available as 3 arc-second DEMs (e.g., CGIAR-CSI, 2006).

The terrain slope database comprises the following elements:

- Elevation (m) of 3 arc-second grid-cells and median within each 5 arc-minute grid cell
- Terrain slopes (%) calculated at 3 arcsec and grouped into eight slope gradient classes of respectively 0–0.5%, 0.5–2%, 2–5%, 5–8%, 8–16%, 16–30%, 30–45%, and > 45%.

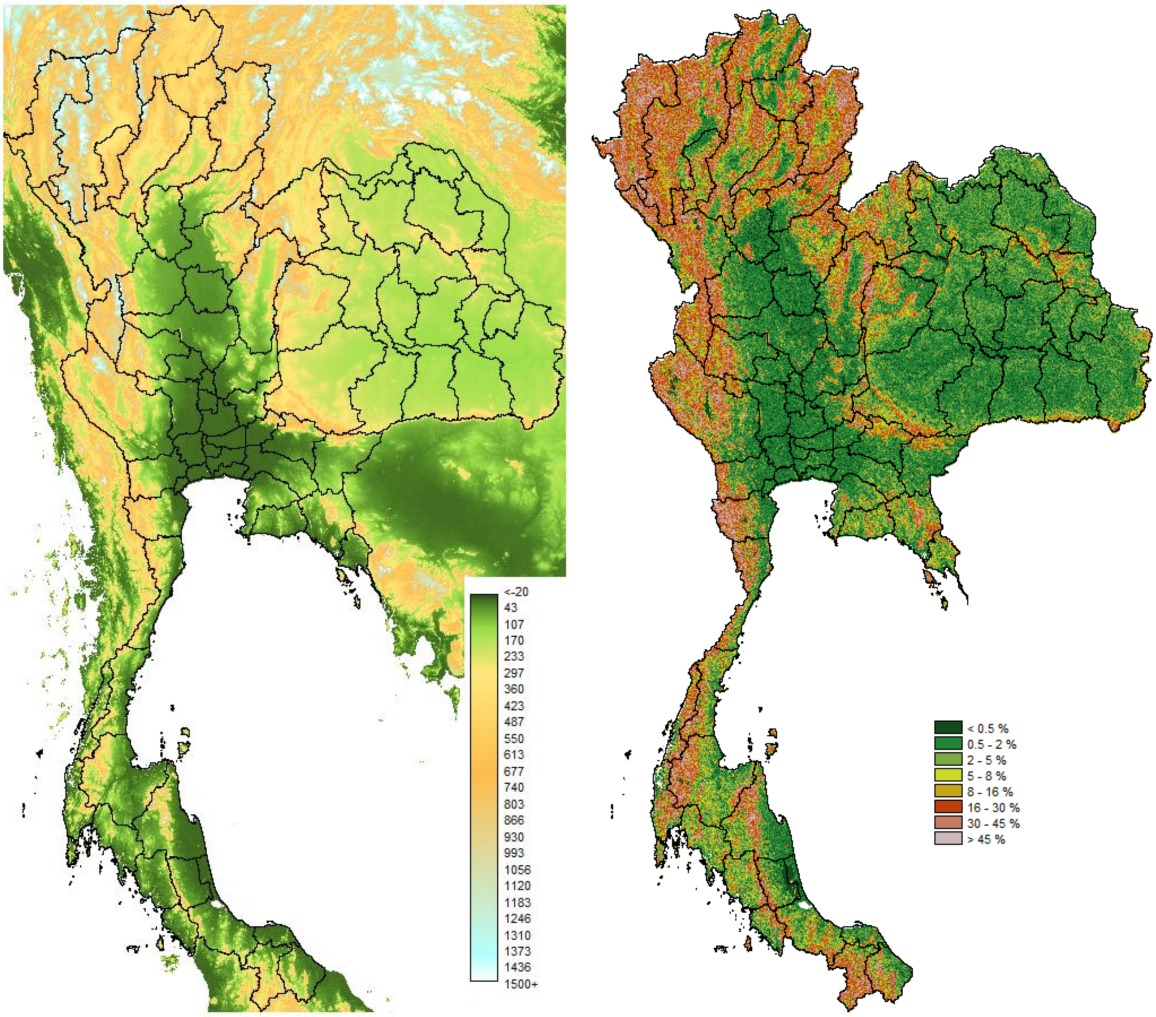


Figure 2-3. Terrain features: Elevation (m) and Terrain slopes (class)

2.4 Land use/cover data

Land use/cover data used in NAEZ Thailand were compiled by Land Development Department (LDD), Thai Ministry of Development. The map of land use types of Thailand is based on the interpretation of orthophotos, remote sensing images and field survey data and is meant to represent land use/cover of the period 2009-2012 (see http://www.ldd.go.th/ldd_en/en-US/land-use-types-of-thailand-in-2009-2012/).

A 3-level hierarchic classification system is used, which differentiates at the finest level more than 100 classes. It allows for a spatial representation of the major economic crops analyzed in this report. Figure 2-4 provides examples derived by aggregation/extraction from the land use types of Thailand. First, a general (10 classes) map of major land uses in 2009-2012 is shown on the left; and second, a map of the spatial distribution of para-rubber extracted from the LDD land use types map is shown on the right.

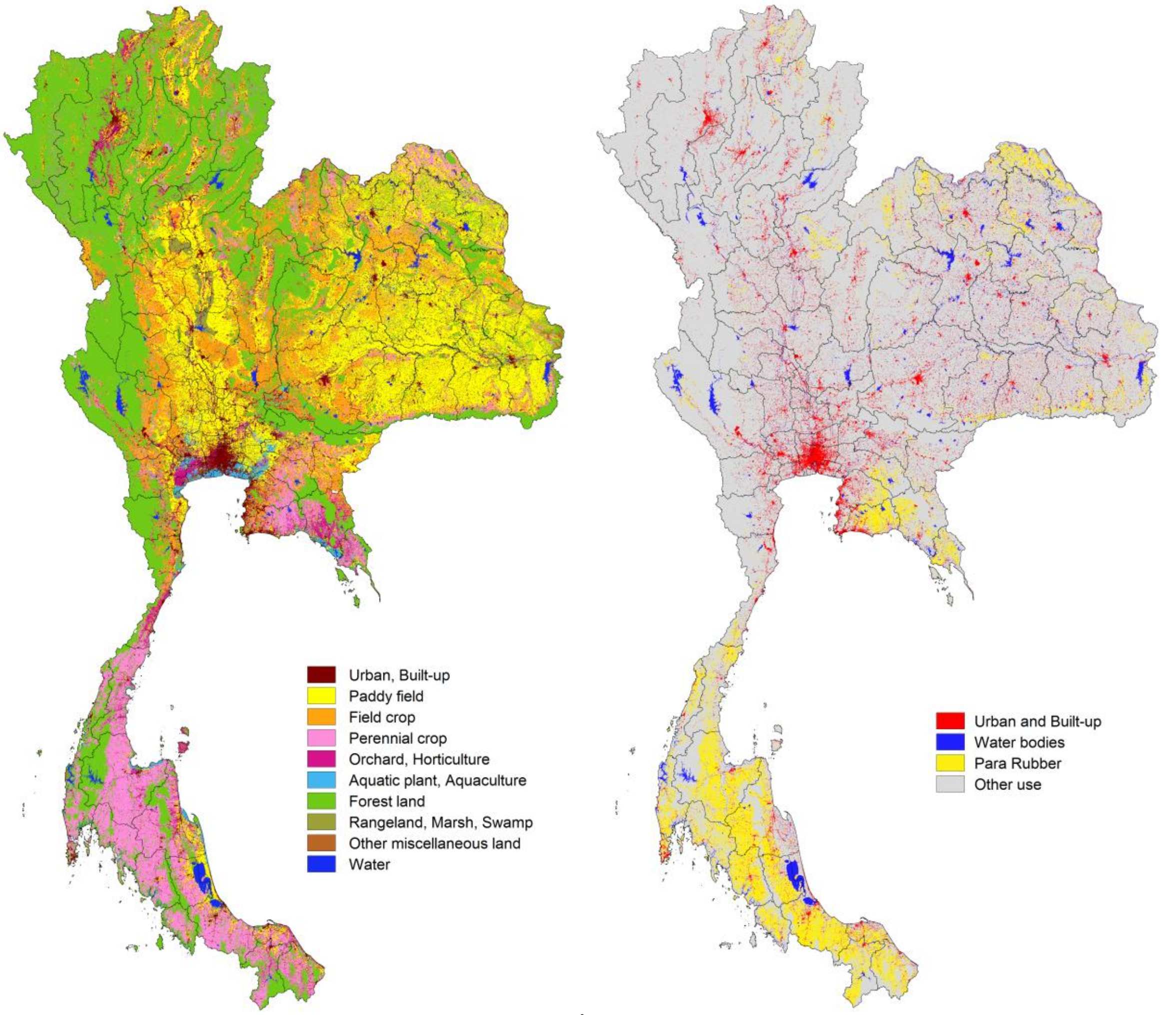


Figure 2-4. Land use/cover in 2009-12: Major land use types (left) and Para-rubber plantations (right)

3 Module 1 (Agro-climatic analysis)

3.1 Overview Module 1

Module I deals with 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 1 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 2 (biomass and yield calculation), Module 3 (agro-climatic yield constraints) and Module 5 (integration of climatic and edaphic evaluation). Spatially explicit climatic databases provide the main input data for Module 1. Figure 3-1 presents the information flow in Module 1.

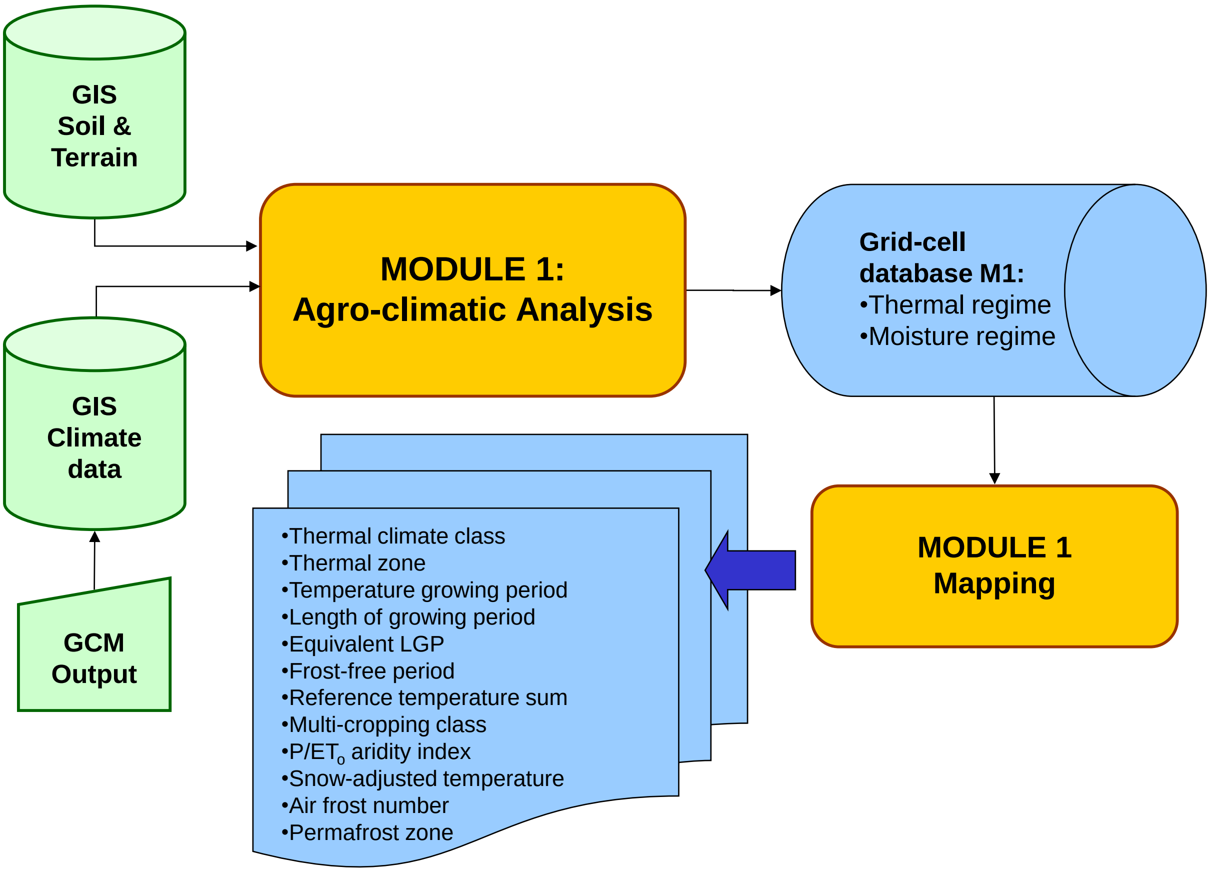


Figure 3-1. Information flow in Module 1 of the AEZ model framework

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.

Day-time and night-time temperatures

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

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

Night-time temperature is calculated as:

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

where Ta is average 24 hour temperature, 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, 1992b, 1998). A detailed description of the implementation of the Penmann-Monteith equations in AEZ is provided in Appendix 1.

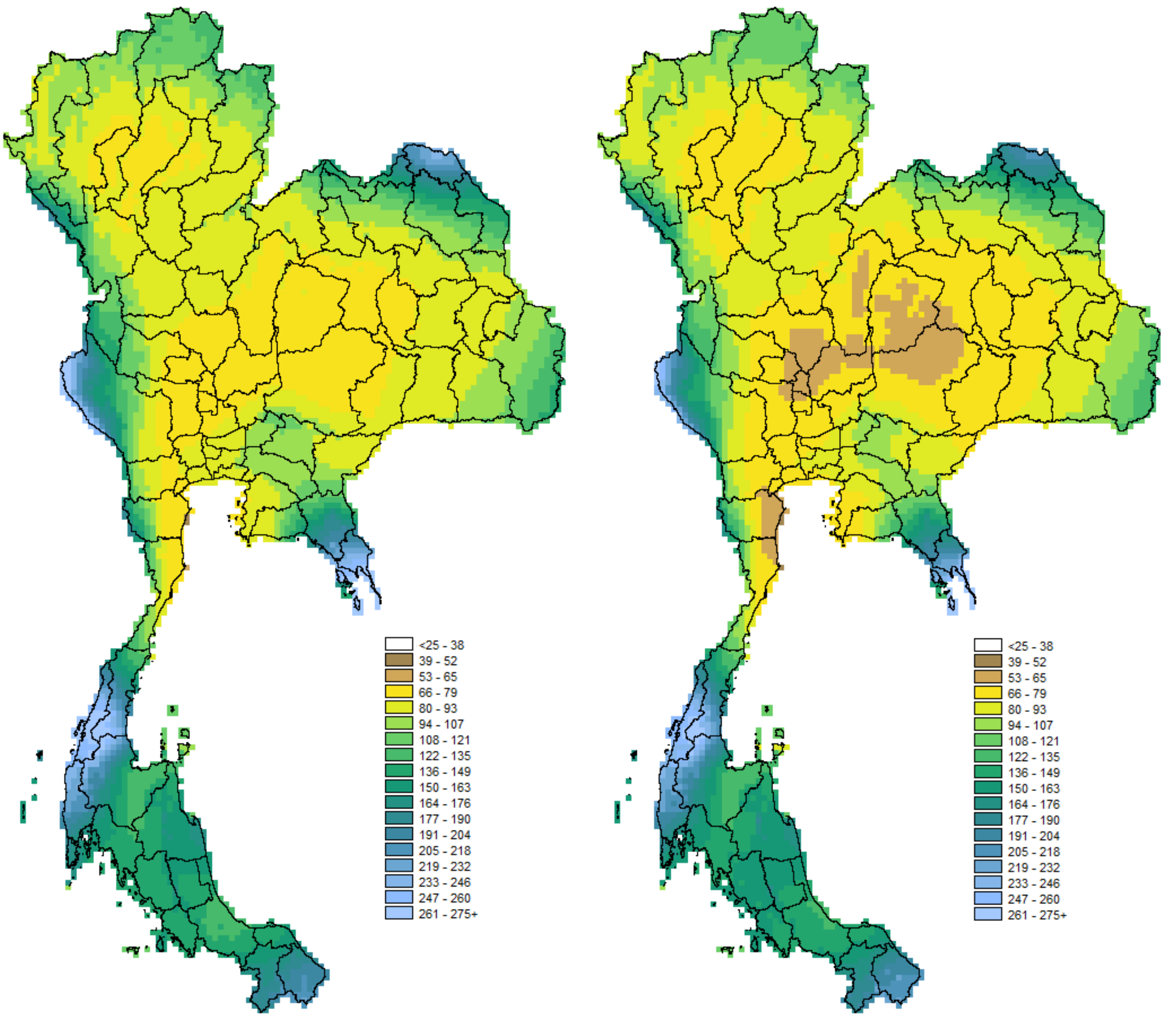


Figure 3-2. Annual P/ET_0 ratio for period 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

Maximum evapotranspiration (ETm)

In Module 1, 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 AEZ Module 1, 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 2, empirically determined kc values for the calculation of crop-specific 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 'reference' 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 1992, 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

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

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. Once the water balance for the 'reference' crop is calculated in Module 1, raster maps of derived variables are produced and used for further computations in other AEZ modules.

3.3 Thermal Regimes

Temperature is a major determinant of crop growth and development. In AEZ 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) Accumulated temperature sums; and (v) Temperature profiles.

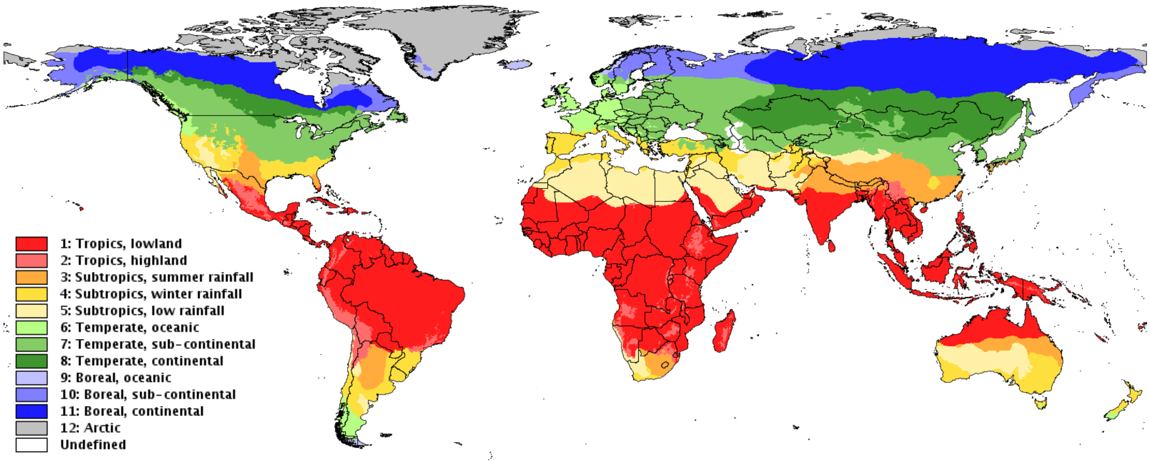


Figure 3-3. Thermal climates, GAEZ v4, climate of 1981-2010

Note that most of Thailand belongs to thermal climate 1, i.e. lowland tropics.

3.3.1 Thermal climates

Latitudinal thermal climates provide a classification that is used in Module 2 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[2], 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" 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 (**Fehler! Verweisquelle konnte nicht gefunden werden.**). 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.

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

3.3.2 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 AEZ three standard temperature thresholds for temperature growing periods are used: (i) periods with Ta >

[2] Rainfall regime has been represented comparing summer respectively winter P/ETo ratios.

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, AEZ 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

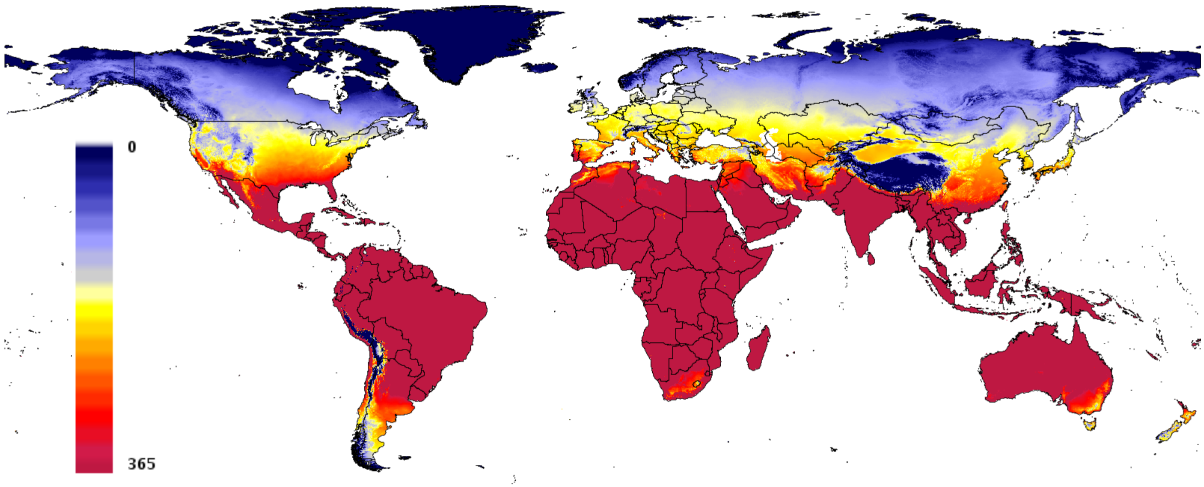


Figure 3-4. 'Frost-free' period (LGPt10), GAEZ v4, climate of 1981-2010

Temperature growing periods provide useful differentiation in temperate and sub-tropical zones. In lowland tropics, and therefore in Thailand, the temperature growing period is year-round, i.e. LGP_t = 365 for each of the three threshold temperatures.

3.3.3 Temperature sums (Tsum)

Heat requirements of crops are expressed in accumulated temperatures (Figure 3-5). 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°C ($Tsum_0$)
- (ii) 5°C ($Tsum_5$)
- (iii) 10°C ($Tsum_{10}$)

3.3.4 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 2 of AEZ, 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

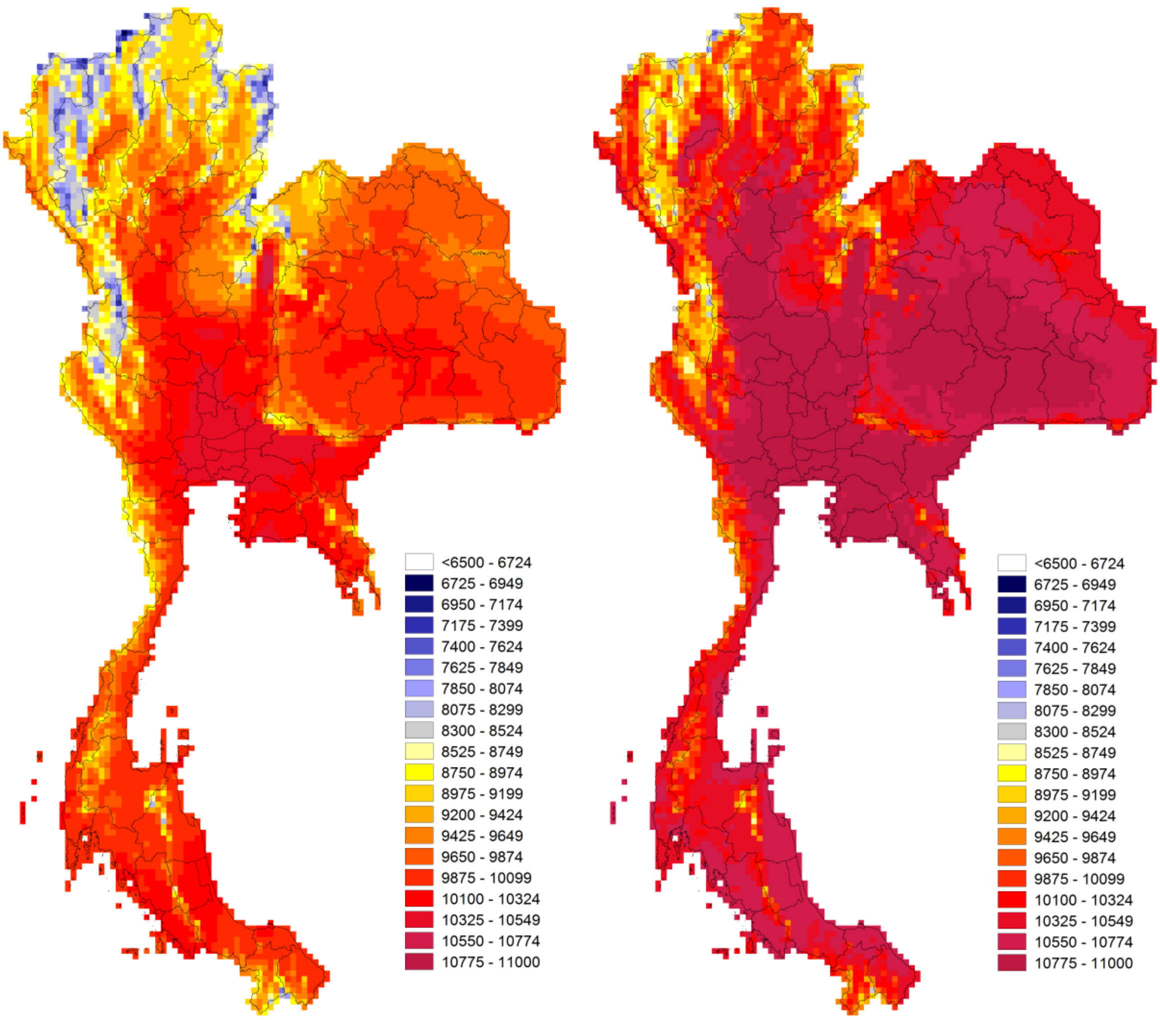


Figure 3-5. Average $Tsum_{10}$ for period 1981-2010 and projected by HadGEM2-ES for RCP6.0 in2041-2070

3.4 Soil moisture regime

In Module 1, AEZ calculates a daily reference soil water balance for each grid-cell and estimates actual evapotranspiration (ETa) for a reference crop. In the Module 2, 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 1985, 1992a) 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 3-6). 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).

