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User Guide for PyAEZ (v2.0.0)

A Python package for Agro-Ecological Zoning

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User Guide for PyAEZ (v 2.0.0)

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Abbreviations and acronyms

AEZ	Agro-Ecological Zones
AIT-GIC	Asian Institute of Technology - Geoinformatics Center
AWC	available soil water capacity
BADC	British atmospheric data centre
CMIP5	Coupled Model Inter-comparison Project Phase 5
CRU	Climate Research Unit
DEM	digital elevation model
ESM	Earth System Model
ETa	actual evapotranspiration
ETm	maximum evapotranspiration
ETo	reference evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FAO-RAP	FAO Regional Office for Asia and the Pacific
Fm	modified Fournier index
GAEZ	Global Agro-Ecological Zones
HI	harvest index
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied System Analysis
LAI	leaf area index
LGP	length of growing period
LGP_{t5}	temperature growing period
LGP_{t10}	frost free period
LUTs	land utilization types
P/ETo	moisture availability index
SQ	soil quality

Introduction

The world population is expected to reach 8.5 billion in 2030 and 9.7 billion in 2050 (UN DESA, 2022). With this eruptive growth in population, an unprecedented increase in demand for food, feed, and fuel is expected, while the agricultural land needed for production continues to shrink in many parts of the world.

The accelerating pace of climate change, combined with global population growth, threatens food security globally. Higher temperatures eventually reduce yields of desirable crops while encouraging weed and pest proliferation and changes in precipitation patterns increase the likelihood of short-run crop failures and long-run production declines (Nelson *et al*., 2009).

Yield increases on existing croplands will, therefore, be an essential component to increase food production (Ray *et al*., 2013). To this end, the Agro-Ecological Zoning (AEZ) framework was developed as a tool to analyse the effect of climate on land use and agricultures, as well as helping to optimise the crop cycle to produce the best yield possible. PyAEZ is an open-source Python package which offers AEZ calculations for user to implement for their regional AEZ analyses. This technical document contains detailed descriptions of all the AEZ modules and functions in PyAEZ.

Background

Over the last thirty years, FAO and the International Institute for Applied Systems Analysis (IIASA) have been developing Agro-Ecological Zoning (AEZ). AEZ is a modelling system for land evaluation to support sustainable land use planning, stimulate agricultural investments, monitor the status of agricultural resources, and assess the impacts of climate change on agriculture.

The Agro-Ecological Zoning (AEZ) approach, developed by FAO jointly with IIASA, is based on the principles of land evaluation and defines matching procedures to identify crop-specific limitations of prevailing climate, soil, and terrain resources with simple and robust crop models, under assumed levels of inputs and management conditions. Main outputs are maximum potential and agronomically attainable crop yields and suitability levels for basic land resources units under different agricultural production systems defined by water supply systems and levels of inputs and management circumstances.

While most countries have adopted land evaluation, land suitability assessment, agro-ecological zoning in the past to prepare agricultural investment plans, most of those are outdated. In parallel, various generations of “AEZ Projects” have served as vehicles to consolidate efforts, structure project goals, and promote funding and resources for the further development of these concepts. And while new datasets and technologies are increasingly becoming available, national capacities to develop, update and use agro-ecological zoning remain limited.

The GAEZ assessment, currently at its fourth update (GAEZ v4), uses seven different modules that are run sequentially to generate agro-climatic and crop-specific information. Each module is made up of a series of FORTRAN routines, documented in GAEZ version 4 model documentation (Fischer *et al*., 2021), that are run through custom batch scripts. Additional scripts in Delphi are used for specific modelling (to be clearly specified by IIASA). Data preparation, although fully documented on the theoretical concepts, is mostly undocumented when addressing the required process to input new data in the modelling system. Limited knowledge on data preparation and lack of a systematic system to run FORTRAN routines make the capacity to generate outputs, limited to a restricted number of experts at IIASA.

The main strategic shift of GAEZ v5 is to focus on how the strong scientific basis for GAEZ can be made available to national entities to support decision-making. GAEZ v5 will focus on taking the last three decades of knowledge and building a standardized, repeatable, accessible yet extensible approach for countries to implement their own, fit for purpose, nationally-adjusted Agro-Ecological Zoning project(s). Countries need guidance on how to collect relevant local data, what tools they can use to create data if it does not exist, how to engage with farmers, local representatives and other stakeholders, and how to process, manage, host and disseminate results of an analysis

With a growing need to address country-specific Agro-Ecological Zoning modelling, the "*Strengthening Agro-climatic Monitoring and Information System (SAMIS)*"[1] project in Lao PDR, in collaboration with the Geoinformatics Center of the Asian Institute of Technology (AIT-GIC) developed a first prototype in Python language, named PyAEZ, that generate national AEZ information. The code, with supporting documentation, and training material is publicly available in the GitHub repository at the https://github.com/gicait/PyAEZ.

What is PyAEZ?

PyAEZ is the first step of GAEZ expansion that utilizes Python scripts to develop users'AEZ projects. The PyAEZ package utilizes climate, soil, and terrain conditions relevant to agricultural production and suitability using crop-specific land resource inventory parameters.

The package is developed with several Python routines and is operated with Jupyter Notebooks, which means it has the capability to be uploaded onto Google Colab, an online Jupyter Notebook system. This compatibility with an online platform such as Google Colab allowed the development team to host two virtual hands-on trainings where attendants were guided through the scientific concepts of AEZ as well as executing the scripts with country-specific input data, through Google Colab.

PyAEZ has been developed to be used within the tropical region, hence some of the complexity of GAEZ in non-tropical regions (e.g. vernalization requirements, permafrost evaluation) is not accounted for. Moreover, the system has not been tested on larger areas where performances of results may be an issue.

PyAEZ package consists of six main AEZ modules and one additional utility module (Figure 1):

- **Module 1: Climate regime** - calculation of agro-climatic indicators for evaluation of climatic suitability of crops.
- **Module 2: Crop simulation** - simulate an optimal crop cycle for the highest attainable yield.

[1] Further information on the *Strengthening agro-climatic monitoring and information systems to improve adaptation to climate change and food security in Lao PDR (GCP /LAO/021/LDF)* SAMIS project can be found at http://www.fao.org/in-action/samis/en/

- **Module 3: Climate constraints** - application of agro-climatic constraints to the calculated yield of a particular crop.
- **Module 4: Soil constraints** - application of edaphic constraints to the calculated yield of a particular crop.
- **Module 5: Terrain constraints** - application of terrain constraints to the calculated yield of a particular crop.
- **Module 6: Economic suitability analysis** - evaluation of economic profitability of a crop based on crop price and the calculated yield.
- **Utilities calculations,** miscellaneous calculation routines used throughout the 6 main AEZ modules.

The package is also equipped with additional calculation routines for:

i. water balance calculation and applying of yield reduction factors based on water limitation (FAO CropWat algorithm) (Smith, 1992);

ii. biomass calculation produced by photosynthesis activities of plants under given radiation conditions;

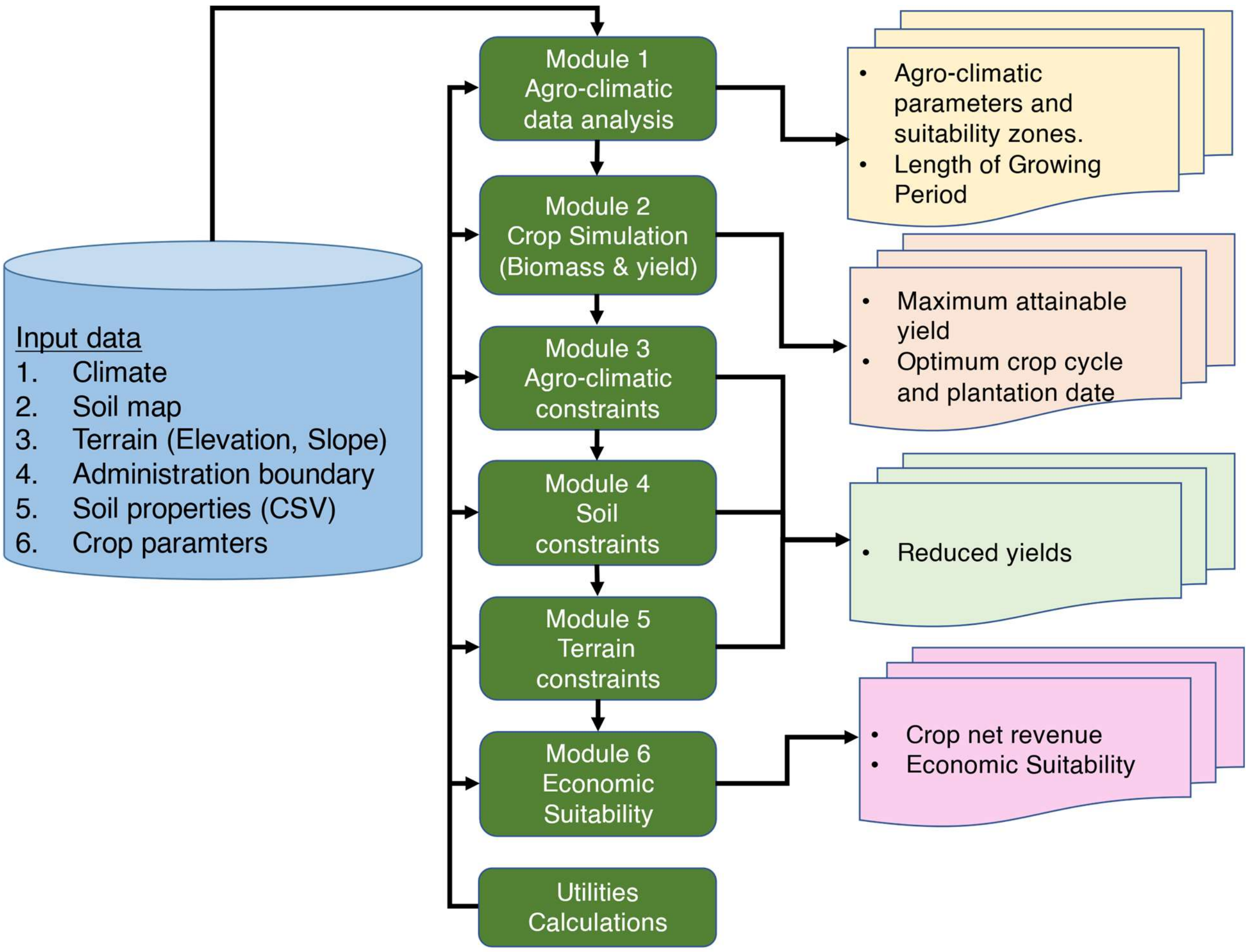
iii. reference evapotranspiration calculation using Penman-Monteith algorithm (Allen *et al*., 1998; Monteith, 1965, 1981).