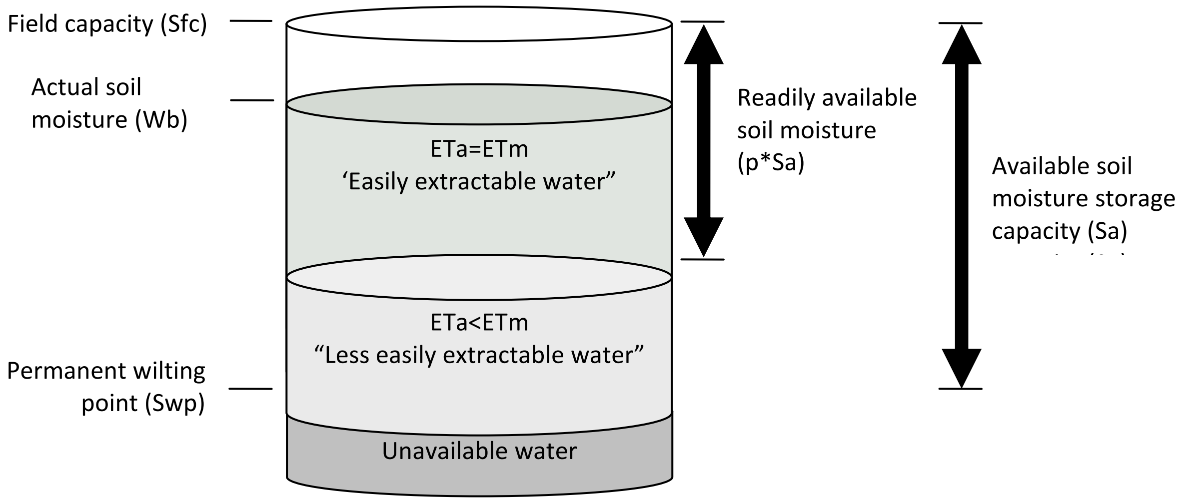
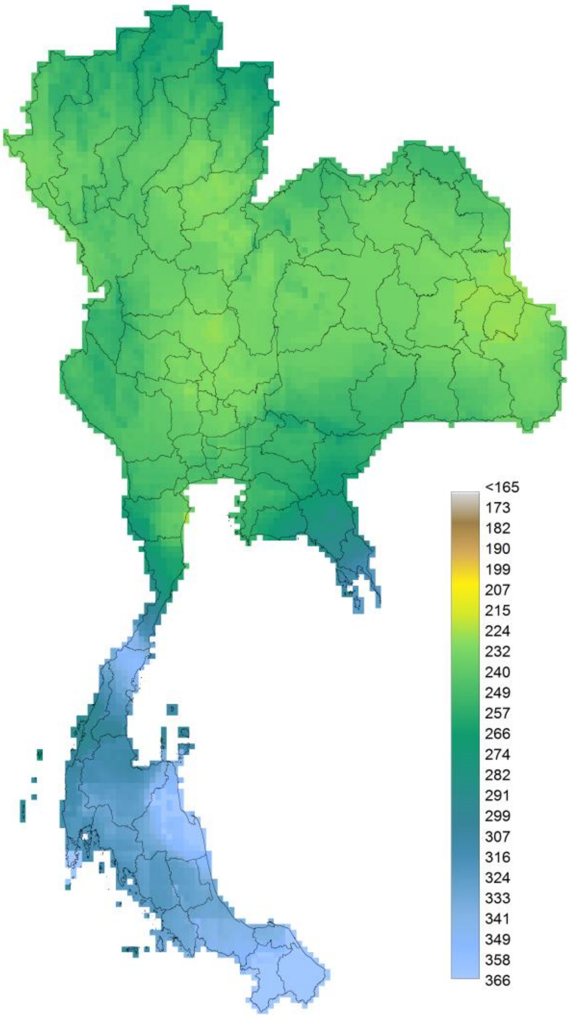


Figure 3-2. Schematic representation of water balance calculations

The values of Sa and rooting depth limitations due to soil are derived from soil information contained in the LDD soil group associations database. Any water input into the soil that exceeds Wx is "lost" from the vertical soil water balance as excess water (We) and considered "not available" in further AEZ calculations. It accounts for the water leaving the soil compartment either as runoff or by deep percolation.

3.4.2 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 AEZ parameterization, LGP days are considered when ETa ≥ 0.5 ETo, which aims to capture periods when sufficient soil moisture is available to allow the establishment of a reference crop. Figure 3-7 presents a map of reference length of growing period, which is based on a soil moisture holding capacity of 100 mm.



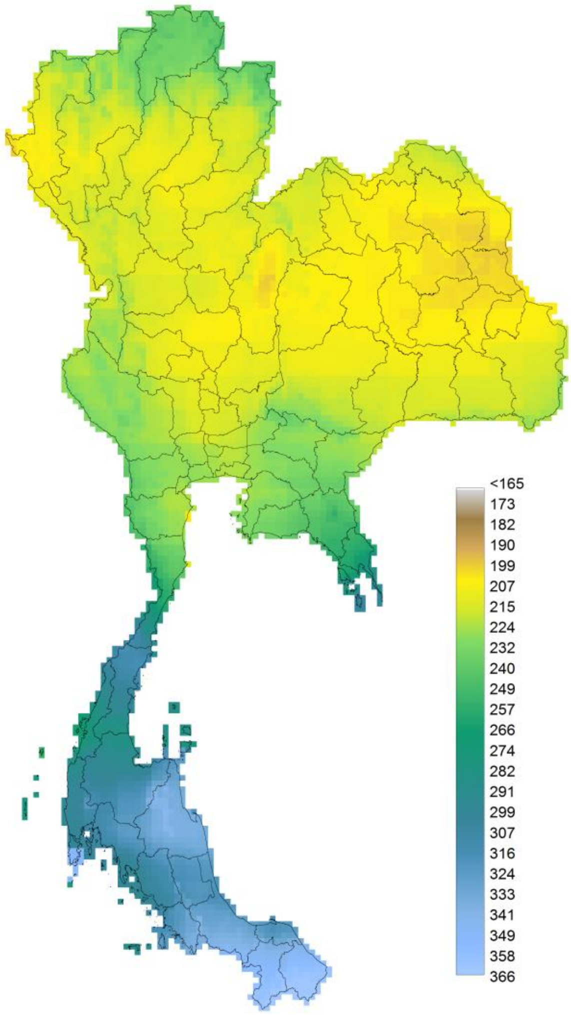


Figure 3-3. Reference LGP days for period 1981-2010 and ensemble mean of RCP6.0 in2041-2070

The length of growing period data is also used for the classification of general moisture regimes classes. The AEZ moisture regimes nomenclature and definitions are presented in Table 3-3.

Table 3-3 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 the crop water requirements are fully met (i.e. no water stress for plants occurs). From a soil water balance point of view these LGP days can further be differentiated as follows:

1. Daily rainfall is higher than crop water requirements (P>ETm) and 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 distinguished and various indicators are calculated as follows:

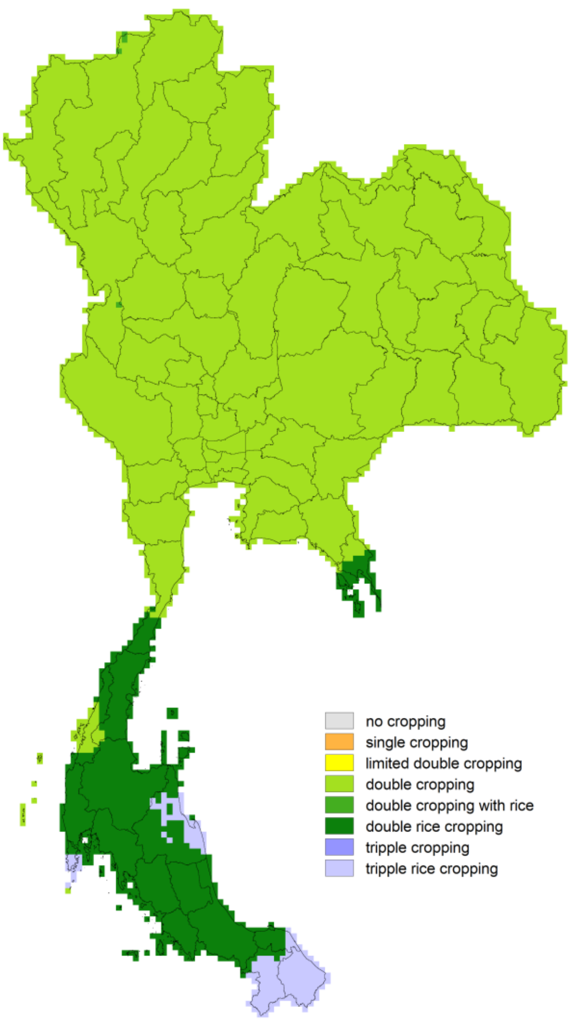
1. Total number of growing period days
2. Number of growing period days, during which ETa=ETm
3. Number of growing period days when P>ETm
4. Number of individual growing periods
5. Length of individual growing periods
6. Begin date of individual growing periods
7. End date of individual growing periods

3.4.3 Multiple cropping zones for rain-fed crop production

In the AEZ crop suitability analysis, the LUTs considered refer to single cropping of sole crops, i.e., a crop is assumed 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 available per unit area of land for rain-fed or irrigated 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

- **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)



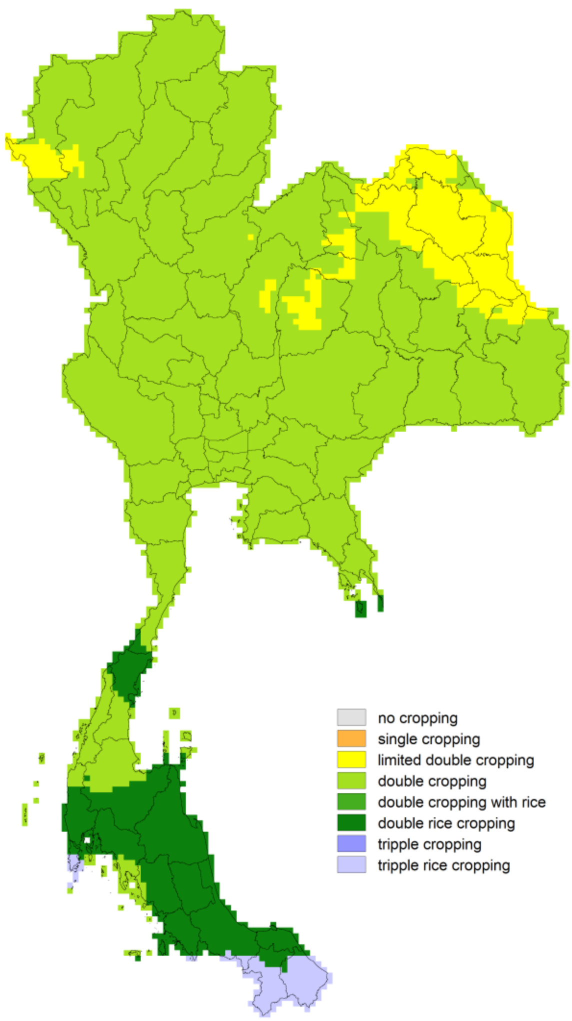


Figure 3-4. Multiple cropping zones for rain-fed conditions, period 1981-2010 (left) and MIROC-ESM-CHEM for RCP6.0 in2041-2070 (right)

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 3-4 and 3-5 summarize the delineation criteria for multiple cropping zones under rain-fed conditions in respectively the tropics and the subtropics/temperate zones.

Table 3-4. 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	-	-
	≥220	≥220	≥	≥5500		≥	≥
C[21]	≥200	≥200	≥120	≥6400	n.a.	≥3200	≥2700
	≥180	≥200	≥	≥7200		≥	≥
	≥270	≥270	≥	≥5500		≥	≥
D[22]	≥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 3-5. 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 respecti
21), 22) Refers to, respectively, high-land, mid high-land, and lowland areas in the tropics.

3.4.4 Equivalent length of the growing period

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.

3.4.5 Net Primary Production (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 AEZ, 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 AEZ water balance calculations for the specific water holding capacity of individual soil types. The variable A_0 is a proportionality constant depending on diffusion conditions of CO_2 and *d* is an expression of sensible heat. The ratio A_0/d can be approximated by a function of the radiative dryness index (RDI) (Uchijima and Seino, 1988).

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

with:

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

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 AEZ reference water balance:

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

b. For an NPP estimate applicable under irrigation conditions, ETa = ETm is assumed and an RDI* = min(1.375, RDI) is used, which results in a maximum for the function term approximating the A_0/d ratio when precipitation is below the optimum (assuming that irrigation can supplement to reach optimum RDI):

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

3.5 Description of Module 1 outputs

Module 1 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 2, 3, and 5.

The output variables from Module 1 are described in Appendix 2.

4 Module 2 (Biomass calculation)

4.1 Introduction

The main purpose of Module 2 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 2 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 2 are shown in Figure 4-1.

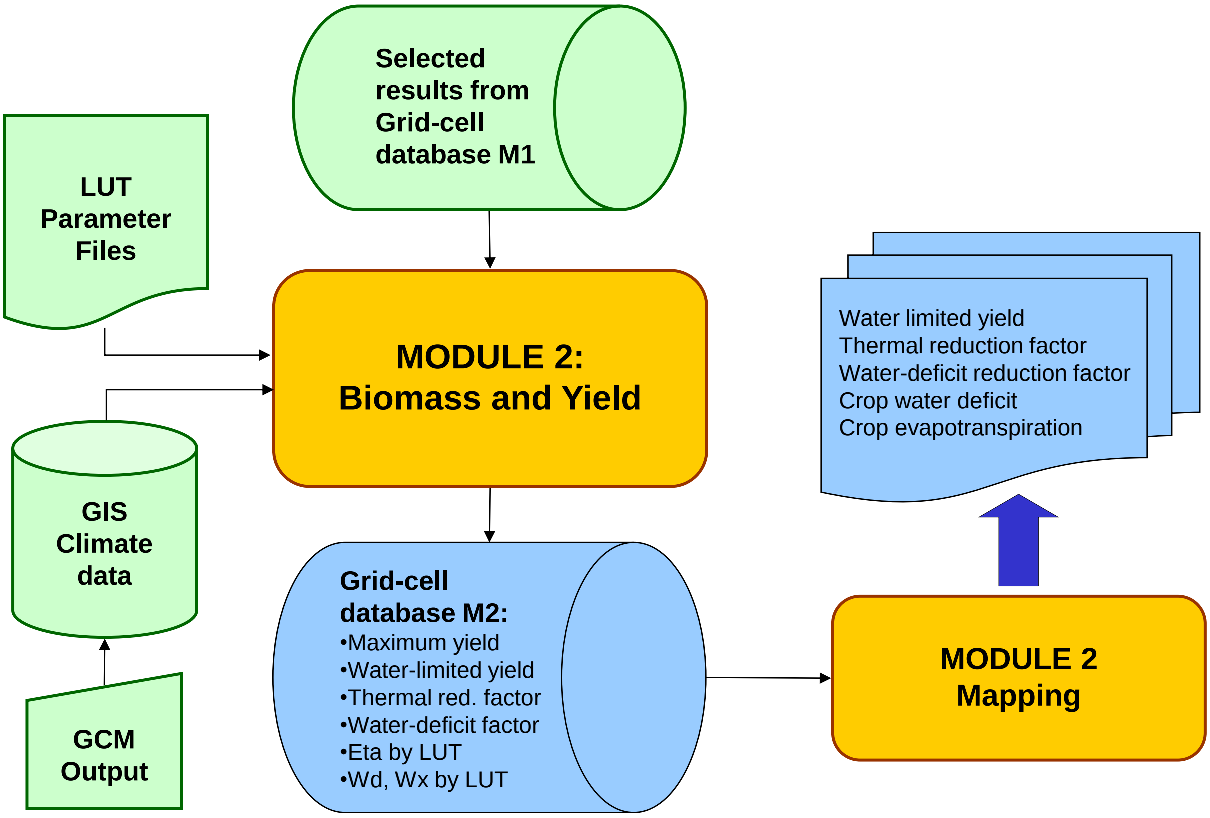


Figure 4-1. Information flow of Module 2

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 NAEZ v4 framework distinguishes about 350 crop/LUT combinations, which can be separately assessed for rain-fed and irrigated conditions. These LUTs are made-up of more than 60 different food, feed, fiber, and bio-energy crops (Appendix

3, Table A-3-2). The calculated yield of each crop/LUT is affected by water source and the intensity of input and management assumed to be applied. In AEZ, three generic levels of input/management are defined: (i) low, intermediate, and high input level. In the assessment for Thailand only the high level of input and management is currently considered.

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.

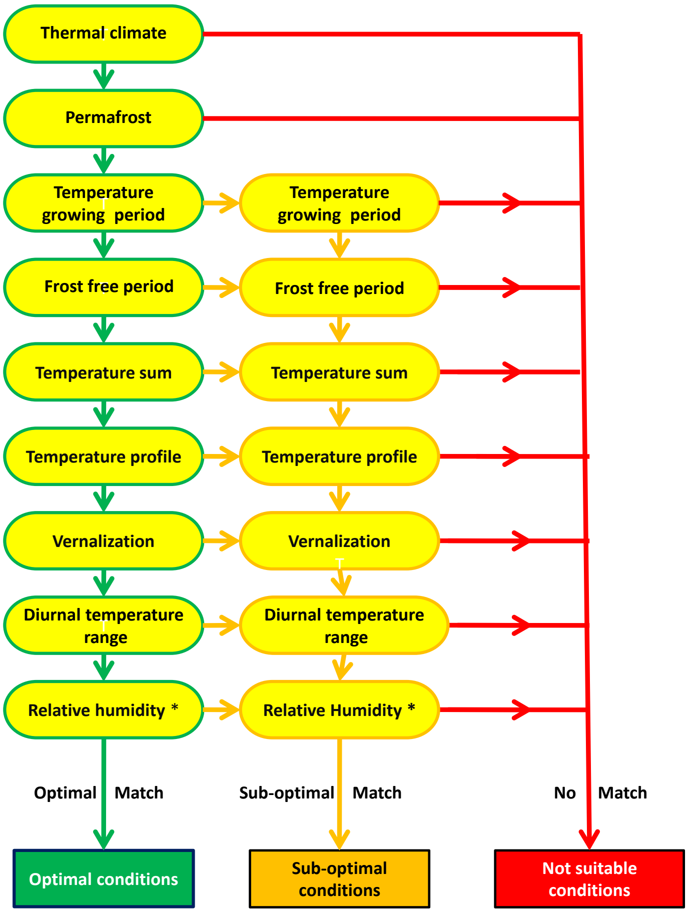
In GAEZ, this variety in management and input levels is translated into yield differences by assigning different parameters for LUTs depending on the input/management level, e.g. such as harvest index and maximum leaf area index.

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.



* Relative humidity requirements for selected perennials are screened in this procedure

Figure 4-2. Schematic representation of thermal suitability screening

Thermal climate

In Module 2, the AEZ 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°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.

Temperature sum

Individual crop/LUT heat unit requirements are matched with temperature sums during the crop/LUT growth cycle ($Tsum^c$). The $Tsum^c$ is defined as the sum of mean daily temperatures calculated from a base temperature of 0^oC.

The match of the crop LUT heat unit requirements with the prevailing $Tsum^c$ 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.

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^oC intervals are defined separately by days with increasing or decreasing temperature trends (Fischer *et al.,* 2002a; Fischer et al., 2012). AEZ 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 AEZ.

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.

Diurnal temperature range and relative humidity conditions

For a number of tropical perennial crops such as coconut, cacao, oil palm and para-rubber 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 2. For that a yield reduction factor $fc_1 = \min_k \{fc_{1k}, k = 1, \ldots, K\}$ 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 an eco-physiological model originally developed by A.H. Kassam (Kassam, 1977; Kassam et al., 1983; Kassam et al., 1993).

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 presents details of the biomass and yield calculation procedures.

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 AEZ 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).

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 AEZ, water requirements for each LUT are calculated and taken into account in the calculation of LUT-specific water balance and actual evapotranspiration in a grid-cell. A water-stress yield-reduction factor (fc_2) is calculated and applied to the net biomass (Bn) and potential yield (Yp) calculated.

4.5.1 Crop water requirements

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 1, multiplied by crop and crop-stage specific parameters 'kc'. The values of kc for different stages of crop development are given as input parameters.

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.

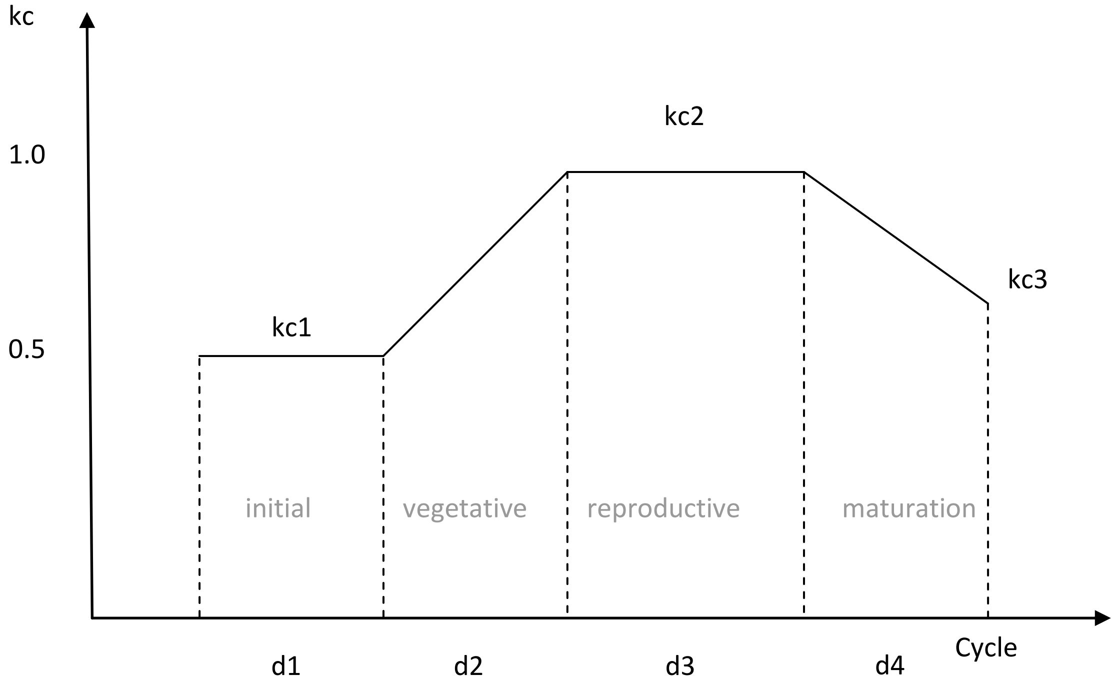


Figure 4-3. Schematic representation of kc values for different crop development stages

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

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

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 1, with the difference of being LUT-specific in Module 2. Also, in Module 2, 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*).

$$fc_2^T = 1 - ky0 \times \left(1 - \frac{\sum_1^{TCL} ETa}{\sum_1^{TCL} ETm} \right)$$

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

$$fc_2^{CS} = \min_{j=1,\ldots 4} \{1 - ky_j \left(1 - \frac{TETa_j}{TETm_j}\right)\}$$

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

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

Hence, fc_2 is taken as the minimum of factor fc^T_2 which represents the effect of overall water deficit and the factor fc^{cs}_2 which represents the 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 AEZ 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).

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

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

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, short	0	180	30	150
Cassava, long	0	240	60	120
Sugarcane	30	240	90	270
Banana	30	240	210	120
Oil palm	0	360	210	150
Yam	120	150	90	210
Citrus	90	120	210	120
Cocoa	180	60	210	120
Tea	90	240	150	180
Coffee (Arabica)	150	90	120	180
Coffee (Robusta)	180	90	210	120
Para rubber	180	60	210	150

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.

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

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. AEZ 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 1981-2010) 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 AEZ 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 AEZ 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, AEZ could also use a selection criterion which would account for the trade-off between additional water use and 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 five crop groups (Table 4-2). 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

Coefficients	Crop Group*				
	I	II	III	IV	V
a	-0.0003500	-0.0003325	-0.0002800	-0.0003850	-0.0004025
b	0.10636	0.10104	0.057888	0.11700	0.12231
c	-31.2870	-29.7227	-16.0540	-34.4157	-35.9801

*I: wheat, barley, sugar beet, highland/temperate beans, chickpea, dry pea, rapeseed, coffee Arabica, cabbage, carrot, tea, alfalfa.
II: rice, cassava, sweet potato, lowland beans, cowpea, gram, pigeon pea, groundnut, sunflower, cotton, banana, oil palm, yam, cocoyam, tobacco, citrus, cocoa, coffee Robusta, onions, tomato, carrots, coconut, jatropha.
III: maize, sorghum, millet, sugarcane.
IV: soybean.
V: white potato.

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 equal to that derived from laboratory experiments could be realized in farmers' fields. For marginally suitable conditions this share is set to two-third (see Table 4-3). This mechanism and the functions used are 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
$f_{sui\ CO2}$	1.000	0.900	0.800	0..667

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

The yield increment due to CO_2 enrichment (without considering land suitability constraints) is shown in Figure 4-4.

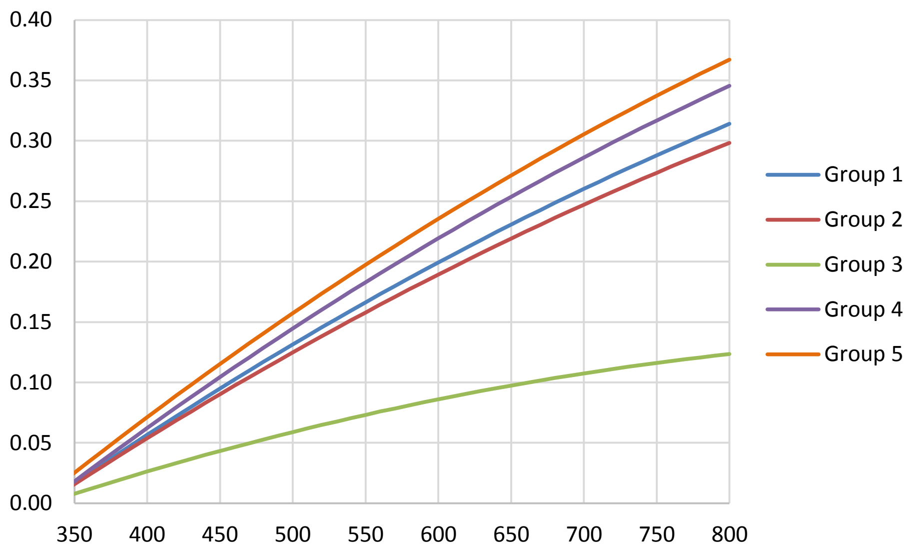


Figure 4-4. Yield response to elevated ambient CO2 concentrations

In AEZ various atmospheric CO_2 concentration scenarios were simulated as used for the IPCC AR5 (IPCC, 2013) and quantified by different climate modeling groups. AEZ 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.

Table 4-4. The CO_2 concentrations (ppm) used to model the fertilization effect in AEZ for different IPCC representative concentration pathways (RCP) and time points

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

(1) RCP: representative concentration pathway from IPCC AR5

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

4.8 Description of Module 2 outputs

The output of Module 2 records for each grid-cell and LUT the relevant results of the biomass calculation, including potential yields, yield-reducing factors, and accumulated temperatures, actual crop evapotranspiration, crop water deficits and crop calendar.

The main output information provided by Module 2 is given in Appendix 5.

5 Module 3 (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 3, such that effects are transparent, well separated and GAEZ assessments can be made with and without these constraints.

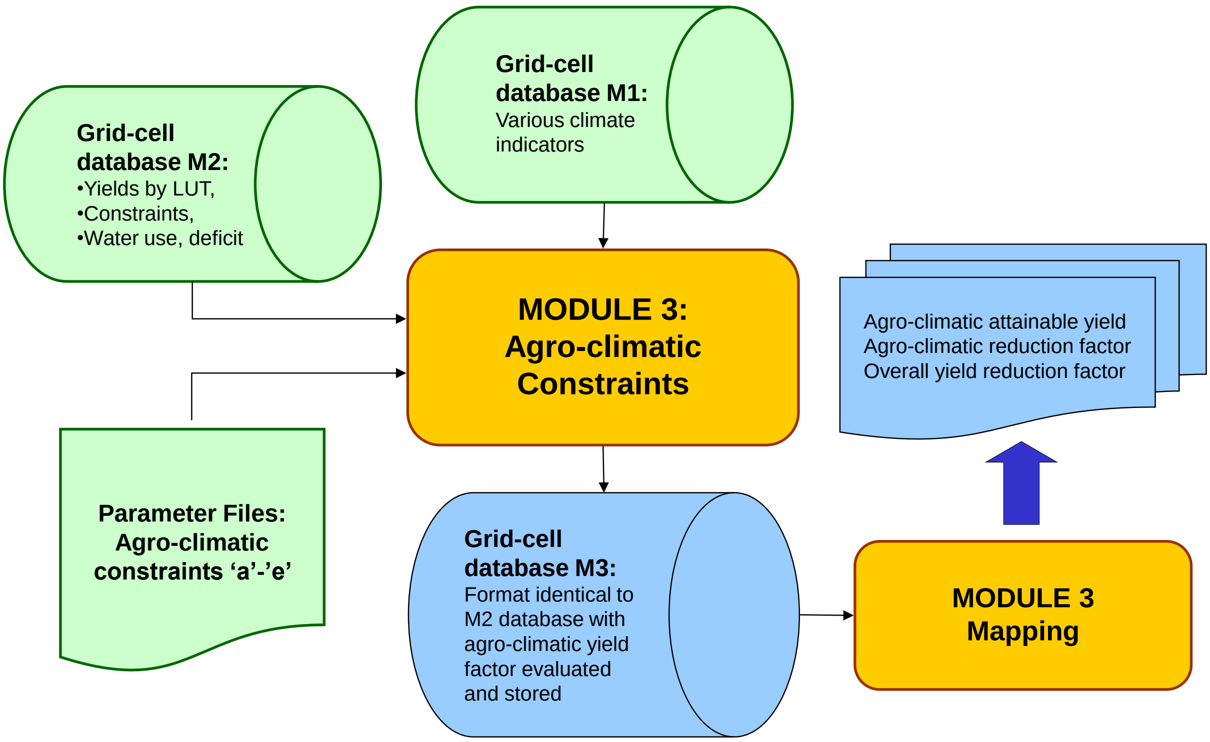


Figure 5-1. Information flows of Module 3

In Module 3, yield losses caused by agro-climatic constraints are subtracted from the yield calculated in Module 2. 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 (for short length of the growing period, 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.