This documentation provides a step-by-step guideline for anyone looking to develop an AEZ project using PyAEZ package, starting from the installation to the description of the functions in each module, as well as the theoretical concepts behind each function/module.

The code, with supporting documentation, and training material (Jupyter Notebooks and example data) is publicly available and can be downloaded and installed through:

- PyAEZ GitHub repository (https://github.com/gicait/PyAEZ).
- Python package management systems '*pip*' and '*conda*'.

Figure 1. Overview of PyAEZ workflow



Source: Authors' own elaboration.

Data requirement and preparation

This section will cover all the system and data requirements to run PyAEZ. These subsections also act as an essential checklist for the necessary elements to every PyAEZ project initiation.

Python dependencies

PyAEZ package requires the following additional open-source Python packages to be installed and imported for the AEZ calculations to work:

- NumPy:[2] NumPy array is the format used throughout PyAEZ for pixel-based calculation;
- GDAL:[3] allow the package to utilize and generate geo-referenced output from non-geocoded NumPy arrays;
- SciPy:[4] offers statistical analyses and is interoperable with NumPy array;
- Pandas:[5] allows PyAEZ to read MS Excel sheets with user-defined parameters ;
- Numba[6] and NumPy: aware optimizing compiler used to speed up some computationally heavy routines within PyAEZ.

Data preparation

Input-data preparation is essential as the current version of PyAEZ requires users to input data of specific format and shape. Depending on the nature of each aspect, one might prepare to transform into 2D or 3D NumPy arrays, in other cases, preparing additional excel sheet information will be required.

Climate data

PyAEZ requires 6 climatic parameters (Table 1) to be prepared as 3D NumPy data cube for a single year (row, column, day-of-year). We encourage users to use daily climatic data for more accurate results. If the monthly climate data is used, it will need to be interpolated to daily data. The input climate data can be Historical-type data or Future-projected data. Example of the possible climate data sources are Corpernicus' Climate Data Store,[7] European Centre for Medium-Range Weather Forecasts (ECMWF),[8] Google Earth Engine (GEE),[9] and etc. Users can also utilize own country data from their national sensor network/database.