5.2 Conceptual basis of agro-climatic constraints procedures

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.

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.

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.

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.

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.

Table 5-1. Agro-climatic constraints for rain-fed maize

RAINFED GRAIN MAIZE, ADVANCED INPT LEVEL												
Growth-LGP$_{eq}$	120 days 60-89	90-119	120-149	150-179	180-209	210-239	240-269	270-299	300-329	330-364	365^-	365^+
High inputs												
a	30-50	30-50	10-25		0	0	0	0	0	0	0	0
b	0	0	0	0	0	0	10-25	10-25	10-25	10-25	10-25	30-50
c	30-50	10-25	0	0	0	0	0	0	0	10-25	10-25	30-50
d	0	0	0	0	0	10-25	30-50	30-50	30-50	30-50	30-50	30-50

*** 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.**

By combining the three agro-climatic yield reducing factors $fct_b, \ldots, fct_d$ for constraint types 'b' to 'd', an overall yield reducing factor (*fc_3*) is calculated:

$$fc_3 = (1 - fct_b)(1 - fct_c)(1 - fct_d)$$

With agro-climatic constraints quantified, the agronomically attainable crop yields have been calculated by applying the factor (*fc_3*) to the potential yields as calculated in Module 2. Note that the evaluation is done separately for rain-fed and irrigated conditions.

5.3 Description of Module 3 outputs

The output format of Module 3 is the same as for Module 2 (see Appendix 5), but with the agro-climatic yield reduction factors *fc_3* evaluated according to the procedures described above. Various utility programs have been developed to map the contents of Module 3 crop databases in terms of agro-climatically attainable yield, agro-climatic reduction factor and overall yield reduction factor.

An example of outputs is provided in Figure 5-2 showing the agro-climatically attainable yields of rain-fed, advanced-input maize and sugarcane.

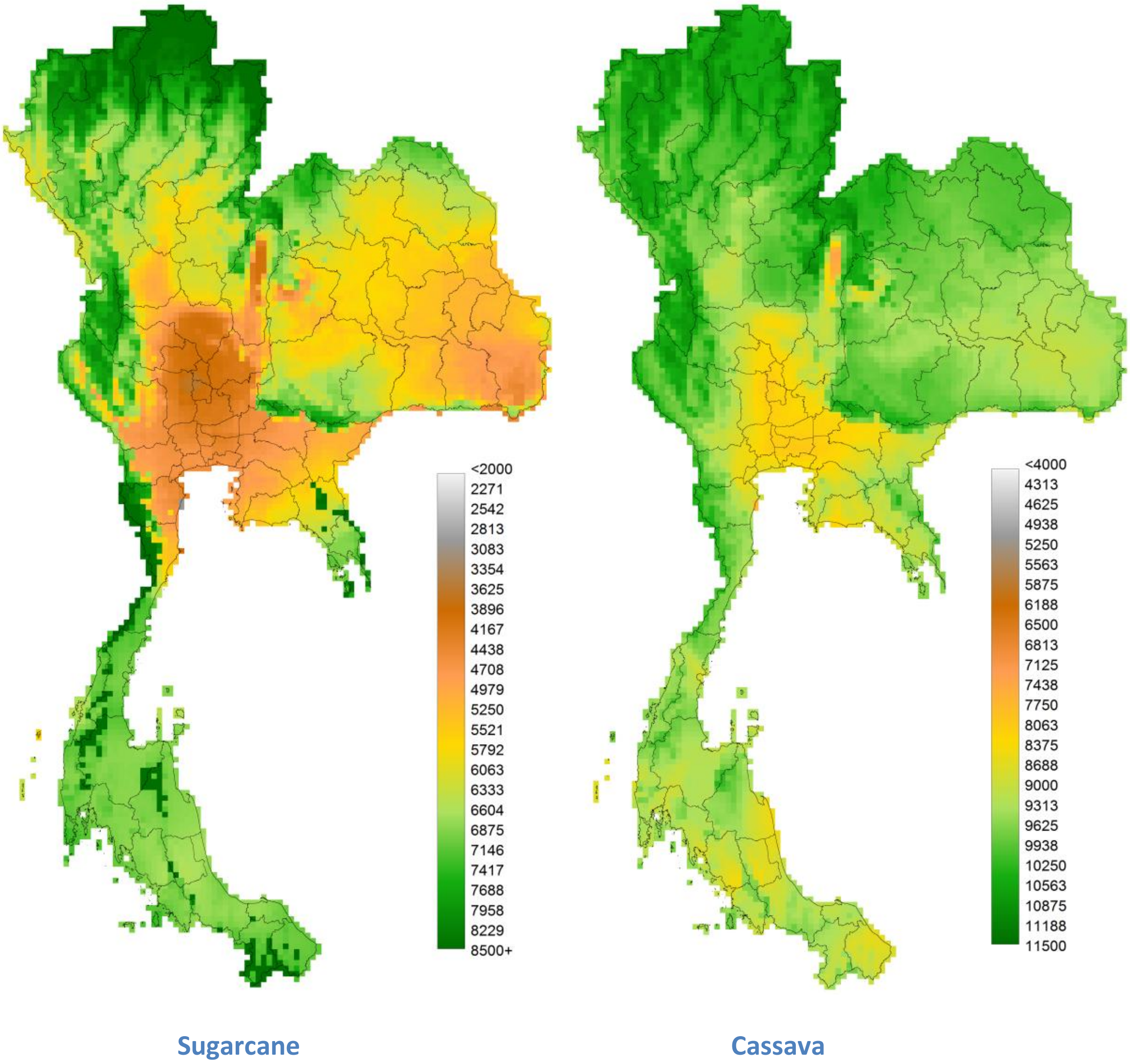


Figure 5-2 Attainable agro-climatic yield of rain-fed sugarcane (kg sugar/ha) and cassava (kg DW/ha)

Note: Agro-climatic yields of cassava in the map on the right are given in dry weight (kg dry weight per hectare). For the calculation of fresh weight multiply, for instance, by a factor of 2.86 (assuming a water content for cassava of 65%).

6 Module 4 (Agro-edaphic suitability)

6.1 Introduction

In the context of this agro-economic zones study of Thailand a soil dataset provided by LDD is used. The LDD map containing associations of 62 soil groups (Figure 6-1, left) is composed of a geographical layer giving reference to some 1,320 unique soil map units, each combining 1 to 3 soil groups.

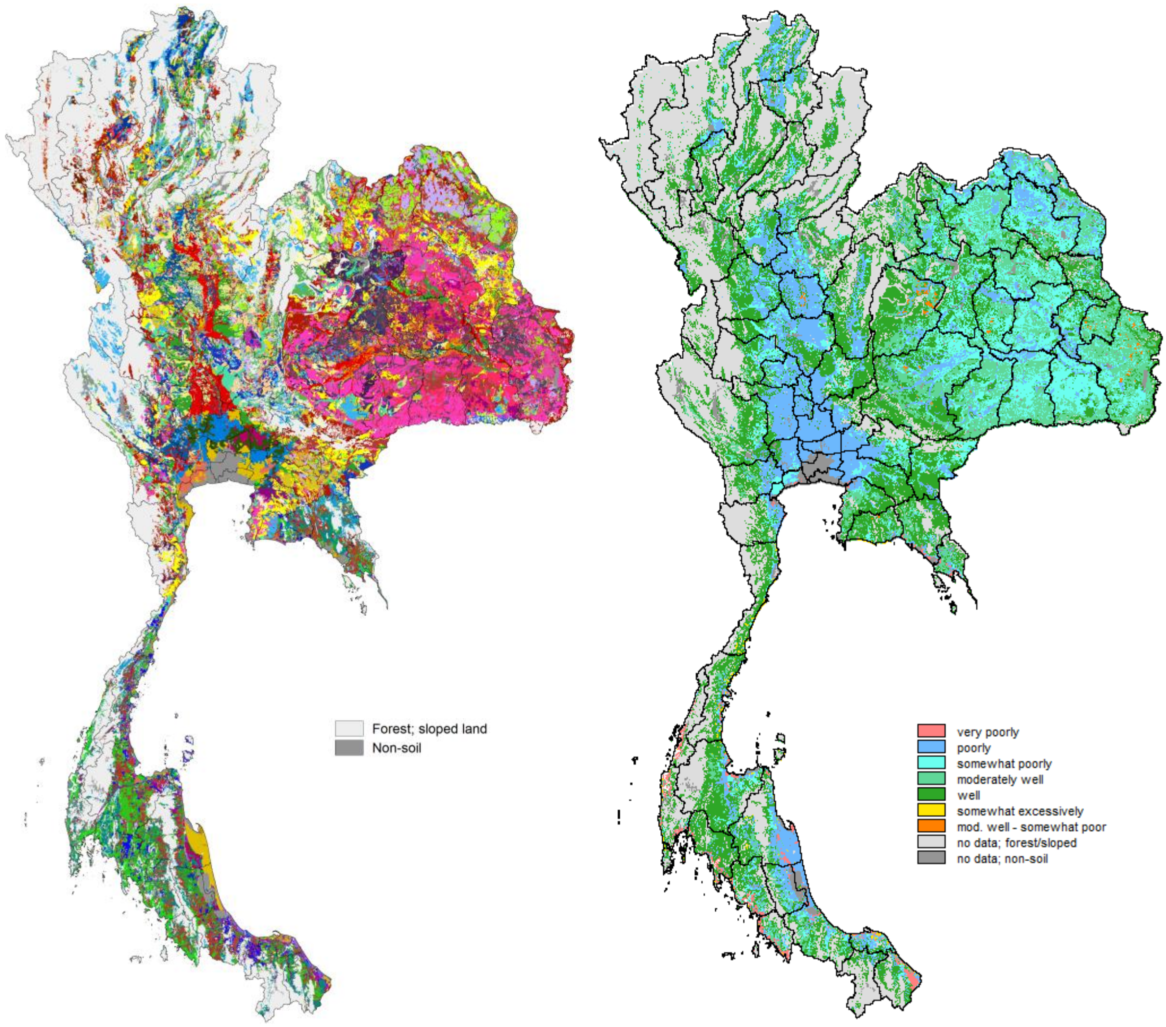


Figure 6-1. Thailand raster map of soil series group associations (left) and soil texture class (right)

This information is stored in NAEZ-Thailand as a 3 arc-second raster, which is linked to an attribute database containing representative soil profile data for a top-soil (assumed 0-30 cm) and a sub-soil layer (30-100cm or less). The characterization of soil series groups includes the following soil attributes: terrain slope (8 classes), soil texture (12 texture classes plus categories with vg, g and sg modifiers indicating gravelly texture, in total 22 classes), drainage class (6 classes), broad classes of fertility status (3 classes), cation exchange capacity (3 classes), base saturation (3 classes), effective soil depth (5 classes), soil reaction (11 pH range classes), salinity (4 classes), gravel content (4 classes), and a field indicating the presence of jarosite (assumed to be present within the top 50cm). From these attributes two additional fields where derived to provide information on total available exchangeable bases (TEB) and on soil water holding capacity. Six classes of TEB were assigned for combinations of CEC and BS classes (TEB1 = CEC1 & BS1; TEB2 = CEC1 & BS2 or CEC2 & BS1; TEB3 =

CEC1 & BS3 or CEC3 & BS1; TEB4 = CEC2 & BS2, TEB5 = CEC2 & BS3 or CEC3 & BS2; and TEB6 = CEC3 & BS3). Based on available data and literature, an estimate of soil water holding capacity for each soil series group is derived from the prevailing texture class indicated for each soil, as follows: for texture classes s, ls, sl,l, sil, scl, cl, sicl, c, sic, sc, gsl, gscl, gcl, gl, gc, vgl, vgscl, vgc,sgscl, sgsl, and fibric the AWC values were respectively set to 75, 138, 159, 225, 270, 203, 228, 228, 180, 192, 135, 172, 194, 191, 153, 146, 132, 117, 217, 151 and 250 mm/m. AWC is further reduced when salinity and/or soil depth limitations are recorded in a soil map unit. Estimates were computed separately for top-soil and sub-soil components. The 3 arcsec raster with soil map unit codes applied in the analysis has 17,900 rows and 10,000 columns, of which about 61 million grid-cells cover Thailand's territory.

In comparison, the Harmonized World Soil Database used in the global analysis (GAEZ v4) applies a geographical layer of soil map units at 30 arc-seconds, which are linked to a harmonized attribute database with 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 agro-edaphic assessment, which is an integral part of the AEZ modeling framework is schematically presented below.

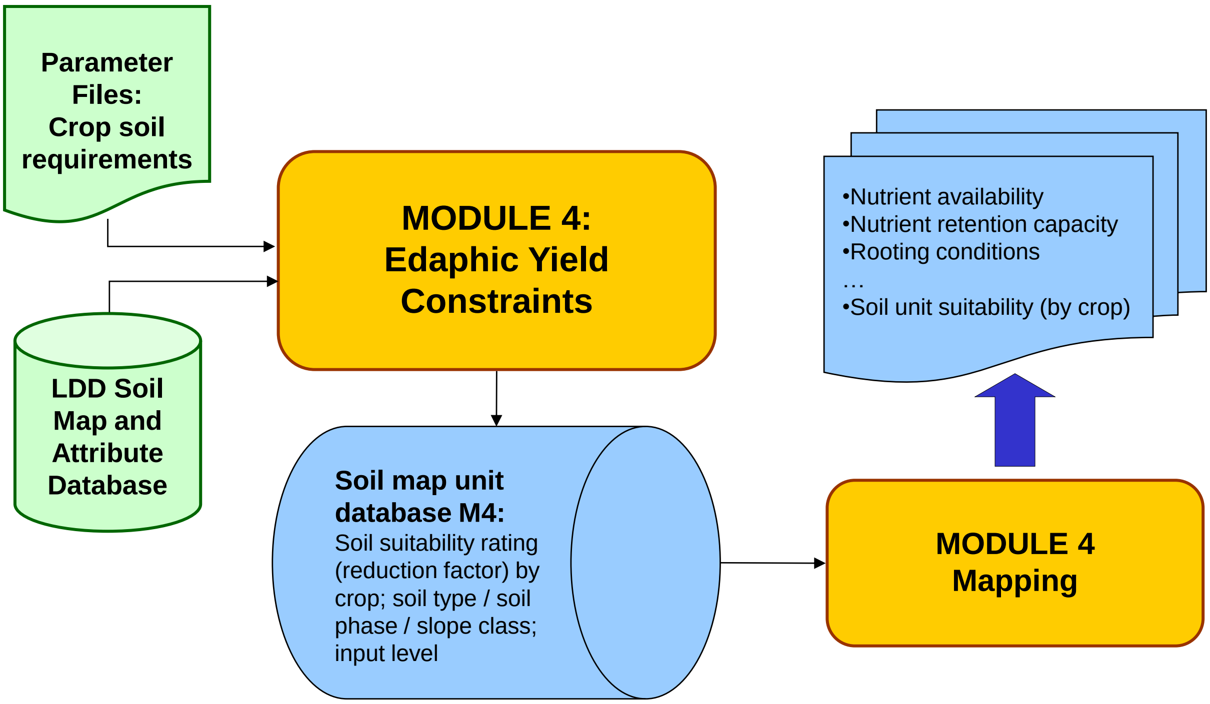


Figure 6-2. Information flow in Module 4

Module 4 of AEZ estimates yield reduction factors due to constraints induced by prevailing soil and terrain-slope conditions. 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 as contained in the resource database. This module calculates edaphic suitability for each soil map unit by separately considering all occurring soil-unit and terrain slope combinations. The calculations are crop/LUT specific and can be performed for different assumed input and management levels as well as different water supply systems (rain-fed, gravity irrigation, sprinkler irrigation, drip irrigation).

6.1.1 Levels of inputs and management

In AEZ the individual soil and terrain characteristics have been related to requirements and tolerances of crops at three basic levels of management and inputs circumstances: advanced, intermediate and low. For NAEZ-Thailand in this study an advanced management level is assumed.

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

6.1.2 Soil suitability assessment procedures

In the AEZ approach, land qualities are assessed in several steps involving specific procedures, which rate soil attributes vis-à-vis crop/LUT requirements in terms of seven soil qualities (see Table 6-1) and further combine the rating of individual soil qualities into an overall soil unit rating. The land qualities related to climate and climate-soil interactions (flooding regimes, soil erosion and soil nutrient maintenance) are treated separately from those land qualities specifically related to soil properties and conditions as reflected in the soil and terrain-slope database.

Assessment procedures and activities employed are schematically represented in Figure 6-3 below:

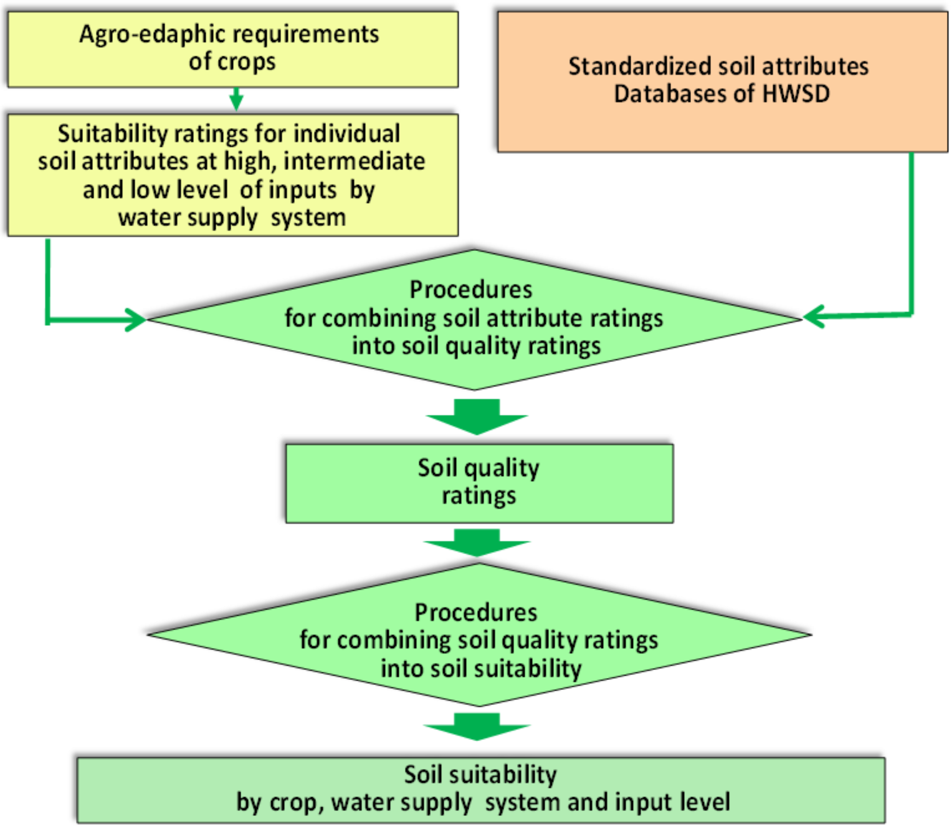


Figure 6-3. Soil suitability rating procedures

The individual soil profile attributes, soil drainage conditions and soil phases prevalence, that have been related to requirements and tolerances of crops, assuming and advanced level of management and inputs circumstances, and for two different water supply systems, need to be combined ultimately into land utilization specific soil suitability ratings.

First individual soil qualities are defined and quantified. Table 6-1 below provides an overview of the seven soil qualities in relation to relevant soil profile attributes, including soil drainage conditions and prevalence of soil phases.

Table 6-1. 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

The seven soil qualities (SQ1-SQ7) are estimated from soil characteristics (e.g. organic carbon content, soil pH, texture) read from the soil attribute 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 in AEZ 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. Note that most but not all of these attributes are currently available in the soil database used for agro-economic zoning in NAEZ-Thailand.

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 6-2.

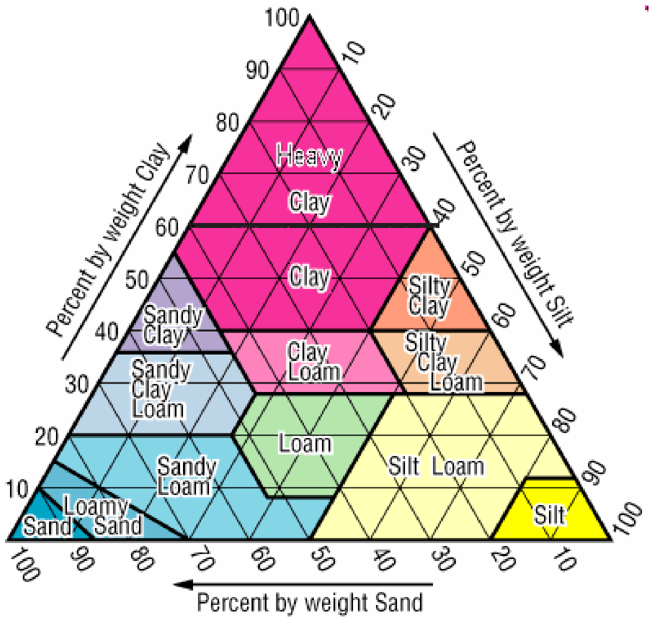


Figure 6-4. Soil texture classification

Table 6-2. 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 influence 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 cannot build up stores of nutrients. Many sandy soils have CEC less than 4 cmol/kg. The clay content, the clay type and the organic matter content all determine the total nutrient storage capacity. Values in excess of 10 cmol/kg are considered satisfactory for most crops.

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

Soil drainage classes used in AEZ are 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 AEZ slope classes. The AEZ 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.

6.3 Soil suitability ratings

The NAEZ-Thailand soil suitability assessment procedures consider all the soil profile attributes available in the LDD soil database: fertility status, cation exchange capacity (CEC), base saturation (BS), total exchangeable bases (TEB), soil reactivity (soil pH), salinity (EC), gravel content (GRV), effective soil depth, presence of jarosite, soil texture class (TXT) and soil drainage class (DRG).

6.3.1 Soil profile attributes ratings

The soil profile attribute suitability ratings are empirical coefficients. They can be compiled by input level (advanced, intermediate and low) and for different water supply systems (e.g., rain-fed, gravity irrigation, sprinkler irrigation and drip irrigation systems). Examples of ratings presented below (Table 6-3 and 6-4) refer to rain-fed production. The rating system is adapted from Sys *et al.* (1993) and uses a parameter scale from 0 to 100% derived from 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 6-3. Soil reaction (pH) SQ1 ratings for rain-fed cropping

	Soil reaction (pH) level at which indicated rating is assigned under high input*										
	10%	40%	60%	85%	95%	100%	95%	85%	60%	40%	10%
Rice, paddy	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	7.9	8.2	8.3
Maize	4.0	4.5	5.0	5.5	6.0	6.4	6.8	7.8	8.0	8.2	8.3
Cassava	4.0	4.5	4.8	5.2	5.5	6.0	6.5	7.0	7.6	8.2	8.3
Soybeans	5.1	5.2	5.4	5.5	6.0	6.5	7.0	7.5	7.8	8.2	8.3
Sugarcane	4.4	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	8.6
Oil palm	3.4	3.5	4.2	5.0	5.5	5.8	6.0	6.5	7.0	7.5	7.6
Para Rubber	3.9	4.0	4.5	5.0	5.2	5.3	5.5	6.0	6.5	7.0	7.1
Coffee	4.4	4.5	5.0	5.3	5.5	5.6	5.8	6.0	6.5	7.0	7.1
Tea	2.9	3.0	3.8	4.5	4.8	5.0	5.2	5.5	5.8	6.0	6.1

* The table defines for each crop a piecewise linear rating function for soil quality SQ1 with regard to soil reaction (pH).

Table 6-4 Soil depth SQ3 ratings and salinity SQ5 ratings for rain-fed cropping

	Effective depth class (cm)					Soil salinity class (dS/m)			
	< 25	25-50	50-100	100-150	> 150	< 2	2-4	4-8	> 8
Rice, paddy	60	90	100	100	100	100	85	50	25
Maize	10	50	85	100	100	100	85	70	30
Cassava	10	35	70	100	100	100	85	50	10
Soybeans	10	60	80	100	100	100	100	85	50
Sugarcane	10	50	85	100	100	100	95	70	30
Oil palm	10	35	85	100	100	100	85	40	10
Para Rubber	10	10	80	100	100	100	30	10	10
Coffee	10	30	85	100	100	100	40	10	10
Tea	30	60	85	100	100	100	85	30	10

* The table defines for each crop a soil quality rating for respectively SQ3 and SQ5 with regard to a soil attribute class.

6.3.2 Soil texture ratings

Table 6-5 Soil texture ratings for rain-fed crops, advanced input/management

	Soil Texture SQ1 Ratings for rain-fed production*											
Crops	sand	Loamy sand	Sandy loam	loam	Silty loam	Sandy clay loam	Clay loam	Silty clay loam	clay	Silty clay	sandy clay	fibric
	1	2	3	4	5	6	7	8	9	10	11	13
Rice, paddy	30	50	90	100	100	100	100	100	100	100	100	100
Maize	30	70	90	100	100	100	100	100	100	100	100	100
Cassava	30	70	90	100	100	100	100	100	100	100	100	100
Soybean	30	70	90	100	100	100	100	100	100	100	100	100
Sugarcane	30	70	90	100	100	100	100	100	100	100	100	100
Oil palm	30	70	90	100	100	100	100	100	100	100	100	100
Para rubber	30	70	90	100	100	100	100	100	100	100	100	100
Coffee	30	70	90	100	100	100	100	100	100	100	100	100
Tea	30	70	90	100	100	100	100	100	100	100	100	100

* Additional reductions are applied in the rating for gravelly, somewhat gravelly and very gravelly texture classes.

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. Table 6-5 below provides example soil texture ratings of basic texture classes used for the assessment of rain-fed crop production in NAEZ-Thailand. Soil texture ratings are compiled separately for rain-fed and irrigated systems.

6.3.3 Soil drainage ratings

Soil drainage is characterized in the NAEZ-Thailand soil database in 6 classes (Table 6-6):

Table 6-6 Soil drainage classes

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

Soil drainage ratings are varying by crop and may vary by input/management conditions. Table 6-7 presents soil drainage ratings for rain-fed cultivation of major economic crops in this NAEZ-Thailand study. Assumptions for artificial soil drainage differ by input levels. At advanced level of inputs it is assumed that a full and adequate artificial drainage system is installed, while low and intermediate inputs assume no artificial drainage.

Table 6-7 Soil drainage ratings for rain-fed cropping

	Drainage class*						
	VP	P	I	MW	W	SE	MW-I
Rice, paddy	85	100	100	85	40	10	95
Maize	25	40	60	100	100	85	85
Cassava	10	10	40	85	100	85	70
Soybeans	10	10	85	100	100	85	95
Sugarcane	10	30	85	100	100	85	95
Oil palm	10	60	85	100	100	85	95
Para Rubber	10	10	40	85	100	85	60
Coffee	10	10	40	100	100	85	85
Tea	10	40	85	100	100	85	95

* Advanced input level drainage ratings assume that full and adequate artificial drainage systems are installed.

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, $0 \le \tau(x_j) \le 100$.

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

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

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

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

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 topsoil and subsoil, the following relationships are used:

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

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

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 property or soil phase that is most severely rated with regard to soil depth and volume conditions. Relevant soil properties considered for assessing SQ3 are: Effective soil depth, soil properties i.e., soil texture/mineralogy/structure, and presence of jarosite.

SQ3 is evaluated separately for topsoil and subsoil attributes.

$$SQ3 = \tau\ (RSD)*min[(\tau\ (GRV), \tau\ (TXT), \tau\ (JAR)]$$

where, τ (RSD) is effective soil depth rating, τ (TXT) is soil texture rating, τ (GRV) is soil coarse material rating, and τ (JAR) is the rating related to the presence of jarosite.