[2] NumPy: https://numpy.org/install

[3] GDAL: e.g. https://anaconda.org/conda-forge/gdal

[4] SciPy: https://scipy.org/install

[5] Pandas: https://pandas.pydata.org/docs/getting_started/install.html

[6] Numba: https://numba.readthedocs.io/en/stable/user/installing.html

[7] Corpernicus' Climate Data Store: https://cds.climate.copernicus.eu/

[8] ECMWF: https://www.ecmwf.int/en/forecasts/datasets

[9] Google Earth Engine: https://developers.google.com/earth-engine/datasets

Table 1. Input climatic parameters

Climatic parameter	Data frequency	Unit	Data format
Minimum air temperature (2 m above surface)	Daily or monthly	Degree celsius	3D NumPy (row, column, time)
Maximum air temperature (2 m above surface)	Daily or monthly	Degree celsius	3D NumPy (row, column, time)
Total precipitation	Daily or monthly	mm/day	3D NumPy (row, column, time)
Solar radiation	Daily or monthly	W/m^2	3D NumPy (row, column, time)
Relative humidity	Daily or monthly	Percentage	3D NumPy (row, column, time)
Windspeed (2 m above surface)	Daily or monthly	m/s	3D NumPy (row, column, time)

Source: Authors' own elaboration.

During the preparation of climatic data, all NaN values (different climate data tend to have some specified no-value values, e.g. -9999) need to be set to zero to prevent any incomputable errors further down the line.

Soil

PyAEZ requires two soil-related data preparations (Table 2).

Table 2. Soil Data preparation

Data	Data source	Data format
Soil map	• Harmonized World Soil Database (HWSD)[10] • Own local/regional soil map	• 2D NumPy array • Each pixel refers to a unique soil mapping unit
Soil characteristics (Table 3)	• Corresponding to the soil map	• .csv file with each soil characteristic parameters as the column headers (Figure 2) • PyAEZ needs 2 .csv files, one for topsoil and another for sub-soil*

**: Pay special attention to the abbreviations when used in the .csv file as PyAEZ reads the data using these*

Source: Authors' own elaboration.

[10] HWSD: https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

Figure 2. Example of the topsoil characteristic input format (.csv)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	CODE	TXT	OC	pH	TEB	BS	CEC_soil	CEC_clay	RSD	SPR	SPH	OSD	DRG	ESP	EC	CCB	GYP	GRC	VSP
2	4260	Coarse	0.3	5.7	2.8	46	5	16	100	0	Lithic	0	MW	2	0	0	0	10	0
3	4261	Coarse	0.3	5.7	2.8	46	5	16	100	0	Lithic	0	MW	2	0	0	0	10	0
4	4264	Medium	0.3	4.7	2	20	12	22	100	0	Lithic	0	P	1	0	0	0	7	0
5	4265	Coarse	0.38	4.8	2.3	31	6	17	100	0	Lithic	0	P	4	0	0	0	8	0
6	4267	Medium	0.42	4.8	2.3	32	6	14	100	0	Lithic	0	MW	2	0	0	0	10	0
7	4284	Medium	0.42	4.8	2.3	32	6	14	100	0	Lithic	0	I	2	0	0	0	10	0
8	4325	Fine	0.45	5.9	17.1	84	23	39	100	0	Lithic	0	VP	2	0	0	0	1	0
9	4383	Medium	0.45	5.9	17.1	84	23	39	10	0	Lithic	0	I	2	0	0	0	1	0
10	4408	Fine	0.6	6.8	31.3	100	20	39	100	0	Lithic	0	P	2	0	0	0	8	0
11	4452	Coarse	0.3	5.7	2.8	46	5	16	100	0	Lithic	0	MW	2	0	0	0	10	0
12	4499	Fine	0.77	4.6	17.1	46	21	36	100	0	Lithic	0	VP	1	0	0	0	1	0
13	4544	Fine	0.52	5.5	4.7	45	10	13	100	0	Lithic	0	MW	2	0	0	0	2	0
14	4587	Fine	0.63	7.4	44.5	100	43	71	100	0	Lithic	0	P	2	0	3.4	0	4	0
15	6651	Fine	0.46	5.7	8	65	13	15	100	0	Lithic	0	MW	1	0	0	0	8	0
16	11788	Fine	0.52	4.9	2.1	21	7	11	100	0	Lithic	0	MW	1	0	0	0	28	0

Source: Authors' own elaboration.

Table 3. Input soil parameters of topsoil and sub-soil properties

Abbreviation*	Parameter name	Data type
CODE	Soil Mapping Unit ID[11]	Numerical
TXT	Soil texture	String
OC	Soil organic carbon	Numerical
pH	Soil pH (0–14)	Numerical
TEB	Total exchangeable bases	Numerical
BS	Base saturation	Numerical
CEC_soil	Cation exchange capacity of soil	Numerical
CEC_clay	Cation exchange capacity of clay	Numerical
RSD	Effective soil depth	Numerical
GRC	Soil coarse material (gravel) percentage	Numerical
DRG	Drainage classes (VP: very poor, P: poor, I: imperfectly, MW: moderately well, W: well, SE: somewhat excessive, E: excessive	String
ESP	Exchangeable sodium percentage	Numerical
EC	Electricity conductivity [dS/m]	Numerical
SPH	Soil phase rating (0 or 1)	Numerical
SPR	Soil property rating (0 or 1)	Numerical
OSD	Other soil depth/volume related characteristics rating	Numerical
CCB	Calcium carbonate content percentage	Numerical
GYP	Gypsum content percentage	Numerical
VSP	Vertical properties (0 or 1)	Numerical

Source: Authors' own elaboration.

[11] Soil Mapping Unit ID as obtained from the soil map

Geographical location and terrain data

PyAEZ requires the elevation and slope maps to be prepared (Table 4). Administrative boundary mask is optional, however, is highly encouraged because it can help minimizing the computational time by considering only area/region of interest.

Table 4. Geographical and terrain data preparation

Data	Data source	Data format
Elevation map	• global elevation map, or • own national/regional data	• 2D NumPy array • unit: metre
Terrain slope map	• global slope map, or • own national/regional data	• 2D NumPy array • unit: percentage
Administrative boundary mask (optional)	• global mask, or • own national/regional mask	• 2D NumPy array • binary: 1 for wanted area, and 0 for unwanted area

Source: Authors' own elaboration.

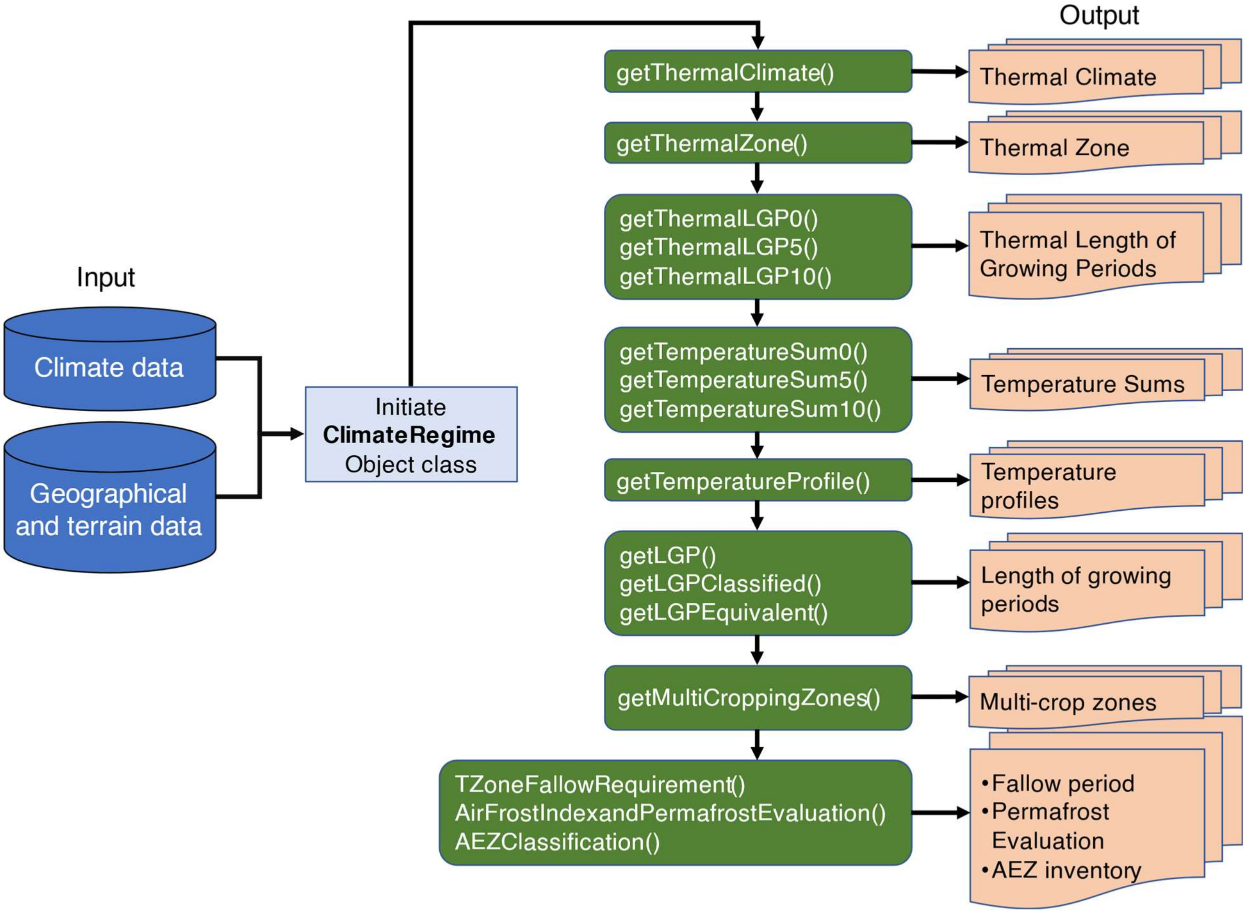
Module 1: Climate regime

Introduction

This module performs climate data analysis and compiling general agro-climatic indicators. These general agro-climatic indicators summarize climatic profiles in the study area for each grid. Figure 3 shows the overall workflow of Module 1. The key input data for this module is the climatic data, and the geographical and terrain data. This section offers descriptions of the all the functions within Module 1, with example code snippets.

It is advisable to always run this module first, as several agro-climatic indicators output from Module 1 will get feed into Module 2 (crop simulation).

Figure 3. Overview of Module 1 (climate regime) workflow



Source: Authors' own elaboration.

Object class creation (mandatory)

PyAEZ codes utilizes '*Object-Oriented Programming*' style, meaning that each module has its own *Classes* containing separate attributes and functions. Therefore, it is essential that the necessary object-classes are initiated at the beginning of each module.

For Module 1, the Class that we need is called ‘`ClimateRegime`’, and is imported and initiated as:

```
# Import PyAEZ Module1:ClimateRegime object class
import ClimateRegime
clim_reg = ClimateRegime.ClimateRegime()
```

Setting up geographical and terrain data (mandatory)

The next mandatory step after object class creation is to input user’s elevation and geographic latitude information into the object class by using this function.

```
# Load geographical location and elevation data into the object class
clim_reg.setLocationTerrainData(lat_min, lat_max, elevation)
```

Function arguments	
lat_min	a single value corresponding to the minimum latitude (decimal degrees) of the study area