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. For the advanced input and management level, drainage ratings assume that adequate artificial drainage systems are installed.
SQ4 has been defined as the most limiting rating for a specific crop of either soil drainage or soil phase. In NAEZ-Thailand soil phases are not used as part of soil unit classification and SQ4 is set to:

$$SQ4 = \tau(DRG)$$

where, τ (DRG) is the attribute rating function for drainage.

Excess salts (SQ5)

Accumulation of salts may cause salinity. Excess of free salts, referred to as soil salinity, is 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).

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.

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. Note, in the case of NAEZ-Thailand only EC is available in the current soil database and SQ5 is evaluated as $SQ5 = \tau(EC)$.

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 et al., 1993).

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

In SQ6, the most limiting of the combination of excess calcium carbonate and gypsum in the soil and occurrence of 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. Note, calcium carbonate, gypsum and petro-gypsic soil phase are not recorded in the LDD soil attribute database and SQ6 is not assessed for soil units in NAEZ-Thailand.

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 AEZ 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 ratings. Soil phases considered for 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.

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

where, τ( ) is the respective input level specific attribute rating function, RSD is effective soil depth, GRV is soil gravel content, τ(SPH) is soil phase rating, TXT is soil texture and VSP indicates vertic properties.

Note that soil phases are not used in the NAEZ-Thailand soil series group associations map and SQ7 is estimated as: $SQ7 = f_{SQ}(\tau(RSD), \tau(TXT), \tau(JAR))$.

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 form the basis for the way soil qualities are combined in AEZ 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 different water supply systems, each soil unit suitability rating (SR) has been estimated. The functional relationships for respectively low, intermediate and advanced 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 are recorded by each crop/soil-unit/input level/water supply system combination for subsequent integration with the results of the agro-climatic suitability assessment (calculated in module 2 and 3).

Appendix 6 provides an explanation of the content of soil evaluation results calculated and stored during execution of Module 4.

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 results in loss 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 AEZ aims to capture 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 comparable 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 daily and 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 the differences in both amount and within-year distribution of rainfall, use has been made of the modified Fournier index (Fm), which reflects the combined effect of rainfall amount and distribution (FAO/UNEP, 1977), as follows:

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

where, P_i is 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 of 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 climatic information on within year rainfall distribution into AEZ 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 6-7 presents terrain-slope ratings for rain-fed conditions by crop group for the advanced level of inputs and management (as applied for the lowest class of the Fournier index, i.e., Fm< 1300).

Table 6-7 Terrain-slope ratings for rain-fed conditions, advanced input (Fm< 1300)

Slope Classes	0-.5%	0.5-2%	2-5%	5-8%	8-16%	16-30%	30-45%	> 45%
Annuals 1	S1	S1	S1	S1	S1/S2	S2/N	N	N
Annuals 2	S1	S1	S1	S1	S1/S2	S2/N	N	N
Annuals 3	S1	S1	S1	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/S22	S2/N	N	N
Perennials 3	S1	S1	S1	S1	S1/S2	S2/N	N	N
Perennials 4	S1	S1	S1	S1	S1	S1/S2	S2/N	N
Perennials 5	S1	S1	S1	S1	S1/S2	S2/N	N	N

Crop Groups: Annuals 1: wheat, barley, rye, oat, buckwheat; Annuals 2: maize, sorghum, pearl millet, foxtail millet, potato, white potato, sweet potato, pulses, rapeseed, soybean, 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, rubber; Perennials 4: pasture legumes, grasses, tea; Perennials 5: alfalfa, switchgrass, miscanthus

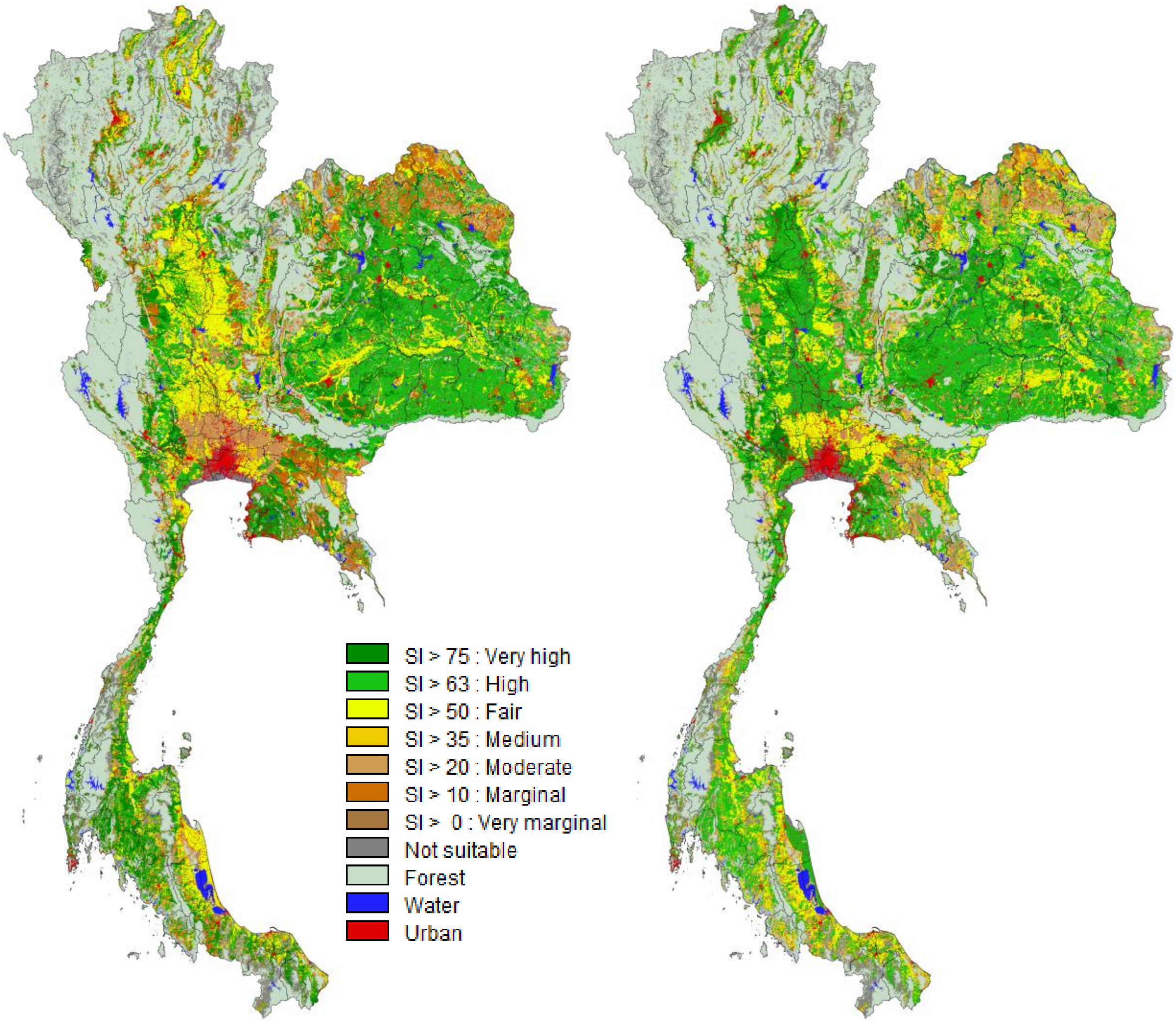


Figure 6-5. Rain-fed soil and terrain suitability, cassava (left) and maize (right)

Figure 6-5 shows two examples of the mapped results of soil unit evaluation for rain-fed cassava and rain-fed maize. Note that these maps refer to soil and terrain suitability only and do not take into account climatic suitability and associated agro-climatic constraints (see next chapter).

7 Module 5 (Integration of climatic and edaphic evaluation)

7.1 Introduction

Module 5 executes the final step in the AEZ crop suitability and land productivity assessment. It reads the LUT specific results of the agro-climatic evaluation for biomass and yield calculated in Module 2/3 for different soil classes and it uses the edaphic rating produced for each soil series group in Module 4. Soil evaluation and slope rules are applied separately for each water supply systems. The information flow in Module 5 is summarized in Figure 7-1.

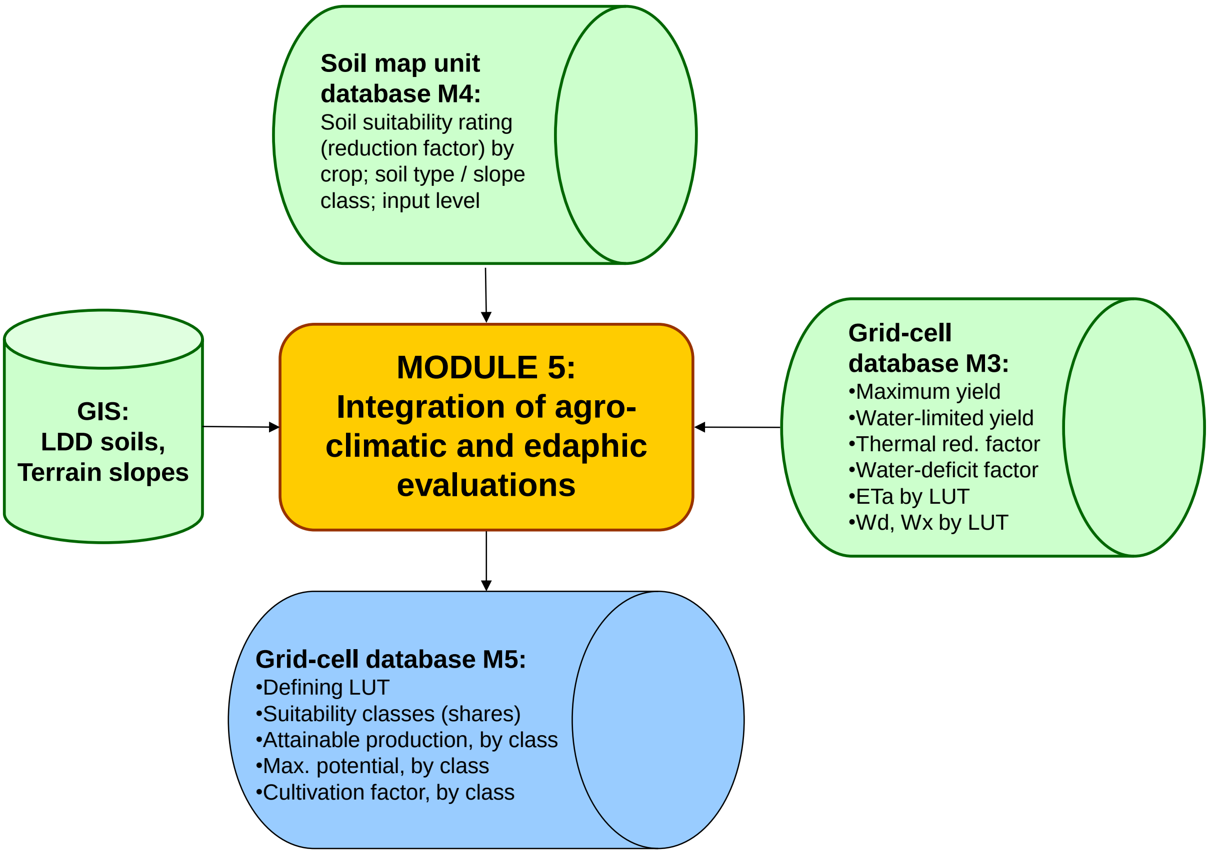


Figure 7-1. Information flow in Module V

7.2 Description of Module 5 outputs

7.2.1 Main processing steps in Module 5

The algorithm in Module 5 steps through the grid cells of the spatial soil association layer of the LDD soil database for Thailand and determines for each grid cell the respective make-up of land units in terms of soil types and slope class. 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 3 arc-second grid cells. As a result, information stored for 3 arc-second grid cells contains aggregate distributions of the individual sub-grid evaluations.

The main purpose of Module 5 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 eight rain-fed and three irrigated soil AWC classes (from Module 2/3);
- Applying reduction factors due to edaphic evaluation for the specific combinations of soil types and slopes making up a grid-cell; and
- Aggregating results over component land units (components of soil group associations).

7.2.2 Module 5 outputs

The results of crop evaluations in Module 5 are stored as a number of separate databases each organized by grid cells. Separate files were generated by crop and water supply system and scenario/time period, with each file containing sub-grid distribution information in terms of suitable extents and potential production by suitability classes. Details of the content of Module 5 binary crop databases are provided in Appendix 7.

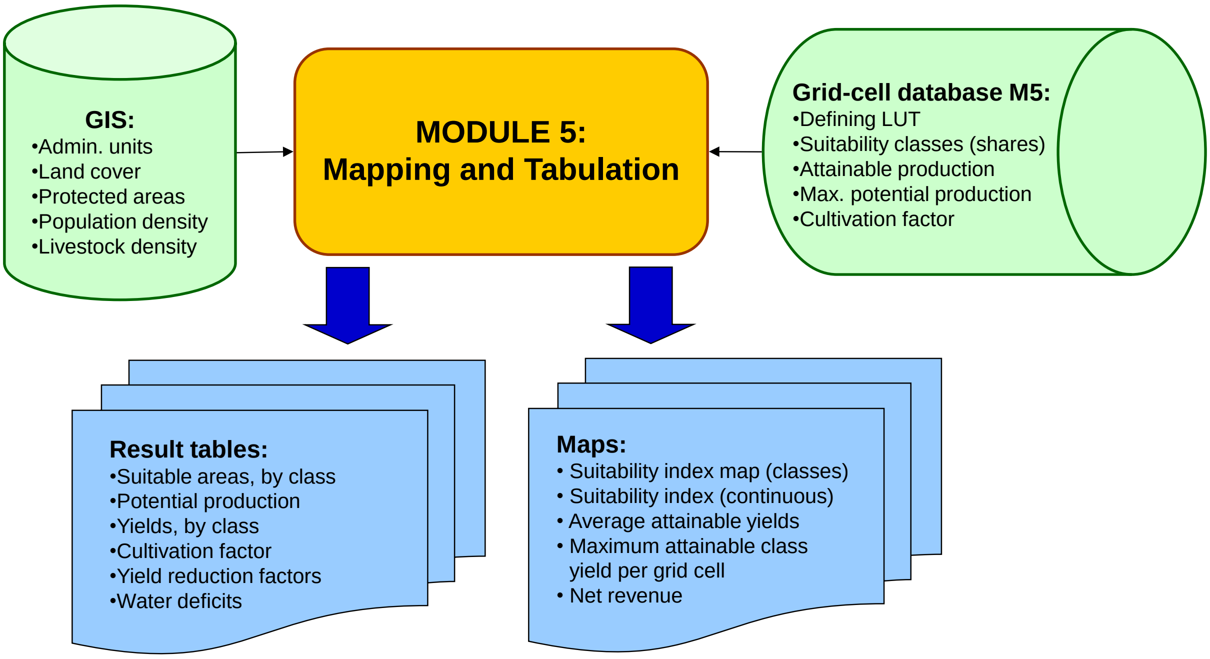


Figure 7-2. Mapping and Tabulation in Module 5 results

Various utility programs have been developed to aggregate and tabulate results by administrative units or to map the contents of Module 5 crop databases in terms of suitability index and potential grid cell output. Figure 7-3 below shows the agro-ecological suitability index and attainable potential crop yield (in kg dry weight per hectare) of rain-fed cassava under advanced input and management conditions in Thailand. Maps produced from Module 5 results include a continuous representation of the calculated suitability index (i.e., a weighted sum of the extents of different suitability classes occurring within a grid cell due to soil associations), a suitability index map in broad classes (see Figure 7-3, left), share of each grid cell assessed as very suitable (VS) or suitable (S), share of each grid cell in the best three classes (very suitable, suitable or moderately suitable), average potential output per unit area of a grid cell, and highest class yield occurring in each grid cell.

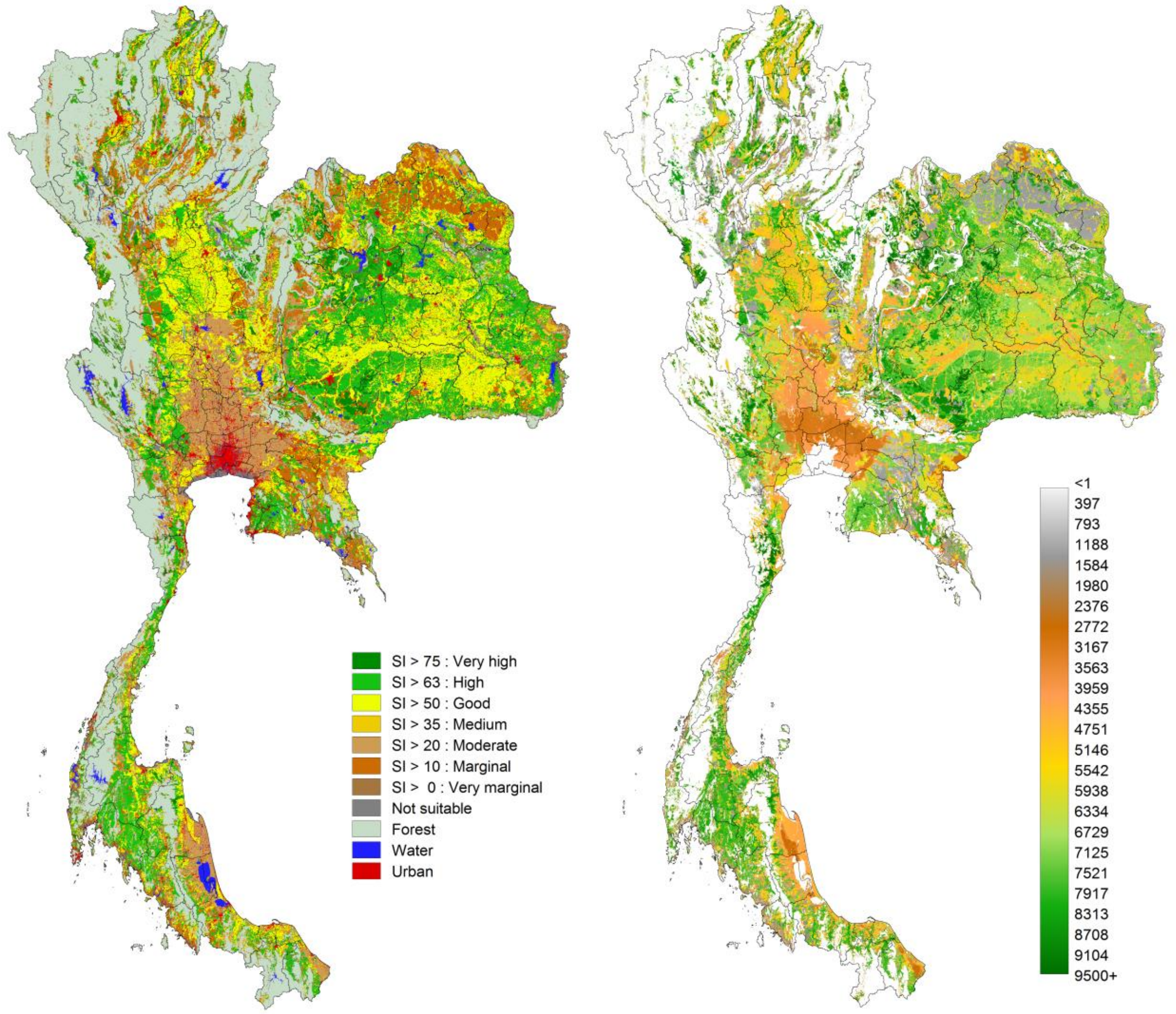


Figure 7-3 Agro-ecological suitability (left) and production potential (right) of cassava

Note: Attainable yields of cassava in the map on the right are given in dry weight (kg dry weight per hectare). For calculation of fresh weight multiply by a factor of 2.86 (assuming a water content for cassava of 65%).

8 Module 6 (Cost of production and Economic suitability)

Module 6 builds on the results of the NAEZ Thailand crop suitability and land productivity assessment. First, Module 6 of the NAEZ Thailand system uses LUT specific production cost functions, where fixed and variable cost components are expressed as linear functions of yield, derived from the statistical information which is representative for the year 2014, and it estimates for each of the economic crops considered in the study the grid-cell specific production cost with respect to the estimated agro-ecological attainable crop yields. Furthermore, using average farm gate prices of 2010-2014, it determines the respective attainable net revenues per unit area.

The different crop-specific results are then used to construct a spatial database showing the 'umbrella' surface of attainable net revenues, which would be obtained for the estimated attainable agro-ecological yields under the assumption that in each grid cell the best performing crop of the eight economic crops considered – rice, maize, cassava, soybean, sugarcane, oil palm, para rubber and coffee - is cultivated. Each of the economic crops is then compared to this umbrella surface in order to indicate and map out its comparative advantage in terms of attainable net revenue relative to the best available option. The general information flow and main results of Module 6 are summarized in Figure 8-1.

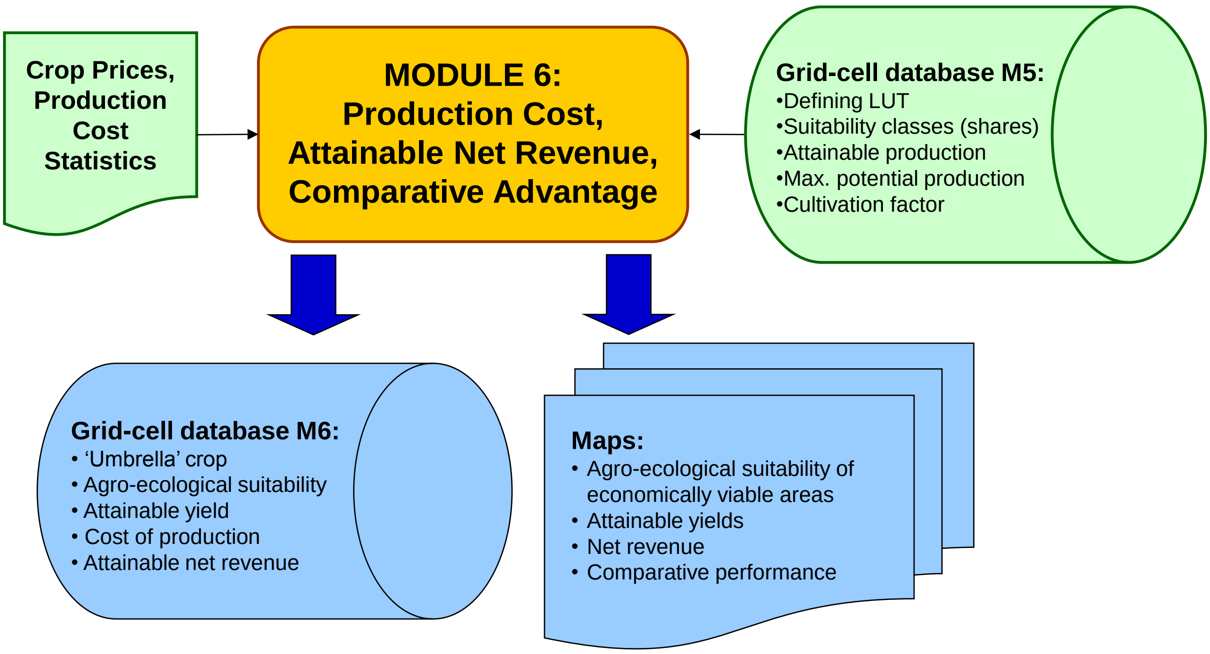


Figure 8-1. Information flow in Module 6 of NAEZ Thailand

8.1 Cost of production and break-even yield

Cost of production data for use in NAEZ-Thailand were compiled by the national economics expert (Apichart 2016). The estimates relate to production conditions in 2014. Data was tabulated for four levels of area classification (S1 = highly suitable; S2 = moderately suitable; S3 = marginally suitable; N = not suitable), providing for each class estimates of variable costs (labor, materials and other) and fixed costs, yields, commodity farm gate prices (average over 2010-2014) and resulting net returns. In order to connect this information with the spatially detailed NAEZ results of crop suitability and land productivity, simple linear regressions were estimated of production cost components, with observed class yield as the independent variable. Figures 8-2 to 8-5 present examples of linear cost functions for major rice, maize, cassava and para-rubber used in the analysis.

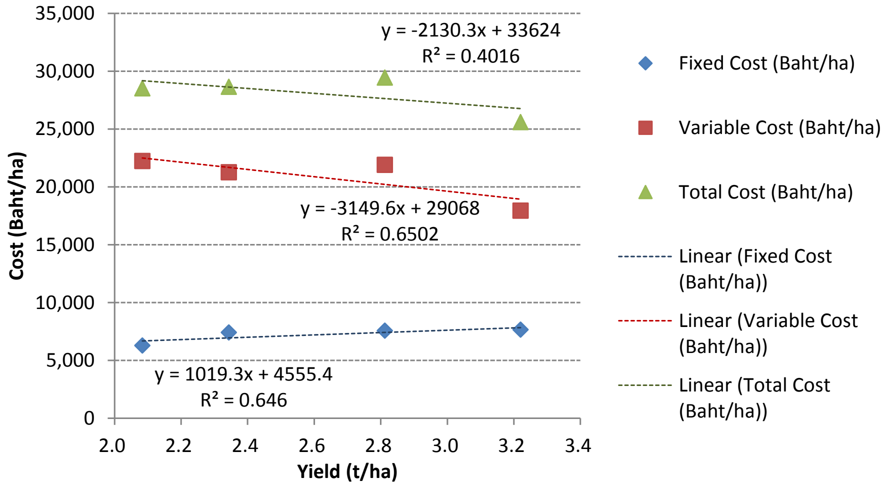


Figure 8-2. Cost of production vs Yield in 2014, Major Rice

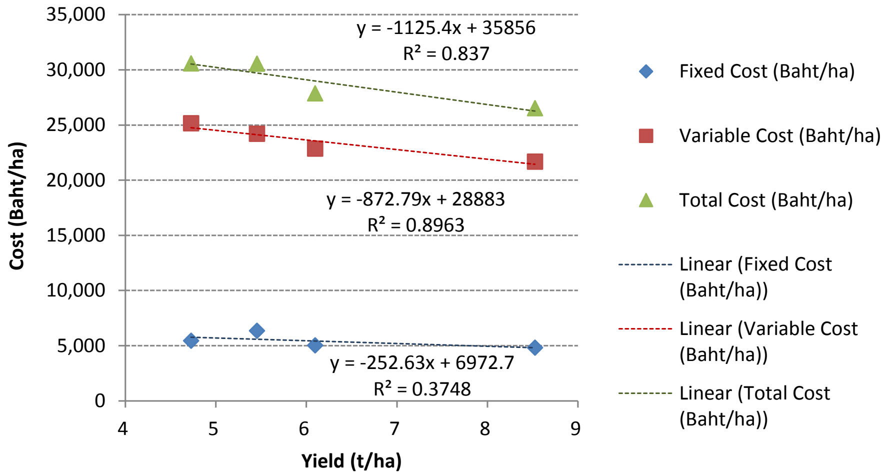


Figure 8-3. Cost of production vs Yield in 2014, Maize

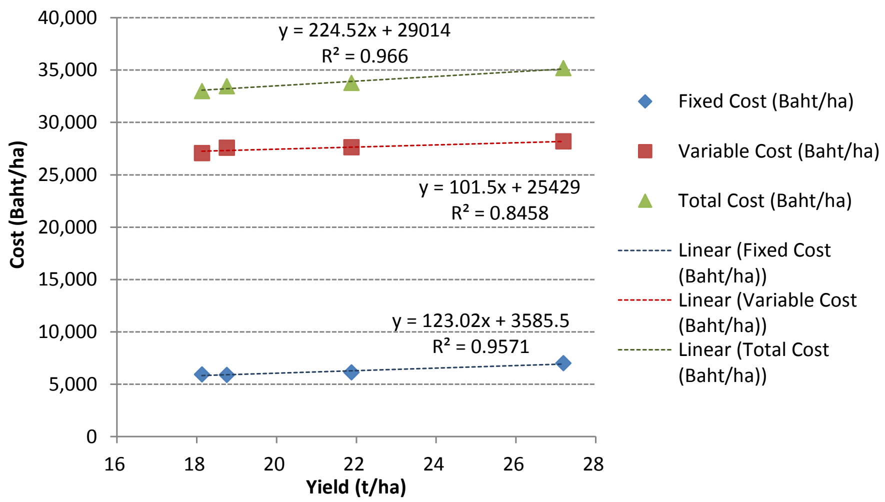


Figure 8-4. Cost of production vs Yield in 2014, Cassava

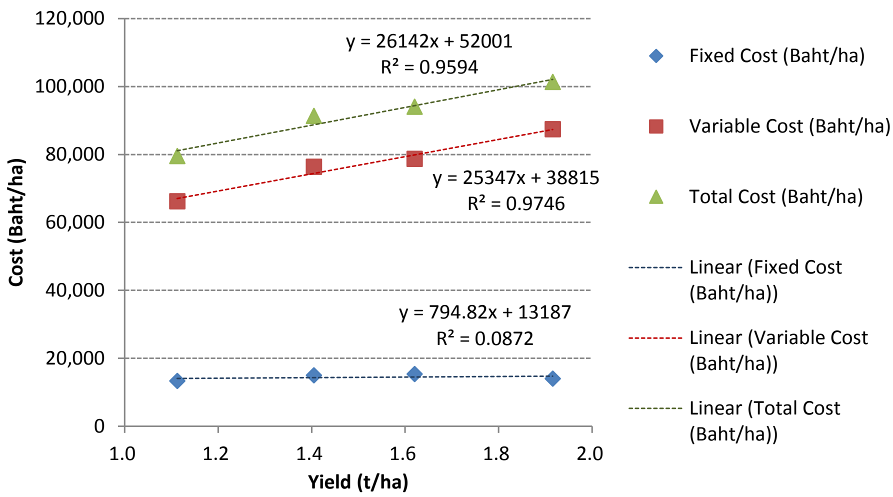


Figure 8-5. Cost of production vs Yield in 2014, Para-rubber

Let Y be the attainable yield, P denotes farm gate price received by farmers, and production cost C (Baht/ha) is expressed as a linear function of yield:

$$C = aY + b$$

Then, a break-even yield Y_{min}, above which a positive net return is achieved, can be calculated by inverting the cost function, as:

$$Y_{min} = \frac{b}{P-a}$$

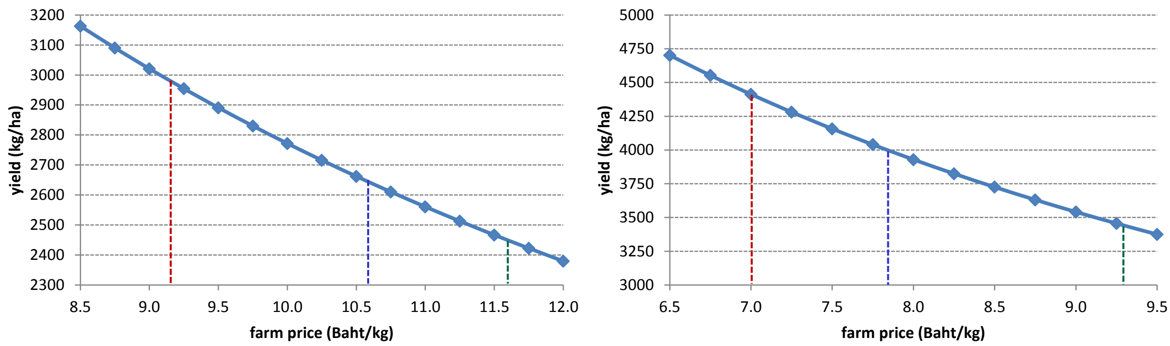


Figure 8-6. Break-even yields at prices received during 2010-2014, Major Rice (left) and Maize (right)

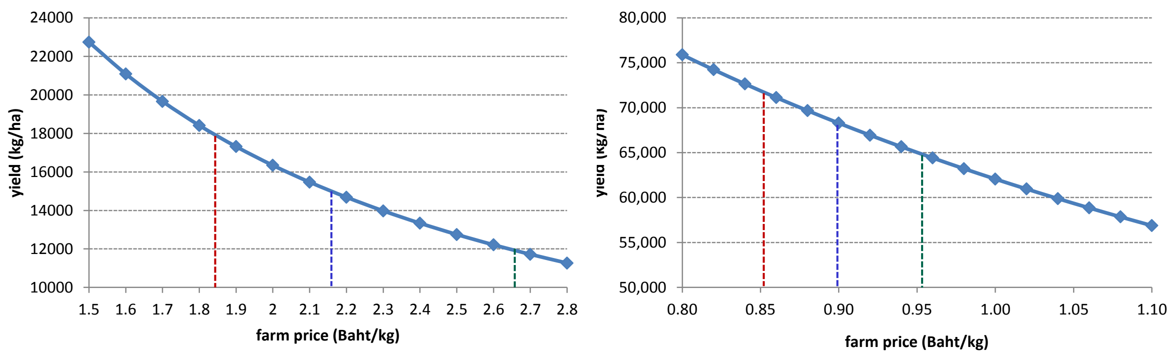


Figure 8-7. Break-even yields at prices received during 2010-2014, Cassava (left) and Sugarcane (right)

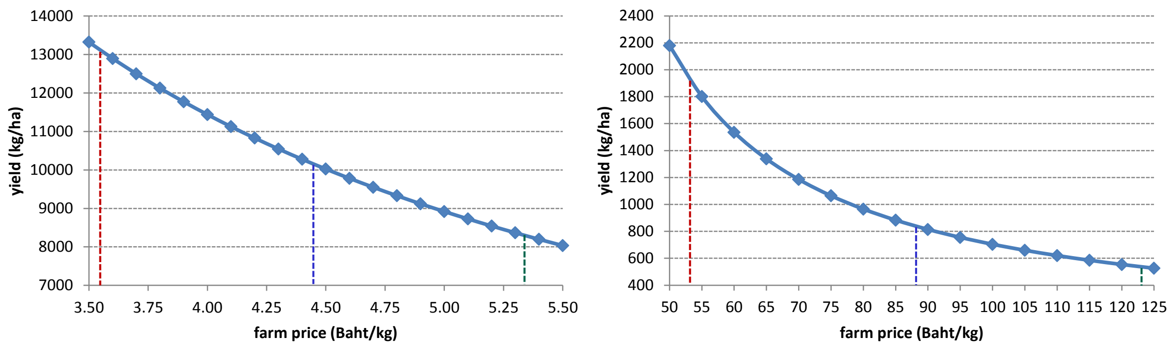


Figure 8-8. Break-even yields at prices of 2010-2014, Oil palm (left) and Para-rubber (right)

Figures 8-6 to 8-8 show for different crops the calculated break-even yields using the production cost relationships estimated for 2014. The diagrams indicate the lowest farm price observed during 2010-2014 (in red), the average price (in blue) and the highest price (in green) from that period. The figures illustrate that prices for some crops – para-rubber, oil palm and cassava – have been quite volatile during recent years. For instance, prices of cassava varied between 1.84 to 2.68 Baht/kg requiring respective break-even fresh weight yields in the range of 18 t/ha to 12 t/ha (or between 6.7 t DW/ha to 4.5 t DW/ha).

Figure 8-6 shows that for an average 2010-2014 rice price of 10.5 Baht/kg the minimum yield required to achieve a non-negative net revenue was about 2650 kg/ha, and for maize the corresponding break-even yield was about 4000 kg/ha. For para-rubber the collected information suggests that break-even yields at 2010-2014 average price is around 830 kg/ha, which is less than half of commercial yields attained in southern Thailand. However, Figure 8-8 also indicates that rubber prices were volatile in this period and that the break-even yield when using the lowest price observed during this 5-year period is as high as 1800 kg/ha, rather close to good commercial yields. A similar, but less pronounced, situation existed for oil palm cultivation (see Figure 8-8). The break-even palm fruit yield at average 2010-2014 price comes to about 10000 kg/ha, less than half of good commercial yields. At lowest observed price during the period this becomes about 13000 kg/ha.

8.2 Attainable net revenue

Based on the spatial evaluation of agro-ecologically attainable yields, the production cost structure of 2014 and using average farm gate prices of 2010-2014, attainable net revenues were calculated for eight major crops – rice, maize, cassava, soybeans, oil palm, para-rubber, sugarcane and coffee. Where production costs exceed gross returns (i.e. price times attainable yield), grid-cells were marked as economically unsuitable for the respective crop. Figure 8-9 shows results for major rice, indicating the agro-ecological suitability for grid cells where attainable net revenues are positive (left map) and estimated attainable net revenues (right map).

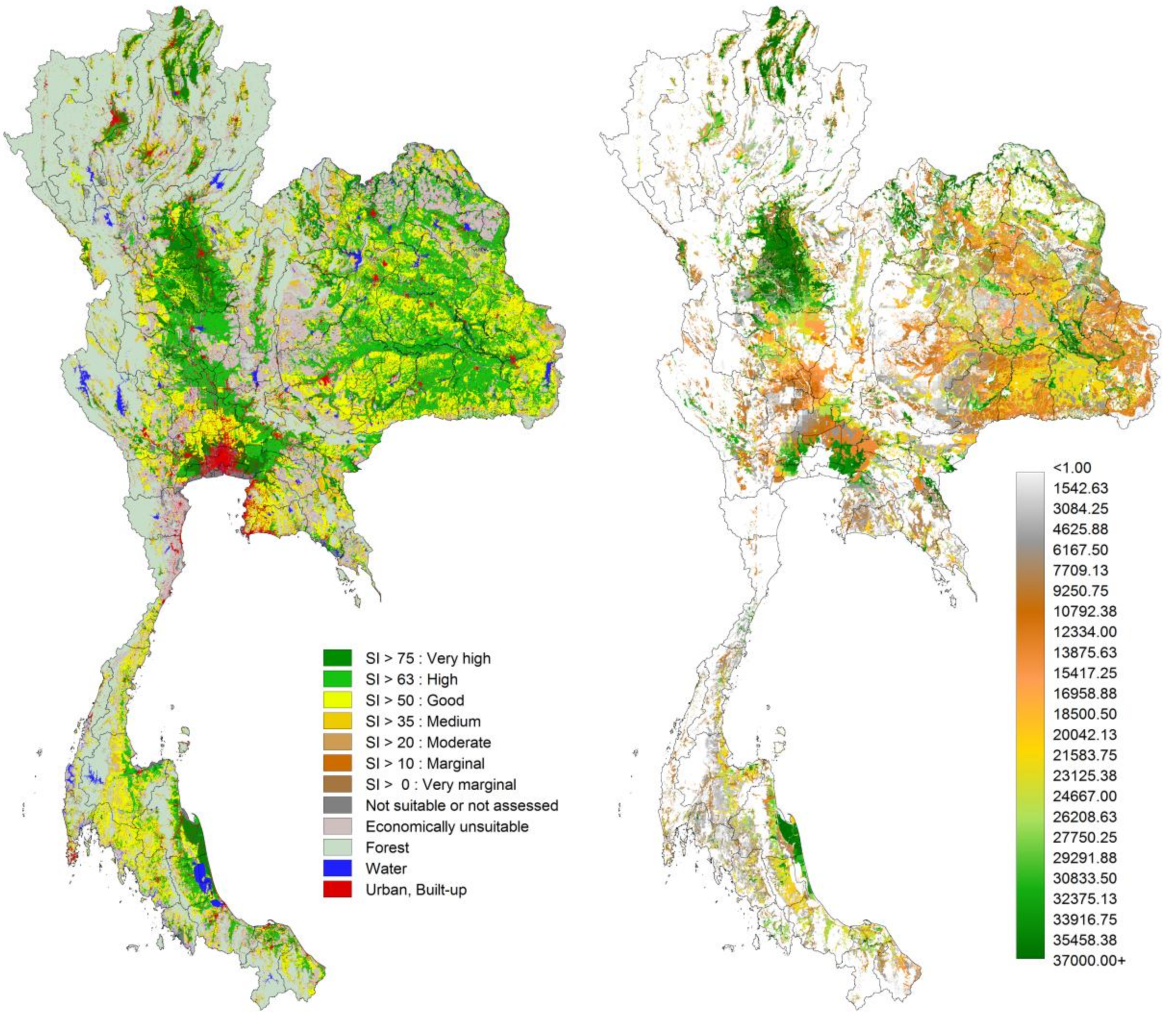


Figure 8-9. Suitability in economically viable areas (left) and potential net revenue (right) of major rice

8.3 Comparative economic performance of major crops

Based on the spatial evaluation of agro-ecologically attainable yields, the production cost structure of 2014 and using average farm gate prices of 2010-2014, attainable net revenues were calculated for eight major crops – rice, maize, cassava, soybeans, oil palm, para-rubber, sugarcane and coffee. Where production costs exceed gross returns (i.e. price times attainable yield), grid-cells were marked as economically unsuitable for the respective crop. Figure 8-9 shows the competitive performance of major rice in comparison to the 'umbrella' crop, which assumes that the best performing crop of the eight economic crops considered is used in each grid cell to define the best attainable net revenue. The result is shown in terms of a few classes denoting ranges of the ratio of each crop's estimated net revenue relative to the best possible net revenue. For instance, for pixels shown in dark green the calculated net revenue of major rice is within 80-100% of the highest value among the eight crops, and in this case rice can be considered as an economically viable option with good comparative advantage. Areas shown in grey mean that major rice is agro-ecologically not suitable or that it is at the estimated attainable yield economically not viable. The results are broadly conditioned by the regional climate and locally determined by soil and terrain characteristics vis-à-vis the soil requirements of major rice and competing economic crops.

Due to ample rainfall, para-rubber and oil palm, and in some locations rice are the most promising crops in southern Thailand. In the flood plans of central Thailand rice is well adapted and performs best among the economic crops considered. Maize, soybean and cassava are often good choices to cultivate on upland soils. The area where rain-fed sugarcane is economically competitive, using average prices of 2010-2014 and the cost structure of 2014, is limited to some locations in northeast and north Thailand. This is due to the fact that high yields of 60 tons per hectare and more are difficult to achieve under purely rain-fed conditions. The competitiveness of sugarcane improves when irrigation is considered (see Figure 8-16). For coffee, agro-ecological suitability of Arabica types is limited to the cooler and wetter parts of northern Thailand. Robusta coffee can be considered in some parts of southern Thailand but expected revenues attainable in this region can hardly compete with other major cash crops such as rubber and oil palm.

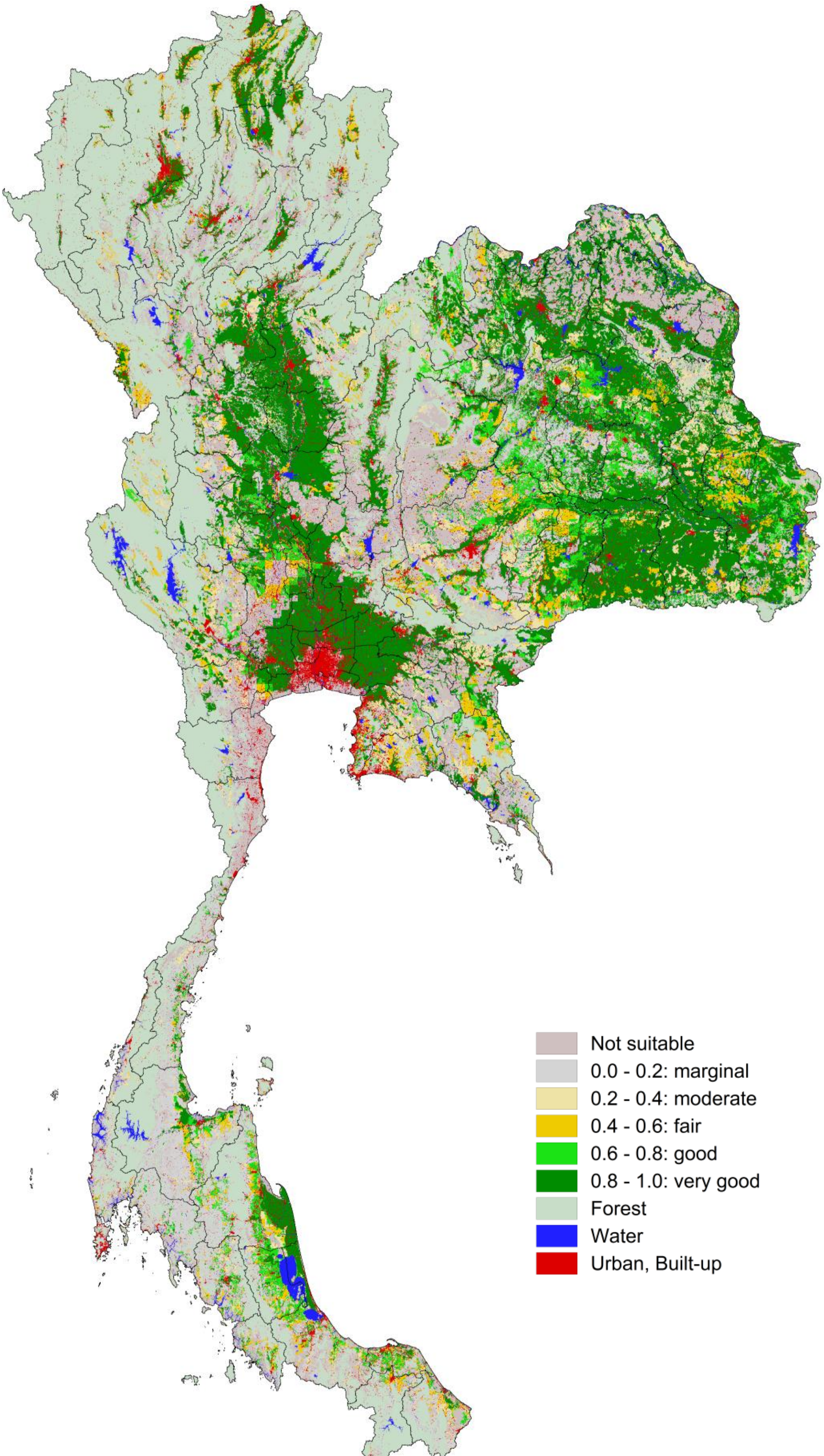


Figure 8-10. Comparative economic performance of major rain-fed rice relative to 'umbrella'

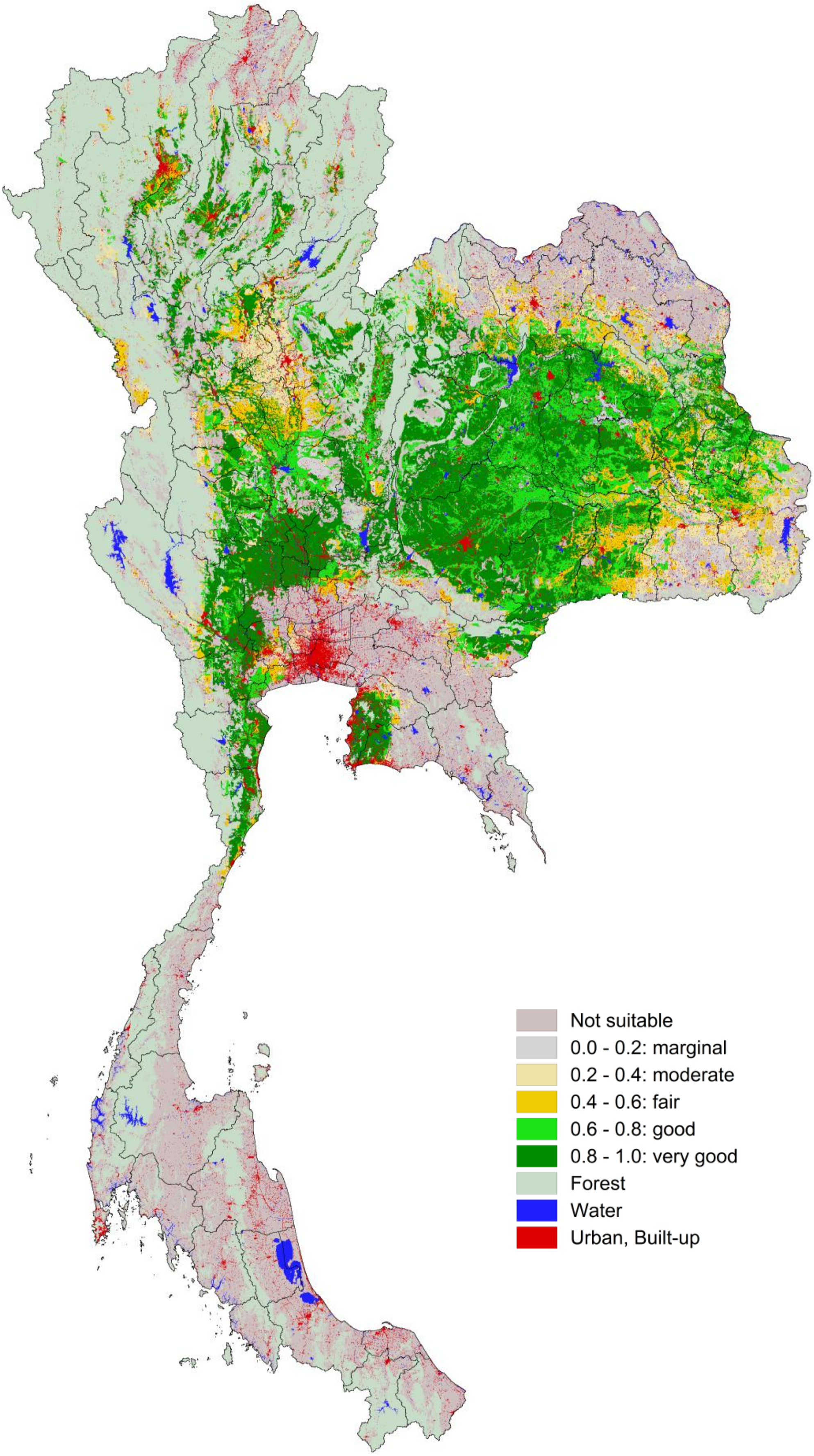


Figure 8-11. Comparative economic performance of rain-fed maize relative to 'umbrella'

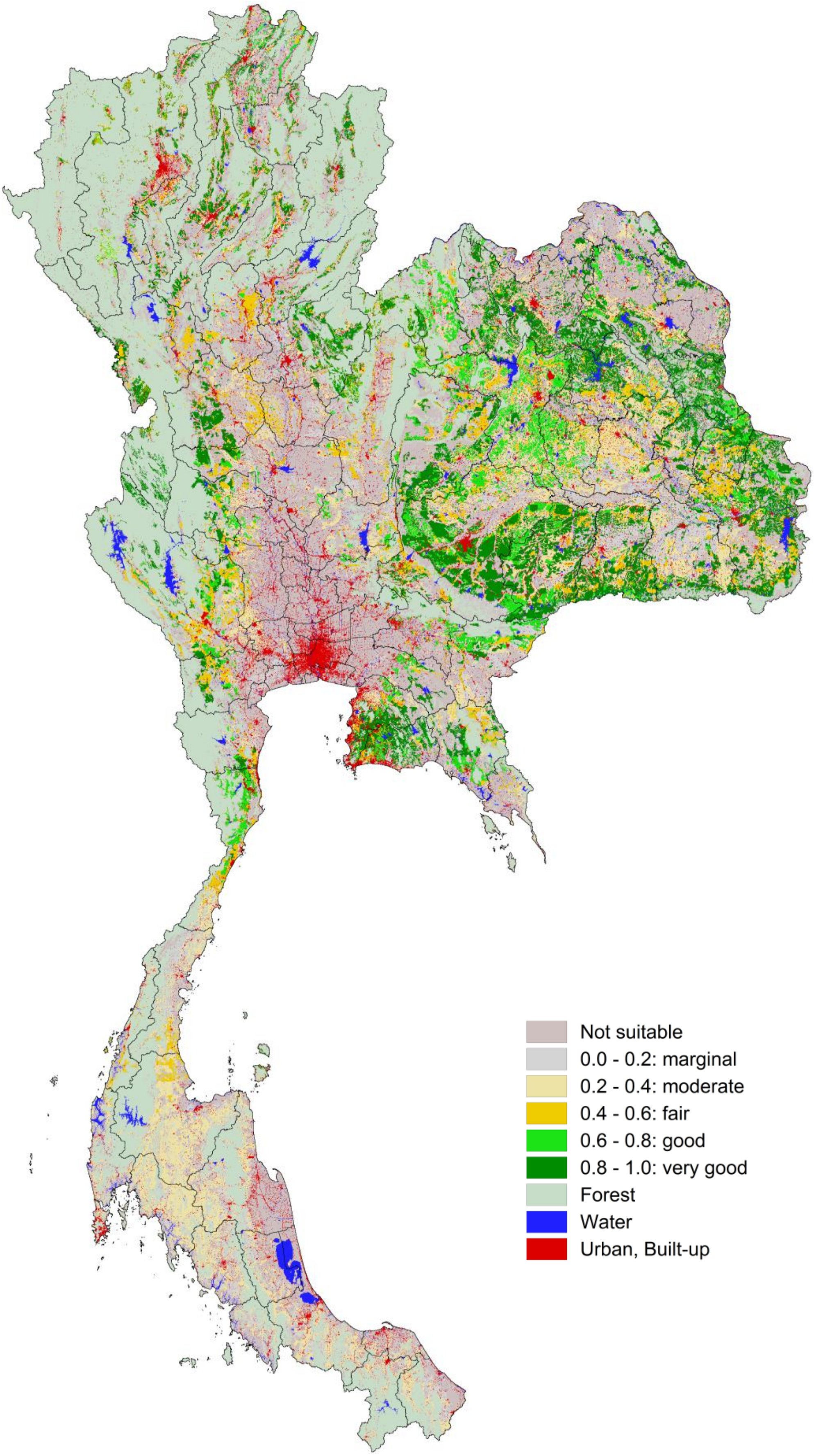


Figure 8-12. Comparative economic performance of rain-fed cassava relative to 'umbrella'

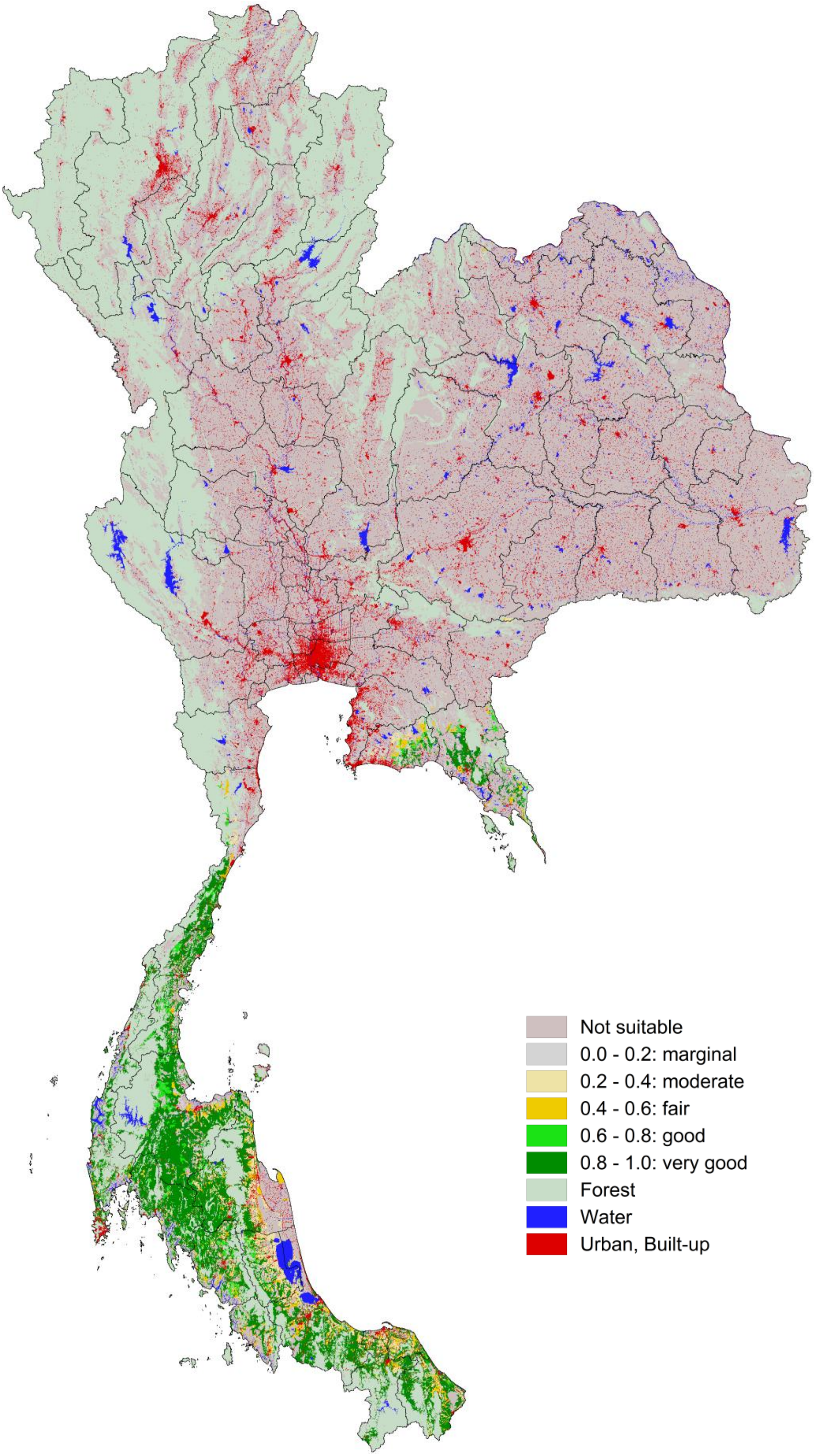


Figure 8-13. Comparative economic performance of rain-fed para-rubber relative to 'umbrella'