lat_max	a single value corresponding to the maximum latitude (decimal degrees) of the study area
elevation	2D NumPy array, elevation of the study area in metres
Function returns	
None	

Read the climate data and load into the class (mandatory)

The third and final mandatory step of preparation is to incorporate all the required climatic datasets into the object class. Depending on the temporal dimension of climatic datasets, user can use either one of the following functions: one for daily datasets and the other for monthly.

```
# Load climate data from NPY files
min_temp = np.load(‘PATH_TO_FILE’) # Continue loading the rest of climate
data
# Deal with NaN or inappropriate negative values, for example:
rel_humidity[rel_humidity<0] = 0
short_rad[short_rad<0]=0
wind_speed[wind_speed<0]=0
# Use the line below if MONTHLY data are used
clim_reg.setMonthlyClimateData(min_temp, max_temp, precipitation, short_rad,
wind_speed, rel_humidity)
# Use the line below if DAILY climate data are used
clim_reg.setDailyClimateData(min_temp, max_temp, precipitation, short_rad,
wind_speed, rel_humidity)
```

Function arguments	
min_temp	3D NumPy array, daily or monthly minimum temperature (°C)

max_temp	3D NumPy array, daily or monthly maximum temperature (°C)
precipitation	3D NumPy array, daily or monthly total precipitation (mm/day)
short_rad	3D NumPy array, daily or monthly solar radiation (W/m^2)
wind_speed	3D NumPy array, daily or monthly windspeed at 2 m elevation (m/s)
rel_humidity	3D NumPy array, daily or monthly relative humidity (percentage decimal, 0–1)
Function returns	
None	

Setting study area inputs (optional)

This function is set up as an optional step which set up the mask layer as input which reduces the computation time outside the pixels of considerations.

```
# Set up mask for the study area (country, regional, or local)
clim_reg.setStudyAreaMask(admin_mask, no_data_value=0)
```

Function arguments	
admin_mask	2D NumPy array, extracted only region of interest (Binary 0/1)
no_data_value	A single value, pixels equal to this value will be omitted during calculation
Function returns	
None	

Thermal climate

The thermal climate function calculates and classifies latitudinal thermal climate, which will be used later in Module 2 for the assessment of potential crops and land utilization types (LUT) presence in each grid cell. It is advisable to use an average of multiple years of temperature data (e.g. 30 years) rather than a single-year data, to obtain better representation of the climate for the study region.