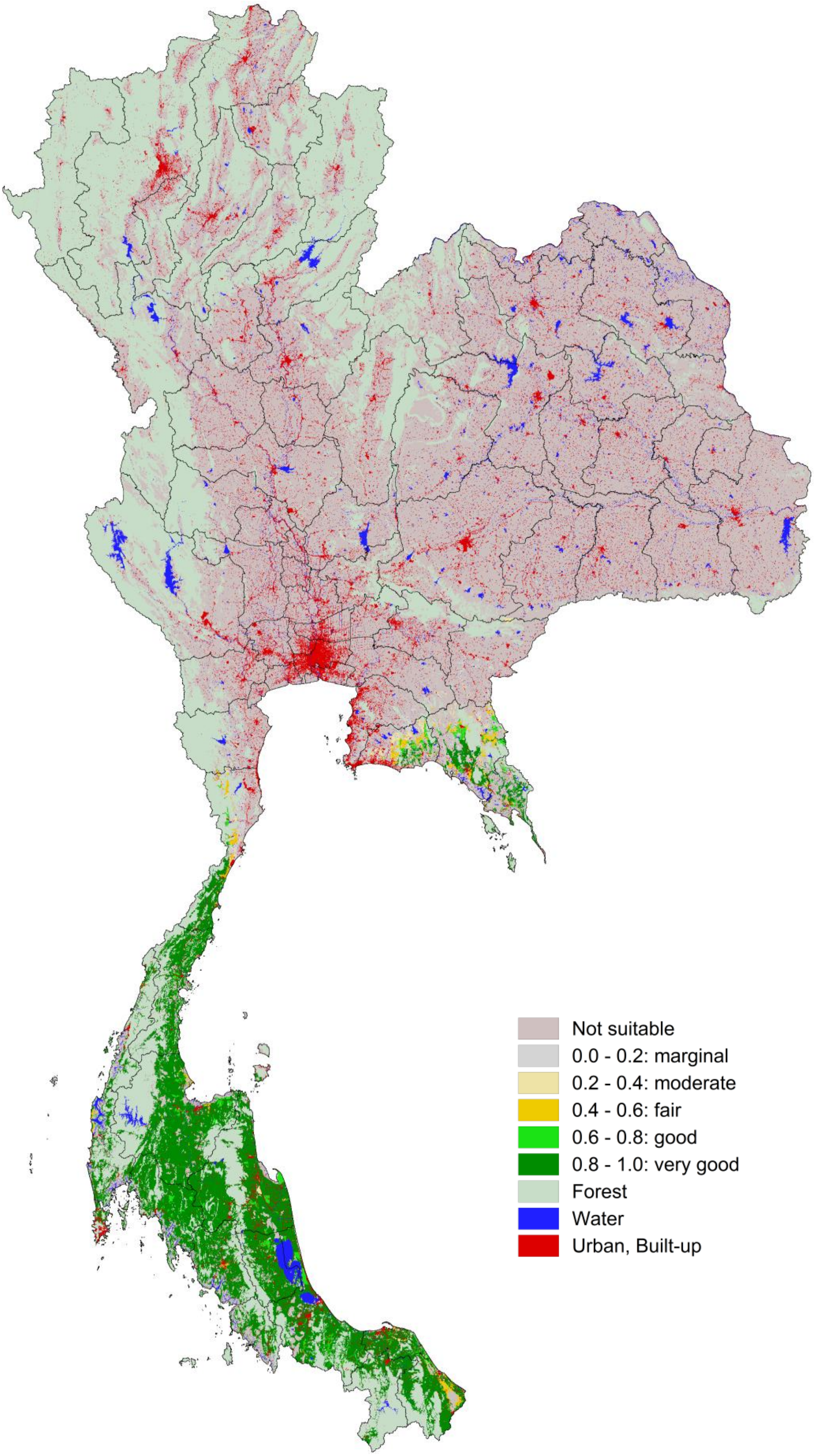


Figure 8-14. Comparative economic performance of rain-fed oil palm relative to 'umbrella'

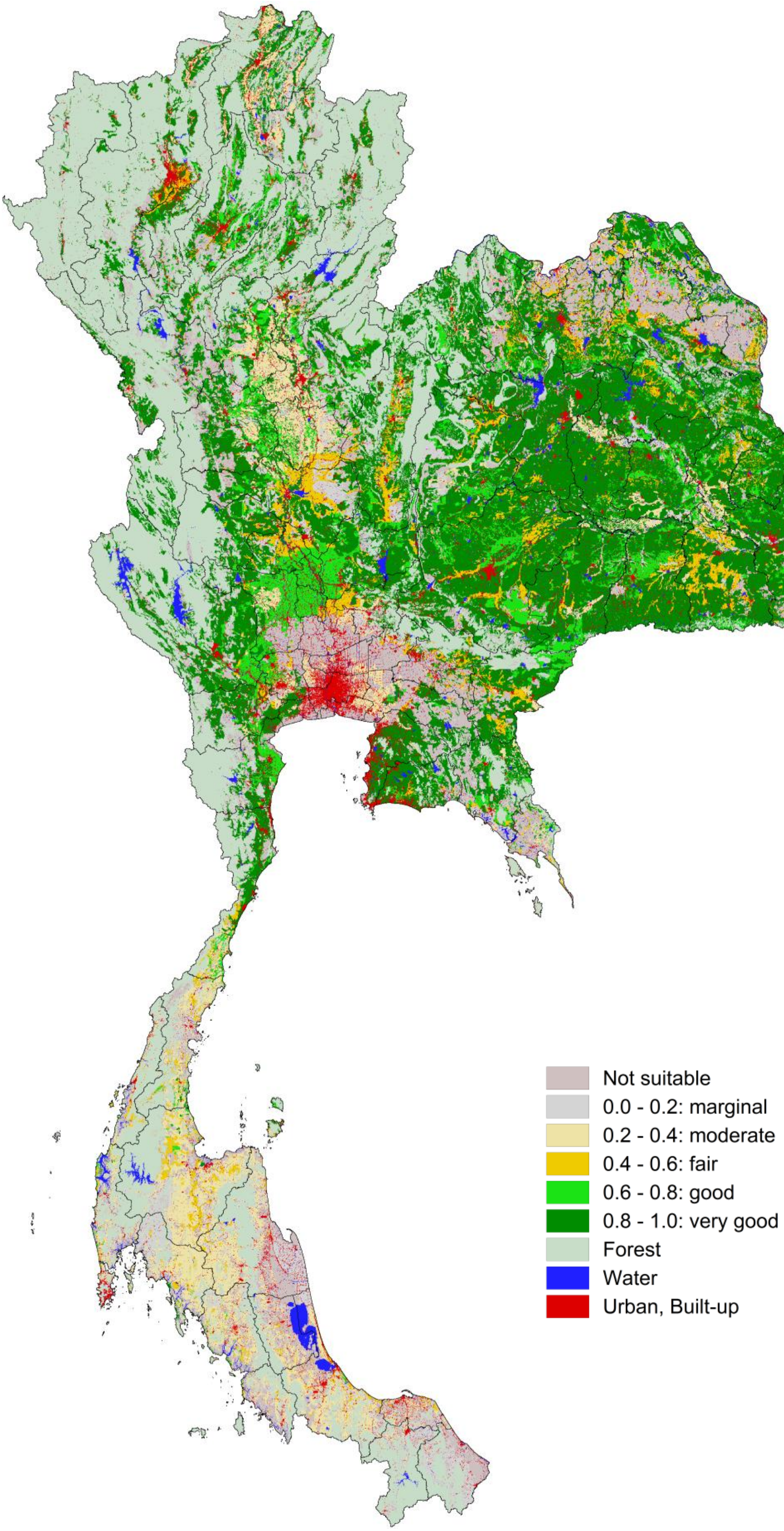


Figure 8-15. Comparative economic performance of rain-fed soybean relative to 'umbrella'

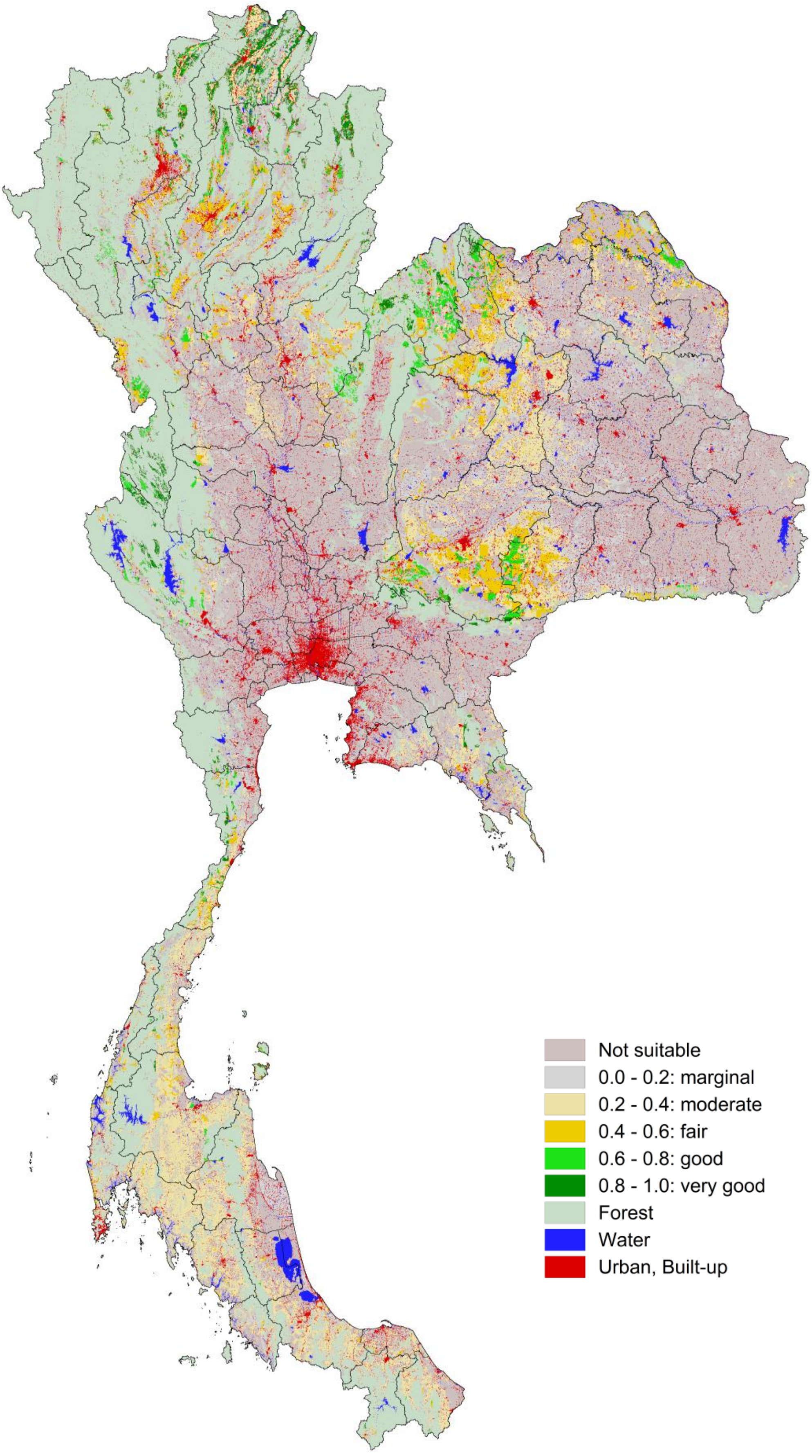


Figure 8-16. Comparative economic performance of rain-fed sugarcane relative to 'umbrella'

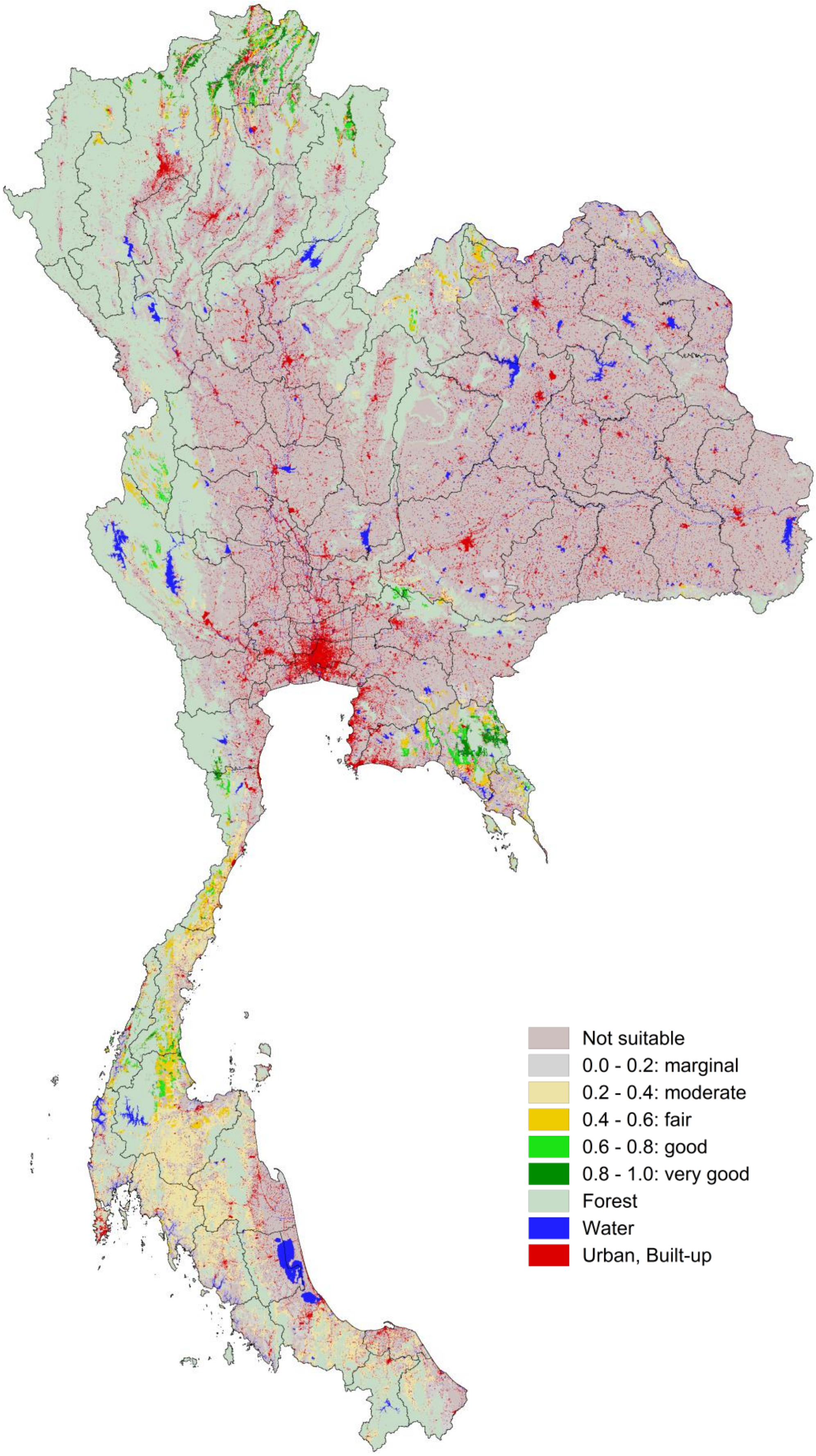


Figure 8-17. Comparative economic performance of rain-fed coffee relative to 'umbrella'

9 Climate change impacts on major economic crops

The global climate is changing and further climate change is unavoidable (IPCC, 2013). The NAEZ Thailand system includes a variety of future climate scenarios and has been used to assess the likely impacts of climate change on the suitability and production potential of major economic crops in Thailand.

9.1 Impact of climate change on agro-ecology indicators

IPCC AR5 (IPCC, 2013) climate model outputs for four Representative Concentration Pathways (RCPs) are used to explore a range of possible future climate changes in Thailand. RCPs are a set of four greenhouse gas concentration trajectories developed for the climate modeling community as a basis for long-term and near-term modeling experiments adopted by the IPCC for its fifth Assessment Report (AR5). The four RCPs together span the range of year 2100 radiative forcing values found in the open literature, i.e. from 2.6 W/m^2 under stringent emission mitigation measures to 8.5 W/m^2 associated with development assumptions of fast and fossil based economic growth. The four RCPs are named after a possible level of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m2, respectively). Climate model simulations based on these RCPs were undertaken as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012).

NAEZ Thailand includes data, bias-corrected and downscaled to 0.5 degree, provided in the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013). ISI-MIP data at 0.5 degree resolution of five climate models (GFDL-ESM2M, HadGEM3-ES, IPSL-CM5A-LR, MIROC-ESM, NorESM1-M) and for four RCPs (RCP 2.6, 4.5, 6.0 and 8.5) – a total of 20 combinations of respectively RCPs and climate models - were used for generating climate input data in AEZ for the 2020s (period 2011-2040), 2050s (period 2041-2070) and the 2080s (period 2070-2099).

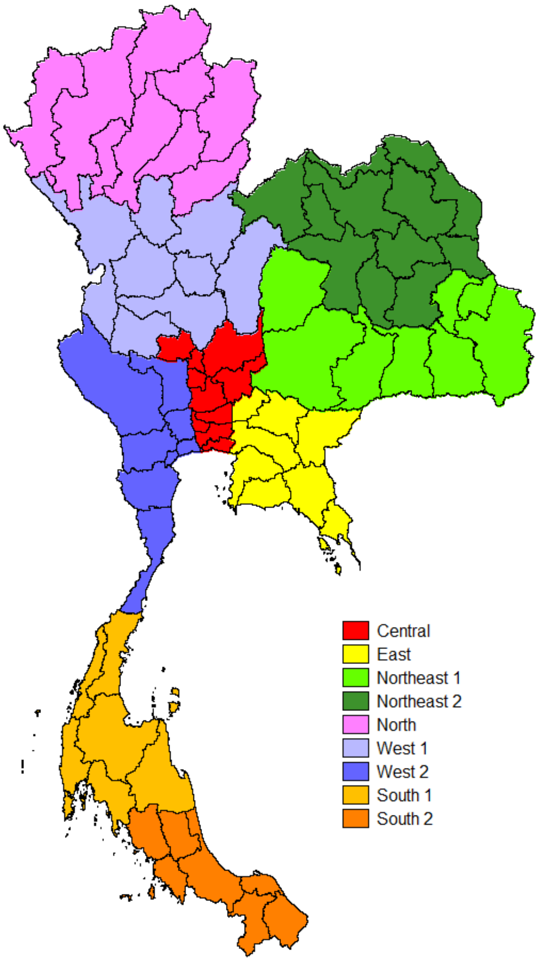


Figure 9-1. Regions of Thailand

For the presentation of tabular results we use a regionalization with nine broad regions as shown in Figure 9-1.

Mean annual temperature of cropland (grid cells classified as paddy land, annual field crops, perennial crops, horticulture and orchards) during the historical reference period 1981-2010 (the 1990s) and projected changes for the 2050s (period 2041-2070) and the 2080s (i.e. 2070-2099) is summarized in Table 9-1 in terms of the deviations of the ensemble means for the five climate models over each period and for the four RCPs.

Mean annual temperature in 1981-2010 is calculated as 27.2°C. The deviations of the 2050s ensemble mean fall in the range of 1.3°C (RCP2.6) to 2.4°C (RCP8.5). For the 2080s the range widens to 1.3°C (RCP2.6) to 4.0°C (RCP8.5).

The temperature change is larger than average in the northern and northeastern parts of Thailand and below average in southern Thailand.

Table 9-1. Mean annual temperature and temperature changes* by region (°C)

REGION	1981-2010	Temperature change in 2050s (°C)				Temperature change in 2080s (°C)			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Central	28.2	1.2	1.7	1.6	2.3	1.3	2.2	2.4	4.0
East	28.1	1.1	1.6	1.5	2.2	1.2	2.1	2.3	3.8
Northeast 1	27.4	1.3	1.8	1.6	2.4	1.4	2.3	2.5	4.1
Northeast 2	26.8	1.3	1.8	1.6	2.5	1.3	2.3	2.5	4.1
North	25.7	1.3	1.8	1.6	2.5	1.4	2.3	2.5	4.1
West 1	27.2	1.4	1.8	1.7	2.5	1.5	2.3	2.6	4.1
West 2	27.7	1.2	1.6	1.5	2.2	1.2	2.0	2.3	3.8
South 1	27.2	1.0	1.4	1.3	2.0	1.0	1.8	2.0	3.4
South 2	27.6	0.9	1.3	1.2	1.8	0.9	1.6	1.9	3.2
TOTAL	27.2	1.3	1.7	1.6	2.4	1.3	2.2	2.4	4.0

* Ensemble mean over 5 GCMs and 30-year periods of respectively 2041-2070 and 2070-2099

Precipitation over cropland in Thailand was on average about 1500 mm during 1981-2010, ranging from about 1200 mm in the central region and northeastern regions, to more than 2000 mm in southern Thailand (Figure 9-2). Overall, precipitation in Thailand may very slightly increase with climate change, yet with negative deviations from historical averages in northeastern Thailand and the largest increases of precipitation in the South.

Table 9-2. Mean annual precipitation (mm) and precipitation changes* by region

REGION	1981-2010	Precipitation change in 2050s (Δ %)				Precipitation change in 2080s (Δ %)			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Central	1194	0.6	3.9	-3.1	2.6	-0.4	4.0	0.2	5.8
East	1706	1.1	2.5	-4.2	0.6	-0.7	1.3	-1.7	1.7
Northeast 1	1368	-1.4	1.0	-4.3	-0.1	-1.3	1.7	-1.3	0.9
Northeast 2	1607	-3.6	-1.1	-5.7	-1.7	-2.3	0.6	-2.5	-2.1
North	1283	-0.3	4.9	-0.1	4.6	1.7	9.4	4.5	8.3
West 1	1231	-1.4	3.0	-2.8	2.8	-0.2	5.2	0.3	5.7
West 2	1232	2.9	6.0	-2.3	4.0	1.8	5.2	1.5	7.9
South 1	2173	6.9	8.4	2.5	6.5	6.4	3.1	4.3	7.2
South 2	2024	8.6	9.2	5.5	8.6	8.2	5.3	7.6	9.0
TOTAL	1509	0.5	3.0	-2.4	2.0	0.7	3.0	0.5	3.2

* Ensemble mean over 5 GCMs and 30-year periods of respectively 2041-2070 and 2070-2099

Table 9-3. Mean annual reference evapotranspiration (mm) and ET0 changes* by region

REGION	1981-2010	ET0 changes in 2050s (Δ %)				ET0 change in 2080s (Δ %)			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Central	1575	3.8	3.6	4.2	6.7	4.3	6.4	8.1	13.2
East	1475	3.9	4.2	4.5	6.4	4.3	7.3	7.4	12.2
Northeast 1	1575	3.3	4.0	3.7	7.0	3.6	6.8	7.6	13.8
Northeast 2	1559	3.4	4.4	3.7	7.6	3.9	7.2	8.1	14.8
North	1380	4.7	5.4	4.2	7.7	5.7	7.2	7.8	13.5
West 1	1477	4.6	4.7	4.6	7.6	5.4	6.9	8.6	13.6
West 2	1451	5.0	5.0	5.4	7.7	5.6	7.6	8.6	13.3
South 1	1360	2.1	3.1	2.8	4.5	2.4	4.9	4.7	8.4
South 2	1345	2.5	4.0	2.7	4.5	3.3	4.9	4.6	7.8
TOTAL	1496	3.7	4.3	3.9	6.9	4.2	6.8	7.6	13.1

* Ensemble mean over 5 GCMs and 30-year periods of respectively 2041-2070 and 2070-2099

Taking the ensemble mean of climate attributes as projected by five major GCMs and calculating reference potential evapotranspiration suggests that the annual balance of incoming precipitation to evaporative demand of vegetation (i.e. potential evapotranspiration) is likely to worsen by the 2050s (period 2041-2070) and beyond compared to reference period 1981-2010. Annual reference evapotranspiration of cropland in Thailand is estimated at about 1500 mm in 1981-2010. With climate change, reference evapotranspiration is expected to increase by 2% (RCP 2.6, South Thailand) to 8% (RCP 8.5, northeast Thailand) in the 2050s and by 2.5% to 15% in the 2080s, which is clearly more than the projected changes in precipitation. The results is a worsening of the annual P/ET0 ratio, an indication that drought periods may occur more frequently.

Table 9-4. Mean annual P/ET0 ratio (%) and changes* by region

REGION	1981-2010	P/ET0 changes in 2050s (Δ %)				P/ET0 changes in 2080s (Δ %)			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Central	76	-2.9	0.4	-6.9	-3.4	-4.2	-2.1	-7.0	-5.9
East	117	-2.6	-1.8	-8.3	-5.5	-4.9	-5.6	-8.2	-9.0
Northeast 1	87	-4.2	-2.8	-7.3	-6.3	-4.6	-4.5	-7.7	-10.6
Northeast 2	104	-6.7	-5.5	-8.8	-8.6	-6.1	-5.9	-9.5	-14.2
North	93	-4.4	-0.4	-4.0	-2.7	-3.6	2.4	-2.7	-4.1
West 1	84	-5.6	-1.7	-6.9	-4.3	-5.2	-1.4	-7.4	-6.3
West 2	86	-1.9	0.9	-7.3	-3.4	-3.6	-2.2	-6.3	-4.3
South 1	160	4.6	5.1	-0.3	1.9	3.8	-1.8	-0.3	-0.8
South 2	151	6.0	5.0	2.7	3.9	4.7	0.3	3.1	1.3
TOTAL	102	-2.5	-1.0	-5.7	-4.0	-3.0	-3.1	-5.8	-7.4

* Ensemble mean over 5 GCMs and 30-year periods of respectively 2041-2070 and 2070-2099

Table 9-4 reveals that projected drying is most pronounced in northeast Thailand. While annual P and ET0 are roughly balanced for this region in the historical reference period, the ratio decreases in the 2080s by -6% to -14% in the region Northeast 2 and by -5% to -11% in the region Northeast 1. Conversely, in the south of Thailand an already high annual P/ET0 ratio even increases.

Table 9-5. Number of growing period days and changes* by region

REGION	1981-2010	LGP changes in 2050s (Δ days)				LGP changes in 2080s (Δ days)			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Central	234	-19	-9	-21	-15	-17	-13	-24	-15
East	264	-21	-18	-31	-25	-22	-27	-36	-23
Northeast 1	238	-22	-17	-28	-25	-21	-22	-27	-24
Northeast 2	236	-23	-23	-32	-30	-23	-25	-29	-28
North	245	-22	-17	-27	-27	-20	-17	-19	-21
West 1	234	-24	-17	-25	-20	-21	-19	-24	-19
West 2	248	-15	-11	-20	-14	-18	-15	-23	-12
South 1	330	-7	-13	-16	-17	-10	-12	-19	-20
South 2	340	-6	-14	-11	-16	-9	-9	-16	-19
TOTAL	254	-20	-17	-26	-23	-20	-20	-26	-22

* Ensemble mean over 5 GCMs and 30-year periods of respectively 2041-2070 and 2070-2099

Soil moisture conditions of rain-fed cropland are also well reflected by the agro-ecology indicator 'number of growing period days', which counts the days during a year when both temperature and soil moisture permit crop growth. For the reference period 1981-2010, the average number of growing period days aggregated over all cropland is 254 days, ranging from 234 days in the central region to 340 days in the south. These numbers are becoming less in all climate change scenarios (see Table 9-5) due to increasing reference evapotranspiration (Table 9-3) as well as changes in precipitation amounts and distribution (Table 9-2), with negative impacts in particular for the rain-fed cultivation of perennial crops (rubber, oil palm, coffee) or long cycle crops (e.g. cassava and sugarcane) in the central and northeastern regions of the country.