Table 5 describes the classification of thermal climates based on (i) the monthly mean temperature (sea-level adjusted[12]), (ii) the ratios between summer/winter rainfall and the reference evapotranspiration (P/ETo), and (iii) the temperature amplitude as a measure of continentality (i.e. the difference between temperatures of warmest and coldest month) (Fischer *et al.*, 2021).

```
# Classification of rainfall and temperature seasonality into thermal climate
classes
tclimate = clim_reg.getThermalClimate ()
```

[12] Sea-level adjusted monthly mean temperature with a fixed lapse rate of 0.55 °C/100 metres of elevation

Function arguments	
None	
Function returns	
tclimate	2D NumPy array (map) of thermal climate classification

Table 5. Classification of thermal climate classes according to rainfall and temperature seasonality

Climate	Pixel value	Rainfall and temperature seasonality	
Tropics All months with monthly mean sea-level adjusted temperatures > 18 °C, and monthly temperature amplitude* < 15 °C	1	*Tropical lowland*	Tropics with actual mean temperatures (Ta) above 20 °C
	2	*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	3	*Low rainfall*	Annual rainfall less than 250 mm
	4	*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
	5	*Winter 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
Temperate At least one month with monthly mean temperatures, corrected to sea level, below 5 °C and four or more months above 10 °C	6	*Oceanic*	Seasonality less than 20 °C**
	7	*Sub-continental*	Seasonality 20–35 °C **
	8	*Continental*	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	9	*Oceanic*	Seasonality less than 20 °C**
	10	*Sub-continental*	Seasonality 20–35 °C **
	11	*Continental*	Seasonality more than 35 °C**
Arctic	12	*Arctic*	All months with monthly mean temperatures, corrected to sea level, below 10 °C

** Monthly temperature amplitude = monthly maximum temperature - monthly minimum temperature*
*** Seasonality = the difference in mean temperature of the warmest and coldest month*

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

Thermal zones

The thermal zone is classified based on actual temperature which reflects on the temperature regimes of major thermal climates (Table 6).

```
# Classification of thermal zone classes
tzone = clim_reg.getThermalZone()
```

Function arguments	
None	
Function returns	
tzone	2D NumPy array (map) of Thermal Zones classification

Table 6. Classification of thermal zone classes according to rainfall and temperature seasonality

Climate	Pixel value	Thermal zones	
Tropics All months with monthly mean sea-level adjusted temperatures > 18 °C, and monthly temperature amplitude* < 15 °C	1	*Warm*	Tropics with annual mean temperature above 20 °C
	2	*Cool/cold/very cold*	Tropics with annual 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	3	*Warm/moderately cool*	Annual mean temperature above 20 °C
	4	*Cool*	At least one month with monthly mean temperatures below 5 °C and 4 or more months above 10 °C
	5	*Cold*	At least one month with monthly mean temperatures below 5 °C and 1-3 months above 10 °C
	6	*Very cold*	All months with monthly mean temperatures below 10 °C.
Temperate At least one month with monthly mean temperatures, corrected to sea level, below 5 °C and four or more months above 10 °C	7	*Cool*	At least one month with monthly mean temperatures below 5 °C and 4 or more months above 10 °C
	8	*Cold*	At least one month with monthly mean temperatures below 5 °C

			and 1-3 months above 10 °C
	9	*Very cold*	All months with monthly mean temperatures below 10 °C
Boreal At least one month with monthly mean temperatures, corrected to sea level, below 5 °C and 1-3 months above 10 °C	10	*Cold*	At least one month with monthly mean temperatures below 5 °C and 1-3 months above 10 °C
	11	*Very cold*	All months with monthly mean temperatures below 10 °C
Arctic	12	*Arctic*	All months with monthly mean temperatures, corrected to sea level, below 10 °C

**Monthly temperature amplitude = monthly maximum temperature - monthly minimum temperature*

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

Thermal length of growing period (LGP_t)

The thermal length of growing period (LGP_t) is defined as the number of days in a year during which the daily mean temperature (Ta) is conductive to crop growth and development. PyAEZ utilizes the AEZ three standard temperature thresholds for LGPt:

i. periods with Ta > 0 °C (LGP_{t0});

ii. periods with Ta > 5 °C (LGP_{t5}) - the period conductive to plant growth and development;

iii. periods, and Ta > 10 °C (LGP_{t10}) - a proxy for the period of low risks for late and early frost occurrences and termed frost-free period.

```
# Calculate Thermal Length of Growing Period (LGPt)
# 3 temperature thresholds
# LGPt>0 degC
lgpt0 = clim_reg.getThermalLGP0()
# LGPt>5 degC
lgpt5 = clim_reg.getThermalLGP5()
# LGPt>10 degC
lgpt10 = clim_reg.getThermalLGP10()
```

Function arguments	
None	

Function returns	
lgpt0	2D NumPy arrays [days]
lgpt5	2D NumPy arrays [days]
lgpt10	2D NumPy arrays [days]

Temperature summations (TS)

Temperature summation corresponds to the accumulated temperature which represent the crop-/LUT-specific heat requirements (Fischer *et al.,* 2021).