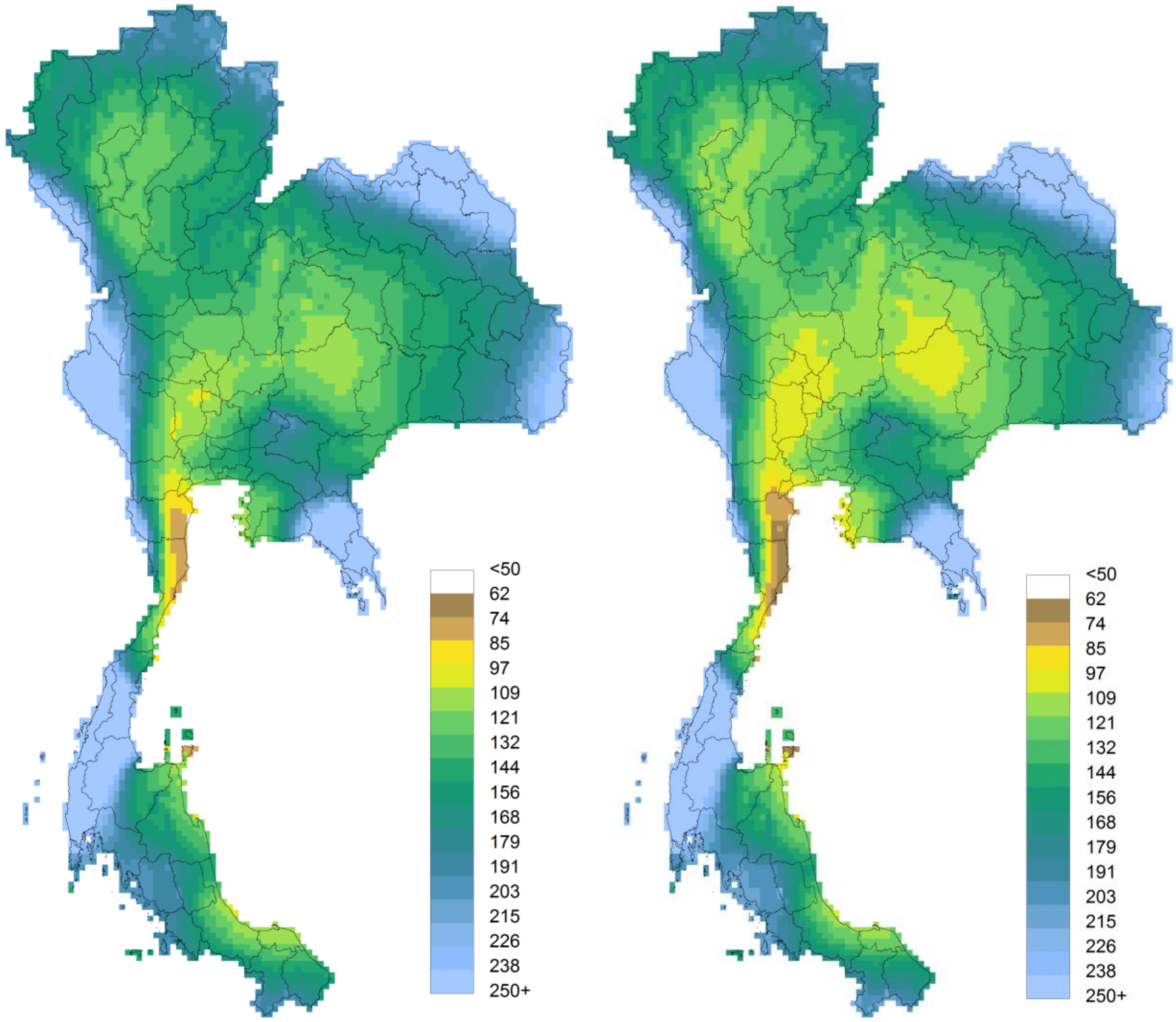


Figure 9-1. Apr-Sep P/ET_0 ratio for period 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

Annual field crops require only 4-5 months for their cultivation. Therefore, in Figure 9-1 we show for the six-month period of April to September, which includes the main rain-fed growing season, the P/ET0 ratios of respectively the reference period 1981-2010 and of the ensemble mean of five GCMs under RCP6p0 for the 2050s (period 2041-2070). As pointed out above in the discussion of Table 9-4 for the year-round conditions, the figure confirms some worsening of the water balance also during the wet season. In the maps of Figure 9-1 this noticeable especially in central and northeast Thailand.

A similar trend of gradual drying is clearly also visible for the months of October to March into which the dry season falls (see Figure 9-2). For these months incoming precipitation in central, north and northeast Thailand is traditionally well below potential evapotranspiration. Hence supplementary irrigation is needed to meet full crop water requirements during the dry season for perennial crops or where a second annual crop is cultivated under multi-cropping.

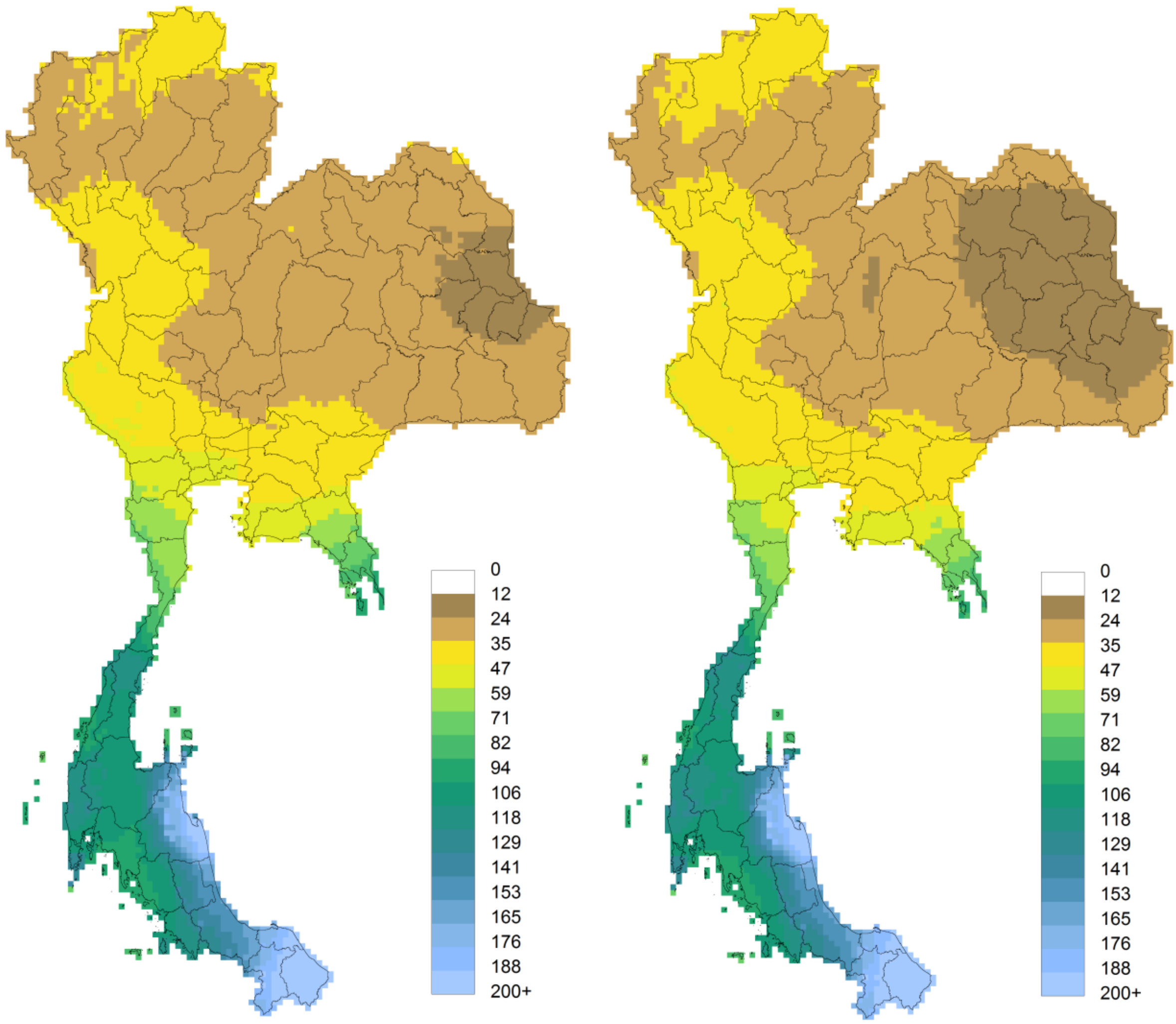


Figure 9-2. Oct-Mar P/ET_0 ratio for period 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

9.2 Impact of climate change on crop suitability and yields

In the previous section the impacts of climate change on general agro-climatic indicators was presented. Here we discuss results concerning rain-fed cultivation of major economic crops. For some annual field crops the estimated future potential yield can be maintained or may even increase due to atmospheric CO2 enrichment, the so-called CO2 fertilization effect, which may results in substantial yield increases especially for crops with the C3 photosynthesis pathway. For comparison, results were also produced without taking CO2 fertilization into account.

For perennial crops, the projected drier future conditions are likely to depress rain-fed yields (e.g. para-rubber, oil palm) and will reduce extents of suitable areas, especially so in the dryer regions of central and northeast Thailand. Also, crops occupying narrow ecological niches or requiring cooler conditions for high quality yields (e.g. Arabica coffee or sugarcane) will be negatively affected by both warming and drying.

Table 9-6 summarizes the results obtained using the ensemble means of simulation results with five GCMs for the period 2041-2070 under RCP 6.0. The table indicates the extents of prime (VS+S) and good (VS+S+MS) land assessed for the historical reference period 1981-2010 and shows percentage changes of suitable extents and estimated potential production in the 2050s, with and without considering yield increases due to elevated atmospheric CO2 concentrations.

Table 9-6. Impact of climate change on crop suitability and potential production

	Reference 1981-2010		Ensemble mean RCP6.0, 2050s with CO2 fertilization			Ensemble mean RCP6.0, 2050s without CO2 fertilization		
	VS+S mill. ha	VS+S+MS mill. ha	VS+S (Δ %)	VS+S+MS (Δ %)	Potential prod. (Δ %)	VS+S (Δ %)	VS+S+MS (Δ %)	Potential prod. (Δ %)
Major rice	10.1	17.9	-12.0	-4.4	-10.0	-34.3	-13.0	-16.8
Maize	8.9	15.6	35.0	6.9	8.1	19.1	6.0	4.1
Soybean	5.8	16.7	2.4	0.4	-1.1	-9.0	-4.3	-9.7
Cassava	8.8	17.5	-55.4	-25.0	-19.9	-70.8	-33.8	-25.8
Sugarcane	1.1	11.8	-82.5	-76.6	-32.0	-94.5	-78.0	-34.1
Oil palm	2.6	3.2	-26.4	-6.5	-49.0	-39.4	-9.9	-53.0
in South	2.5	2.8	-26.0	-6.1	-12.8	-37.9	-8.6	-19.7
Rubber	1.7	2.9	-20.6	-19.9	-55.0	-28.8	-27.2	-58.5
in South	1.6	2.5	-17.5	-11.4	-11.9	-25.4	-19.4	-18.7
Coffee	0.5	2.4	-96.6	-98.1	-97.5	-98.5	-98.3	-97.7
All 8 crops*	16.9	19.9	-3.7	-0.8	-9.6	-15.5	-2.6	-23.7

Note: VS=very suitable, S=suitable, MS=moderately suitable; * 'Umbrella' of crops giving highest net revenue

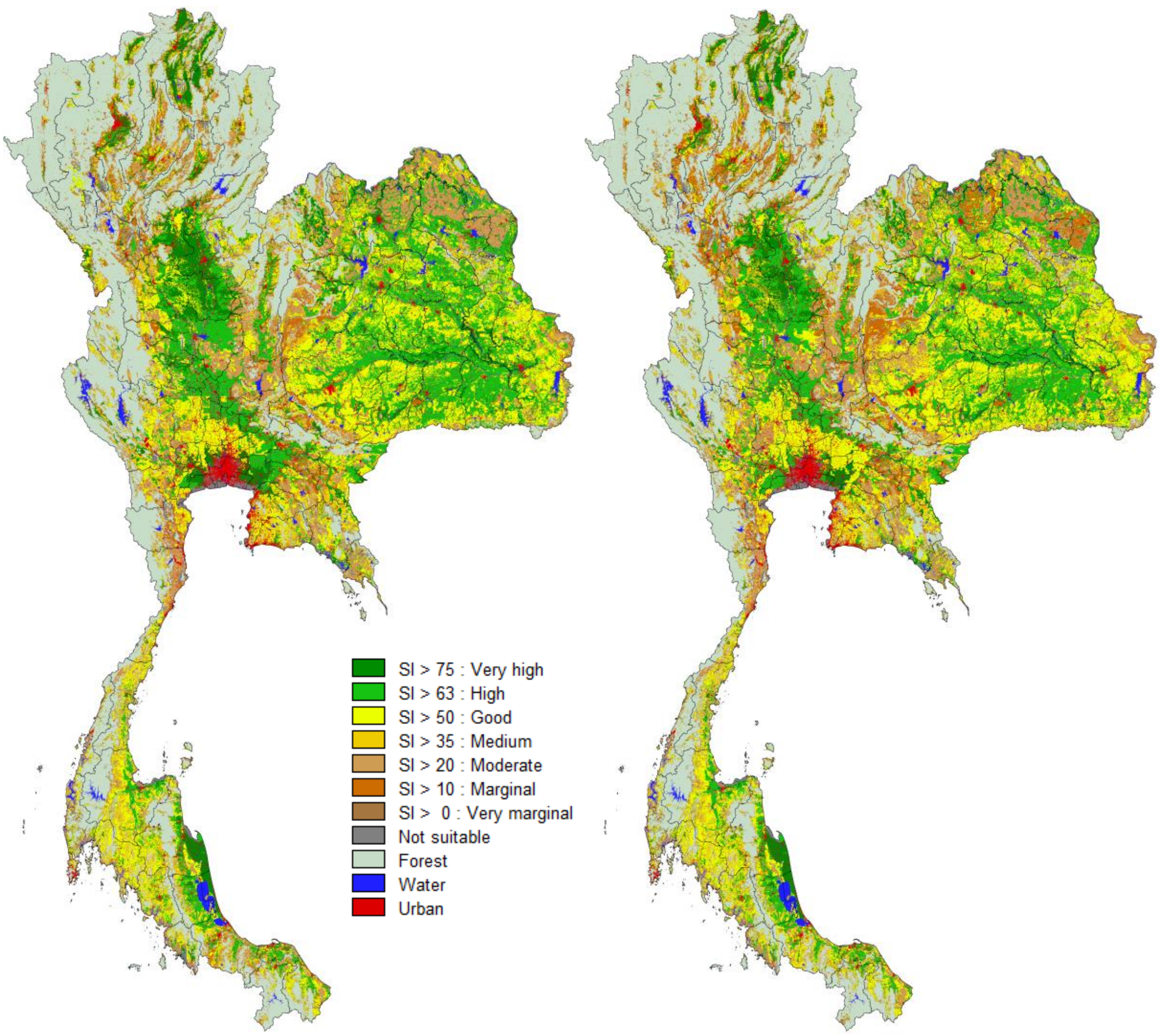


Figure 9-3. Suitability of rain-fed major rice in 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

Figure 9-3 shows suitability of rain-fed major rice under historical climate of the period 1981-2010 (left) and suitability of simulated ensemble mean of period 2041-2070 under the RCP 6.0 concentration pathway (right). Figure 9-4 provides the same kind of information for cassava.

Results for major rice indicate a gradual decrease of rain-fed suitability and a modest loss of rice production potential. The data compiled in Table 9-6 suggest that Thailand may lose about -10% of the rain-fed rice production potential. Extents of prime land for rice cultivation (i.e. land rated very suitable or suitable) of 10.1 million hectare in 1981-2010 reduces to 8.9 million hectares (-12%) in the 2050s when using the ensemble mean of results for five GCMs, under RCP 6.0, and taking into account yield improvements due to the CO_2 fertilization effect. Taking the top three suitability classes – very suitable (VS), suitable (S) and moderately suitable (MS) – rice area in the reference period is 17.9 million hectare and the sum of these classes reduces to 17.1 million hectares (-4.4%) in the 2050s. Without taking CO_2 fertilization into account the respective numbers are 6.6 million hectare (VS plus S land), 15.5 million hectare (VS plus S plus MS land) and an overall decline of rice production potential of -16.8%.

For other field crops, maize and soybean, the impacts of climate change are more benign (Table 9-6). Rain-fed suitability and production potential of maize is somewhat improving (an increase of 8.1%). For soybean the assessed production potential remains nearly unchanged in the 2050s compared to the reference period.

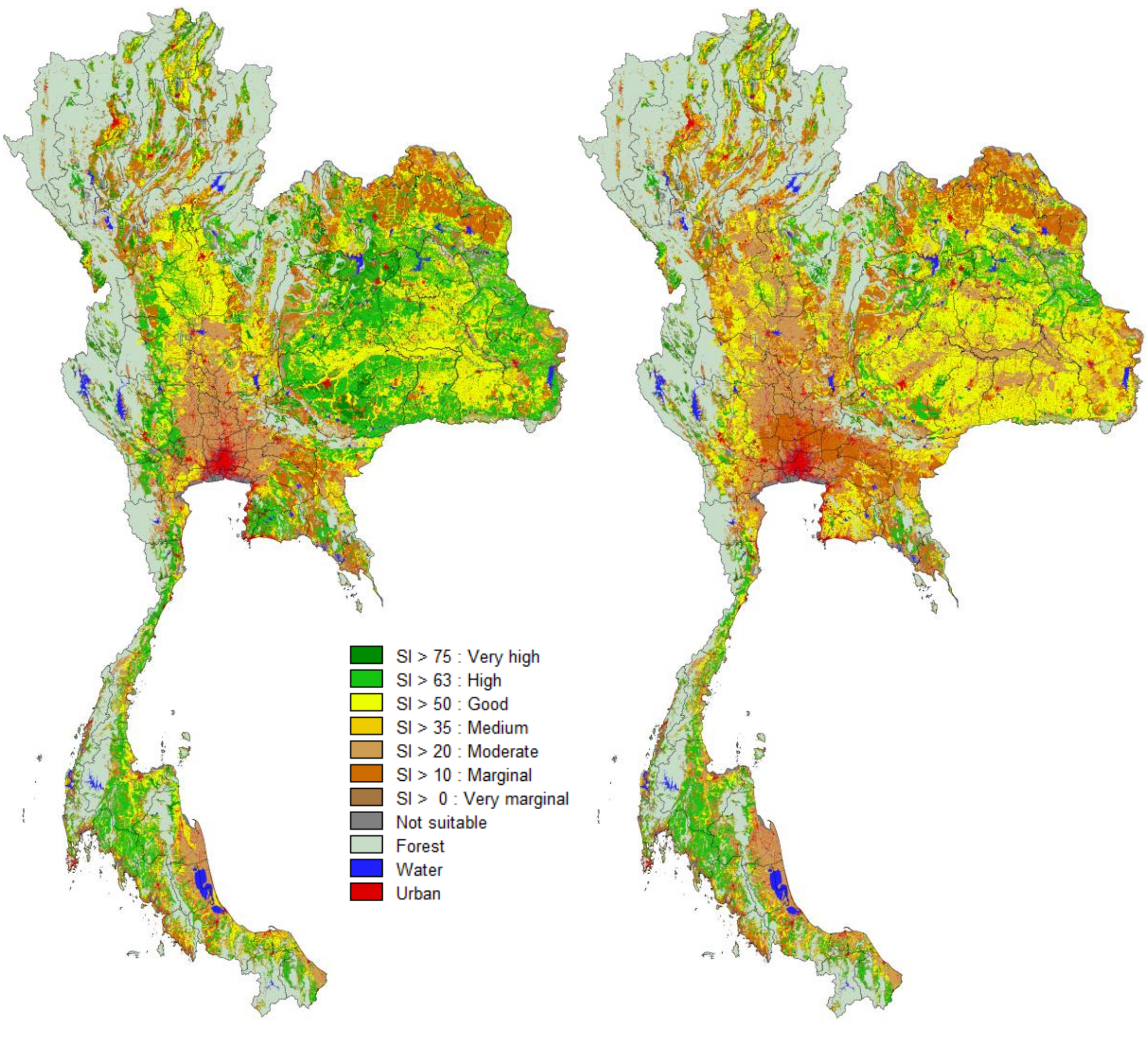


Figure 9-4. Suitability of rain-fed cassava in 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

As can be seen in Figure 9-4, the impact of climate change on rain-fed cassava suitability and production potential is much more severe than for major rice. This is due to the longer growth cycle of cassava as compared to rice. Under climate change crops with long crop cycles are severely affected by the reduced soil moisture supply and reduced number of rain-fed growing period days. NAEZ Thailand simulations suggest that of 17.5 million hectares (VS plus S plus MS) suitable for cassava in the 1981-2010 reference period about 25% would become marginal or not suitable and overall rain-fed cassava production potential would decline by -19.9%. The assessed climate change impacts are even more severe for rain-fed sugarcane where roughly one-third of the rain-fed production potential is lost by the 2050s (using ensemble mean of five GCMs under RCP 6.0).

With irrigation available, the simulated production potential of cassava decreases by -8.2% and for sugarcane by -11.0%. The analysis clearly shows that supplementary irrigation will be needed for these crops to safeguard yields and the production potential, albeit some losses will still be likely to occur due to warming.

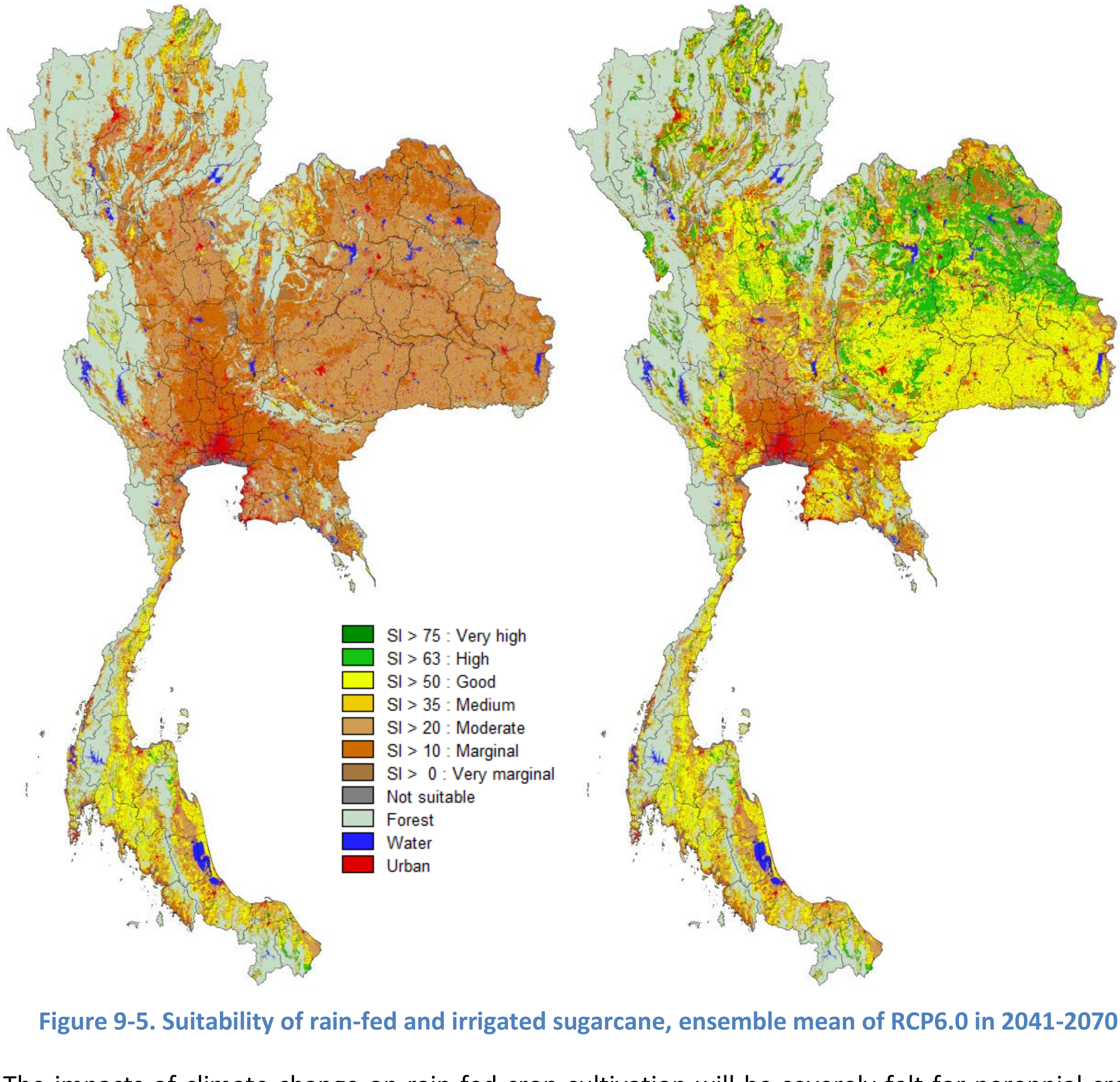


Figure 9-5. Suitability of rain-fed and irrigated sugarcane, ensemble mean of RCP6.0 in 2041-2070

The impacts of climate change on rain-fed crop cultivation will be severely felt for perennial crops such as oil palm, para-rubber and coffee. In the case of oil palm and rubber the production capacity of land in the north and northeast regions, where land is mostly marginally or moderately suitable for these crops under current climate, will nearly entirely vanish by 2050s (Figure 9-6) due to insufficient moisture available. In the major production regions of southern Thailand the situation is less dramatic but still some losses are expected to occur. For both crops the rain-fed production capacity in the southern region is reduced in the 2050s by about -12%, and decreases by about -19% when yield increases due to the CO2 fertilization effect are not taken into account.

For coffee, the combination of higher temperatures and reduced soil moisture supply in the 2050s renders Thai cropland as mostly unsuitable for rain-fed cultivation of either Arabica (northern Thailand) or Robusta coffee (southern Thailand).

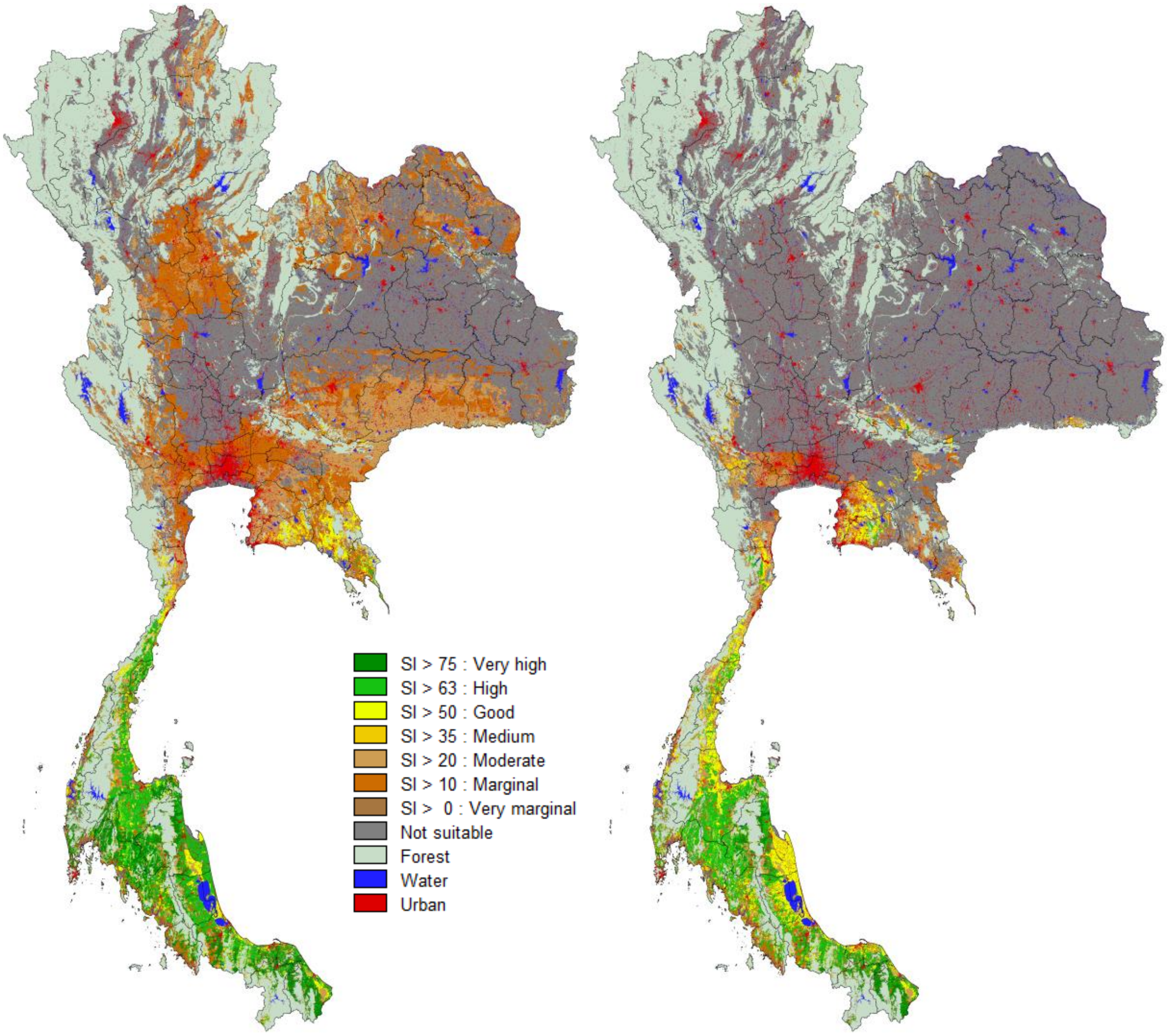


Figure 9-6. Suitability of rain-fed oil palm in 1981-2010 and ensemble mean of RCP6.0 in 2041-2070

When taking the approach of the 'umbrella' crop, i.e. chosing in each grid cell the crop that would produce the highest estimated attainable net revenue (at average 2010-2014 prices), and generating the respective umbrella crop separately for rain-fed conditions in 1981-2010 and (the ensemble mean of) 2041-2070, the picture of Figure 9-7 emerges. For the aggregate national level in 1981-2010, the total prime land (sum of VS and S classes) is 16.9 million hectares and total land in the top three classes (VS plus S plus MS land) is 19.9 million hectares with an average net revenue for Thai cropland of 21,249 Baht/ha. With climate change, the simulated prime land becomes 16.3 million hectares (-3.7%) and total VS plus S plus MS land is 19.8 million hectares (-0.8%). The estimated average attainable net revenue of cropland decreases to 19,198 Baht/ha, a reduction of -9.6%. When the impact of CO2 fertilization on yields is not taken into account, then a clearly negative impact on the estimated best attainable net revenue results, which is as much as -23.7%.

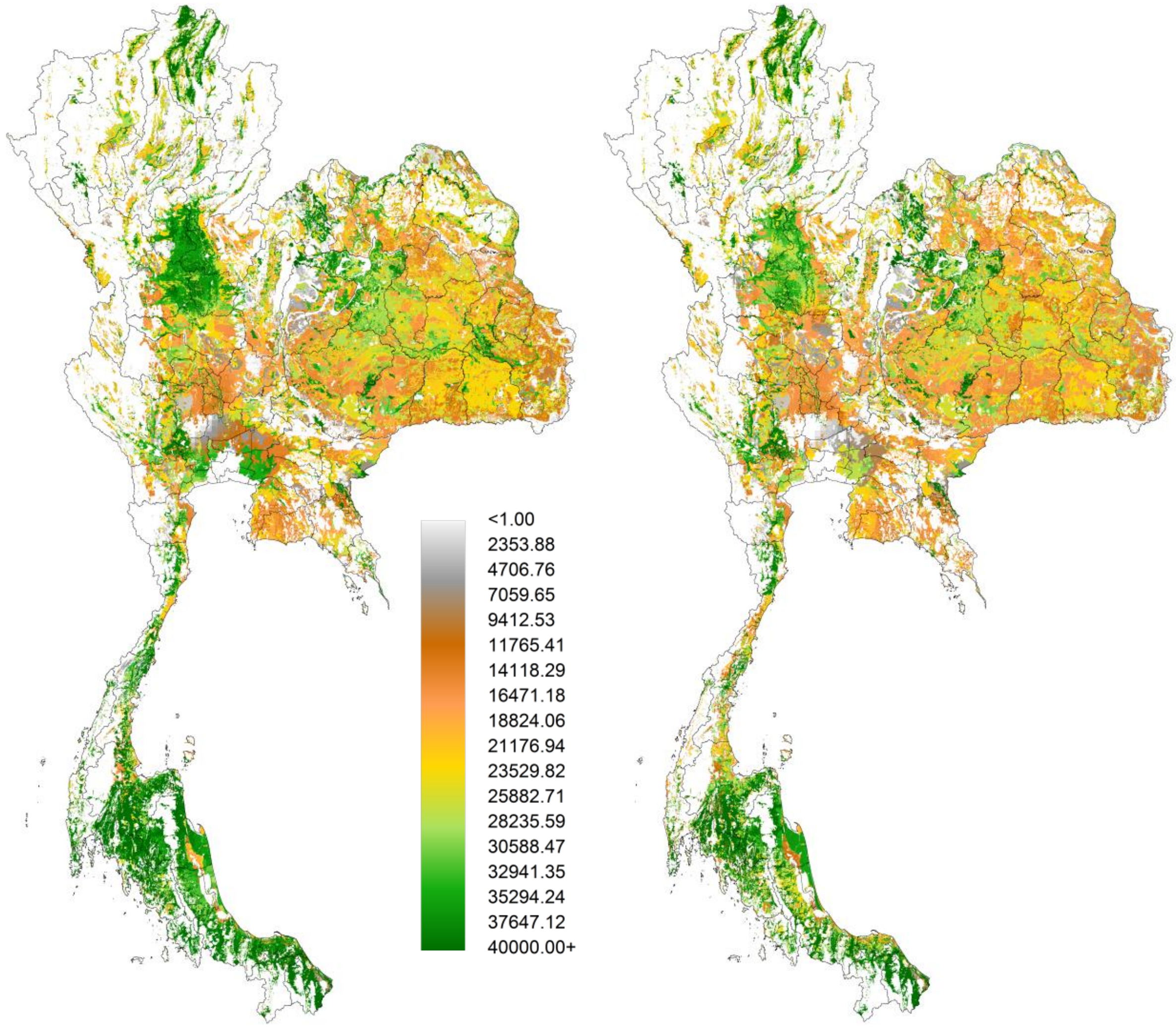


Figure 9-7. Attainable net revenue of rain-fed 'umbrella' crop at prices of 2010-2014 under historical climate of 1981-2010 and for ensemble mean of RCP6.0 in 2041-2070

10 Concluding remarks

This report introduces the NAEZ system applied in this agro-economic zoning study of Thailand. The assessment logic follows the basic principles developed by FAO and IIASA for the global assessment of GAEZ v4, with adaptations to the specific needs and data availability of the project. AEZ follows an environmental approach and used detailed spatial data.

NAEZ Thailand first undertakes a thorough agro-ecological assessment of major economic crops. It then provides a spatial quantification of production costs and attainable net revenues based on statistical information and prices prices of 2010-2014 and assessed attainable agro-ecological yields.

The results where used to map the comparative advantage of eight major economic crops and to compare their economic performance with regard to current land use patterns as derived from high resolution spatial data of 2009-2012. This permits detection of locations where curent land use deviates from assessed agro-ecological suitability or produces poor agro-economic results in comparison to best available options.

The assessment of agro-ecological attainable yields and quantification and mapping of the comparative advantage of each crop was then repeated for future climate conditions as projected by five major global climate models in the IPCC CMIP5 process. The spatial databases generated by the NAEZ assessment provide the agronomic backbone for various applications including the quantification of current and future agricultural land productivity.

Using the ensemble mean of results based on climate projections of five major climate models, the NAEZ Thailand assessment indicates for future decades a gradual worsening of soil moisture supply to crops under rain-fed conditions. The results show that the annual balance of incoming precipitation to evaporative demand of vegetation (i.e. potential evapotranspiration) is likely to deteriorate by the 2050s (period 2041-2070) and beyond compared to reference period 1981-2010. Annual reference evapotranspiration of cropland in Thailand is estimated at about 1500 mm in 1981-2010, increasing with climate change by 2% (RCP 2.6, South Thailand) to 8% (RCP 8.5, northeast Thailand) in the 2050s and by 2.5% to 15% in the 2080s, which is much more than the projected changes in precipitation and an indication that drought periods will likely occur more frequently.

With few exceptions, e.g. such as rain-fed maize, climate change will mostly cause negative impacts on crop suitability and potential production. Expected losses are most pronounced for long cycle crops, for instance sugarcane and cassava in central and northeast Thailand, and for cultivation of perennial crops (rubber, oil palm, coffee). When selecting the most profitable crop in each grid cell (the 'umbrella' crop), separately for the climate of 1981-2010 and for 2041-2070, the attainable net revenue under rain-fed conditions, summed over all cropland, decreases by nearly -10%. Safeguarding yields of major economic crops will require supplementary irrigation to be installed. Even with irrigation some negative impacts will likely occur due to the higher temperatures.

The NAEZ Thailand study has employed best available spatial national data provided by the Land Development Department, Thai Ministry of Development. For further application at detailed spatial resolution it is important to update and refine these datasets, in particular the soil and land use databases. The analysis has revealed some inconsistencies between the current soil series associations map and the land use map of 2009-2012. For instance, there are discrepancies between locations mapped as cropland (LDD land use) and land mapped as slope complexes unavailable for agriculture (i.e., soil series association number 62 for which no soil attributes are provided). Also, future applications of the NAEZ Thailand system would benefit from extending and refining available attributes of the soil database. Availability of statistical information on production costs and net revenues by soil types and geographic regions would be another desirable future improvement of the data employed in NAEZ, which would strengthen the reliability of the assessed spatial economic performance of crops.

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APPENDIXES

Appendix 1 Calculation of Reference Evapotranspiration

The calculation of reference evapotranspiration (ET_O), i.e., the rate of evapotranspiration of a hypothetic 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; FAO 1998). 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; FAO 1998):

$$ET_o = ET_{ar} + ET_{ra} \tag{1}$$

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:

$$\lambda = 2.501 - 0.002361\,T_a \quad (5)$$

Atmospheric pressure (kPa) at elevation A:

$$P = 101.3\left(\frac{293 - 0.0065\,A}{293}\right)^{5.256} \quad (6)$$

Psychrometric constant:

$$\gamma = 0.0016286 \cdot \frac{P}{\lambda} \quad (7)$$

Aerodynamic resistance:

$$r_a = \frac{208}{U2} \quad (8)$$

Crop canopy resistance:

$$r_c = \frac{R_l}{0.5\,LAI} \quad (9)$$

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:

$$\gamma^* = \gamma\left(1 + \frac{r_c}{r_a}\right) \quad (10)$$

Saturation vapor pressure e_a for given temperatures $T_{\min}$ and $T_{\max}$

$$e_{ax} = 0.6108\exp\left(\frac{17.27\,T_{\max}}{237.3 + T_{\max}}\right) \quad (11)$$

$$e_{an} = 0.6108\exp\left(\frac{17.27\,T_{\min}}{237.3 + T_{\min}}\right) \quad (12)$$

$$e_a = 0.5\,(e_{ax} + e_{an}) \quad (13)$$

Vapor pressure at dew point, e_d:

$$e_d = \frac{RH}{100} \cdot \frac{0.5}{\left(\frac{1}{e_{ax}} + \frac{1}{e_{an}}\right)} \quad (14)$$

Slope of vapor pressure curve, ϑ, for given temperatures $T_{\max}$ and $T_{\min}$:

$$\vartheta_x = \frac{4096\,e_{ax}}{(237.3 + T_{\max})^2} \quad (15)$$

$$\vartheta_n = \frac{4096\,e_{an}}{(237.3 + T_{\min})^2} \quad (16)$$

$$\vartheta = (\vartheta_x + \vartheta_n) \quad (17)$$

Using (4)-(17) all variables in (2) can be calculated from the input parameters. To determine the remaining variables R_n and G used in the radiation term ET_{ra} of equation (3), we proceed with the following calculation steps:

Latitude expressed in rad:

$$\varphi = \frac{L\pi}{180} \tag{18}$$

Solar declination (rad):

$$\delta = 0.4093 \sin\left(\frac{2\pi}{365} J - 1.405\right) \tag{19}$$

Relative distance Earth to Sun:

$$d = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \tag{20}$$

Sunset hour angle (rad):

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

Extraterrestrial radiation (MJ m^{-2} d^{-1}):

$$R_a = 37.586\, d\,(\psi \sin\varphi \sin\delta + \cos\varphi \cos\delta \sin\psi) \tag{22}$$

Maximum daylight hours:

$$DL = \frac{24}{\pi}\,\psi \tag{23}$$

Short-wave radiation R_s (MJ m^{-2} d^{-1})

$$R_s = \left(0.25 + 0.5\frac{SD}{DL}\right) R_a \tag{24}$$

For a reference crop with an assumed albedo coefficient $\alpha = 0.23$ *net incoming short-wave radiation* R_{ns} (MJ m^{-2} d^{-1}) is:

$$R_{ns} = 0.77\, R_s \tag{25}$$

Net outgoing long-wave radiation R_{nl} (MJ m^{-2} d^{-1}) is estimated using:

$$R_{nl} = 4.903 \cdot 10^{-9}\left(0.1 + 0.9\frac{SD}{DL}\right)\left(0.34 - 0.139\sqrt{e_d}\right)\frac{(273.16 + T_{max})^4 + (273.16 + T_{min})^4}{2} \tag{26}$$

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 2 Outputs Module 1

Outputs calculated in Module 1 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 with header records holding a copy of the main control parameters used to run the model. The output variables stored from Module 1 runs are described in the tables below.

Table A-2-1 Content of fixed output (header) records from AEZ Module 1

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	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	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
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
Rplim3	Rainfall start-up criterion RPLIM3	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
flnmap1	Input file name: grid-cell land mask	6	Character	80
flninp	Input file name: land pixel file	7	Character	80
flntc1	Output file name: thermal regime pixel values	8	Character	80
flnlgp	Output file name: moisture regime pixel values	9	Character	80
flntmx	Input file name: average monthly temperature	10	Character	80
flntmn	Input file name: average monthly temperature range	11	Character	80
flnpcp	Input file name: monthly precipitation	12	Character	80
flnwnd	Input file name: monthly wind-run	13	Character	80
flnsol	Input file name: monthly sunshine fraction	14	Character	80
flnrhu	Input file name: monthly relative humidity	15	Character	80
flnpcp2	Input file name: daily precipitation share in monthly total P	16	Character	80
flntmx2	Input file name: daily deviation from monthly mean Tmax	17	Character	80
flntmn2	Input file name: daily deviation from monthly mean Tmin	18	Character	80
EoH	End of header string 'EOH'	19	Character	3

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

Table A-2-2 Module 1 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
alat	Latitude of grid-cell center [deg]	Real	4
alng	Longitude of grid-cell center [deg]	Real	4
itcc	Thermal climate class	Integer	2
Itcc2	Thermal zones class	Integer	2
KG2	Koeppen-Geiger 2-letter classification	Integer	2
KG3	Koeppen-Geiger 3-letter classification	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, lgptb, lgpte (1-3)	Number of days [days], beginning day [Julian day], ending day [Julian day] of period with average daily temperature greater or equal 0°C, 5°C, 10°C	Integer	3*3
dtmin	Date of coolest day in year (from smoothed data), i.e. starting date of period with upward temperature trend [Julian day]	Integer	2
dtmax	Date of warmest day in year (from smoothed data), i.e. starting date of period with downward temperature trend [Julian day]	Integer	2
ndx35	Number of days with maximum temperature >35°C [days]	Integer	2
ndx30	Number of days with maximum temperature >30°C [days]	Integer	2
ndn00	Number of days with minimum temperature >0°C [days]	Integer	2
ndn05	Number of days with minimum temperature >5°C [days]	Integer	2
nda00	Number of days with average temperature >0°C [days]	Integer	2
nda05	Number of days with average temperature >5°C [days]	Integer	2
nda10	Number of days with average temperature >10°C [days]	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-2-3 Module 1 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
alat	Latitude of grid-cell center [deg]	Real	4
alng	Longitude of grid-cell center [deg]	Real	4
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
lgptot2	Sum of growing period days in component LGPs	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)*	Number of growing period days, number of days with ETa = ETm, number of days with P> ETm, beginning date, ending date of each component LGP	Integer	5*nact*2

*nact … number of component growing periods up to 5: nact = min (nlgp, 5)

Appendix 3 Crop groups and crops

Suitability and potential agro-climatic yields can be assessed for 11 crop groups (Table A-3-1) and 51 crops (Table A-3-2). The 4-character label shown in Table A-3-2 indicates is used to identify raster maps produced in Module 2/3 of agro-climatic yields, constraint factors, water deficits, etc. of the respective crop

Table A-3-1 Crop groups

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

Table A-3-2 Crops

Code	Common name	*Scientific name*	Crop group	4-char label
1	Wheat	*Triticum spp.*	Cereals	whea
2	Wetland rice	*Oryza sativa*	Cereals	ricw
3	Dryland rice	*Oryza sativa*	Cereals	ricd
4	Maize	*Zea mays*	Cereals	maiz
5	Barley	*Hordeum vulgare*	Cereals	barl
6	Sorghum	*Sorghum bicolor*	Cereals	sorg
7	Rye	*Secale cereale*	Cereals	ryes
8	Pearl millet	*Pennisetum glaucum*	Cereals	pmlt
9	Foxtail millet	*Setaria italica*	Cereals	fmlt
10	Oat	*Avena sativa*	Cereals	oats
11	Buckwheat	*Fagopyrum esculentum*	Cereals	bckw
12	White potato	*Solanum tuberosum*	Roots and tubers	wpot
13	Sweet potato	*Ipomoea batatas*	Roots and tubers	spot
14	Cassava	*Manihot esculenta*	Roots and tubers	casv
15	Yam and Cocoyam	*Dioscorea spp. and Colocasia esculenta*	Roots and tubers	yams
16	Sugarcane	*Saccharum spp.*	Sugar crops	sugc
17	Sugar beet	*Beta vulgaris L.*	Sugar crops	sugb
18	Phaseolus bean	*Phaseolus vulgaris and Ph. lunatus*	Pulses	bean
19	Chickpea	*Cicer arietinum*	Pulses	chkp
20	Cowpea	*Vigna unguiculata*	Pulses	cowp
21	Dry pea	*Pisum sativum L.*	Pulses	dpea
22	Gram	*Vigna radiata*	Pulses	gram
23	Pigeonpea	*Cajanus cajan*	Pulses	pigp
24	Soybean	*Glycine max*	Oil crops	soyb
25	Sunflower	*Helianthus annuus*	Oil crops	sunf
26	Rapeseed	*Brassica napus*	Oil crops	rape
27	Groundnut	*Arachis hypogaea*	Oil crops	grnd
28	Oil palm	*Elaeis oleifera*	Oil crops	oilp
29	Olive	*Olea europaea*	Oil crops	oliv

Code	**Common name**	***Scientific name***	**Crop group**	
30	Jatropha	*Jatropha curcas.*	Oil crops	jatr
31	Cabbage	*Brassica oleracea*	Vegetables	cabb
32	Carrot	*Daucus carota*	Vegetables	carr
33	Onion	*Allium cepa*	Vegetables	onio
34	Tomato	*Lycopersicon lycopersicum*	Vegetables	toma
35	Banana/Plantain	*Musa spp.*	Fruits	bana
36	Citrus	*Citrus Sinensis*	Fruits	citr
37	Coconut	*Cocos nucifera*	Fruits	cocn
39	Cotton	*Gossypium hirsutum.*	Industrial crop	cott
40	Flax	*Linum usitatissimum*	Industrial crop	flax
41	Para rubber	*Hevea brasiliensis*	Industrial crop	prub
42	Cocoa	*Theobroma cacao*	Narcotics and stimulants	coco
43	Coffee	*Coffea arabica*	Narcotics and stimulants	coff
44	Tea	*Camellia Sinenses var. Sinensis*	Narcotics and stimulants	teas
45	Tobacco	*Nicotiana tobacum*	Narcotics and stimulants	toba
46	Miscanthus	*Miscanthus spp*	Bioenergy feedstocks	misc
47	Switchgrass	*Panicum virgatum*	Bioenergy feedstocks	swgr
48	Reed canary grass	*Phalaris arundinacea*	Bioenergy feedstocks	rcgr
49	Alfalfa	*Medicago sativa*	Fodder crops	alfa
50	Pasture legume	*various*	Fodder crops	grlg
51	Grass	*various*	Fodder crops	gras

Appendix 4 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:

$$B_n = B_g - R \tag{1}$$

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:

$$b_n = b_g - r \tag{2}$$

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:

$$B_n = 0.5\ b_{nm} \times N \tag{3}$$

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:

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

where:

- F = the fraction of the daytime the sky is clouded, $F = (A_c - 0.5\ R_g) / (0.8\ A_c)$, where A_c (or PAR) is the maximum active incoming short-wave radiation on clear days (de Wit, 1965), and R_g is incoming short-wave radiation (both are measured in cal cm^{-2} day^{-1})
- 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:

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

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

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

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:

$$r_m = k\ b_{gm} + c\ B_m \tag{7}$$

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:

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

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:

$$B_m = 0.25\ b_{nm} \times N \tag{9}$$

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

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

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:

$$B_n = (0.36\ b_{gm} \times L) / (1/N + 0.25\ c_t\ ) \tag{11}$$

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:

$$Y_p = H_i \times B_n \tag{12}$$

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 5 Output file of Module 2

Outputs calculated in Module 2/3 are stored in a binary file holding for each included LUT variables related to agro-climatic yield potential, temperature and moisture constraint factors, accumulated temperature durng growth cycle, crop water deficit, and crop calendar. The file begins with header records holding a copy of the main control parameters used to run the model. The output variables stored from Module 2/3 runs are described in the tables below.

Table A-5-1 Content of fixed output records from NAEZ Module 2/3

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	4	Integer	2
CR1SEL	Index of first crop in output file	4	Integer	2
CR2SEL	Index of last crop in output file	4	Integer	2
irow0	Row number of upper left corner of sub-window	4	Integer	2
icol0	Column number of upper left corner of sub-window	4	Integer	2
irow1	Row number of lower right corner of sub-window	4	Integer	2
icol1	Column number of lower right corner of sub-window	4	Integer	2
admsel	Code of administrative unit selected for running (if used, else 0)	4	Integer	2
itech	Input level	4	Integer	2
iflmst	Control parameter IFLMST	4	Integer	2
iagclc	Control parameter IAGCLC	4	Integer	2
irtawc	Control parameter IRTAWC	4	Integer	2
daymin	Control parameter DAYMIN	4	Integer	2
lenmin	Control parameter LENMIN	4	Integer	2
itflg	Control parameter ITFLG	4	Integer	2
Rlps	Lapse rate applied (degree C per 1m)	5	Real	4
Ppm	Atmospheric CO2 concentration (ppm)	5	Real	4
Sa0	AWC level (mm/m)	5	Real	4
Sdep0	Maximum applicable soil depth (m)	5	Real	4
Rplim1	Water balance control parameter RPLIM1	5	Real	4
Rplim2	Water balance control parameter RPLIM2	5	Real	4
Rplim3	Rainfall start-up criterion RPLIM3	5	Real	4
Tastr	Temperature threshold TASTRT (usually 5 deg C)	5	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
Idxok	Indicator of LUTs used in simulation (0=off, 1=on)	6	Integer	2 × ncrp
Hidx	Reference harvest index (kg produce/kg biomass)	7	Real	4 × ncrp
flnmap1	Input file name of grid-cell land mask used	8	Character	80
flninp	Input file name of land pixel file	9	Character	80
flncl1	Input file name: average monthly temperature	10	Character	80
flncl2	Input file name: average monthly temperature range	11	Character	80
flncl3	Input file name: monthly precipitation	12	Character	80
flncl4	Input file name: monthly wind-run	13	Character	80
flncl5	Input file name: average monthly sunshine fraction	14	Character	80
flncl6	Input file name: average monthly relative humidity	15	Character	80
flnpcp2	Input file name: daily precipitation share in monthly total P	16	Character	80
flntmx2	Input file name: daily deviation from monthly mean Tmax	17	Character	80
flntmn2	Input file name: daily deviation from monthly mean Tmin	18	Character	80
EoH	End of header string ‘EOH’	19	Character	3

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

Table A-5-2 Information contained in each pixel data record of Module 2/3

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

ncrp … number of crops/LUTs: ncrp = number of last crop – number of first crop + 1

Appendix 6 Output files of Module 4

The main purpose of Module 4 is to provide for each crop/LUT a comprehensive soil suitability evaluation for all the soil units contained in the LDD soil group association database of Thailand. This is done by first determining individual soil quality ratings (SQ), which are then combined in an overall soil unit suitability rating (SR). The SR represents the percentage of potential yield expected to be attainable for a given crop/LUT with respect to the soil characteristics present in a soil map unit of the LDD soil database and is also depending on input/management level.

Module 4 produces a separate output file with soil evaluation results for each crop/LUT. A subset of the information contained in these files is used in Module 5 where agro-ecological potential yields are estimated, accounting for yield reductions due to constraining agro-climatic as well as soil and terrain-slope conditions. The output file of Module 4 is as a large matrix (in plain ASCII), with rows organized by soil map unit and individual component soil types and columns representing estimated values of different soil qualities and the computed overall soil suitability rating (see Table A-6-1).

Table A-6-1 Content of output file from NAEZ Thailand Module 4

Name	Description	Type of variable	Field width
ID	Soil mapping unit identifier	Integer	6
(blank)	Blank text space	Character	1
SOIL_SYM	Soil group association symbol	Character	16
SEQ	Component sequence number within current soil group association	integer	3
SHARE	Component share within current soil group association	Real	6
SL	Soil group association slope class	Integer	3
AWC	Available soil water storage capacity class of current soil association component	Integer	4
SCORE	Soil unit rating for LUT/management level/watersource and current soil association component	Real	6
SQ1,.., SQ7	Soil quality ratings for SQ1 to SQ7 assessed for LUT/management level/watersource and current soil association component	Real	6

Appendix 7 Output files of Module 5

Each run of Module 5 - typically executed for combinations of selected crops, water source (rain-fed or irrigated), input level, and time period (historical or future climate change scenario) - generates a a set of four 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 Thailand 3 arc-second latitude/longitude raster and counting along pixels in rows down to the lower right corner. A record is stored for each land/soil pixel, i.e. excluding grid-cells not included in the NAEZ Thailand land mask or marked as non-soil units (soil group association 62 (complex slope area having slope more than 35 percent) and various units referring to water and built-up areas). 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 SR rating due to soil/terrain constraints) for extents in each suitability class, and a calculated cultivation factors (= 1 – fallow requirement factor). Information contained in Module 5 binary output files are described in Table A-7-1.

Table A-7-1 Information contained in each pixel data record of Module 5

Variable	Description	File suffix	Type of variable	Length of variable (in bytes)
af1	Crop indicator to identify LUT and input level defining results stored in grid-cell record.	px1-px4	Integer	2
acut1	Shares of grid-cell by suitability class (VS, S, MS, mS, vmS, NS). (Note: shares over suitability classes and all soils for total grid-cell add to 10000).	px1	Real	4*6
aqu1	Attainable production by suitability class (VS, S, MS, mS, vmS, NS).	px2	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).	px3	Real	4*6
acf1	Cultivation factor by suitability classes (VS, S, MS, mS, vmS, NS).	px4	Real	4*6