Reference temperature sums (TS) are calculated for each grid-cell by accumulative daily average temperature (Ta) for days when Ta is above the thresholds as follows: (i) 0 °C, (ii) 5 °C, and (iii) and 10 °C.

```
# Calculate temperature summation at 3 temperature thresholds
# Tsum>0 degC
tsum0 = clim_reg.getTemperatureSum0()
# Tsum>5 degC
tsum5 = clim_reg.getTemperatureSum5()
# Tsum>10 degC
tsum10 = clim_reg.TemperatureSum10()
```

Function arguments	
None	

Function returns	
tsum0	2D NumPy arrays [°C]
tsum5	2D NumPy arrays [°C]
tsum10	2D NumPy arrays [°C]

Temperature profiles

Temperature profiles (Table 7) can be classified into 9 classes of different daily 'temperature ranges' between Ta < -5 °C to Ta > 30 °C. This classification uses 5 °C intervals as well as distinguishes the increasing and decreasing temperature trends within a year (Fischer *et al.*, 2021). The output from this classification will be used in Module 2 (Crop Simulation), where these profiles are matched with crop-specific temperature profile requirements to assess the crop-growth suitability for any specific locations.

```
# Classification of temperature ranges for temperature profile
tprofile = clim_reg.getTemperatureProfile()
```

Function arguments	
None	
Function returns	
tprofile	18 2D NumPy arrays [A1-A9, B1-B9] correspond to each Temperature Profile class [days]

Table 7. Temperature profile classes

Mean daily temperature (°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

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

Length of growing period (LGP)

The length of growing period (LGP) is defined as the number of days during the year when the temperature regime and moisture supply are conductive to crop growth and development. LGP, therefore, acts as an agro-climatic indicator of the potential productivity of an area of land.

Reference evapotranspiration (ETo)

The reference evapotranspiration (ETo) represents evapotranspiration from a defined reference surface, which closely resembles an extensive surface of green, well-watered grass of uniform height (12 cm), actively growing and completely shading the ground. GAEZ calculates ETo from the attributes in the climate database for each grid-cell according to the Penman-Monteith equation (Allen *et al*., 1998; Monteith, 1965, 1981; Doorenbos and Pruitt, 1977). A description of the implementation of the Penmann-Monteith equations is provided in Appendix 3-1 of Fischer *et al*., (2021).

Maximum evapotranspiration (ETm)

In Module 1, the calculation of maximum evapotranspiration (ETm) for a 'reference crop' assumes that sufficient water is available for uptake in the rooting zone. The value of ETm is related to ETo through applying crop coefficients for water requirement (Kc), reflecting phenological development and leaf area. The Kc values are crop- and climate-specific. They vary generally between 0.3–0.5 at initial crop stages (emergence) to 1.0–1.2 at reproductive stages. PyAEZ utilizes the 'reference crop' whose Kc values depend on the thermal characteristics of a grid cell, as described Table 8.

$$ETm = Kc \times ETo$$

Actual evapotranspiration (ETa)

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

i. adequate soil water availability (Eta = ETm);

ii. limiting soil water availability (Eta < ETm).

<u>Water balance calculation</u>

The calculation of Eta involves daily soil water balance (Wb), which is defined as the volume of water available for plant uptake. The water balance, Wb, accounts for the accumulation of daily water inflow from precipitation (P), snowmelt (Sm), and outflow from the actual evapotranspiration (Eta), and excess water lost due to runoff and deep percolation (amount of water that exceeds the upper limit of water available to plants, Wx). For the 'j' day of the year, the daily water balance is calculated as:

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

The upper limit Wx of water available to plants is the product of the available soil water (Sa) and rooting depth (D),

$$Wx = Sa \times D$$

The threshold of readily available soil moisture Wr is, in turn, calculated from Wx and the soil moisture depletion fraction (p),

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

<u>Snow balance calculation</u>

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

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

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

Further details of the two possible cases of ETa calculation are as follows:

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

A condition of 'adequate soil moisture availability' is defined when:

i. daily precipitation (P) is greater or equal to ETm, and/or

ii. combination of P and the difference between Wb and the readily-available-water threshold Wr is greater than Etm

$$ETa = ETm, \qquad for \begin{cases} P \geq ETm \\ P + (Wb - Wr) > Etm \end{cases}$$

<u>ETa for limited water availability</u>

When the soil water is limiting, then ETa falls short of ETm. In this case, ETa is calculated as a fraction ρ of ETm, where

$$\rho = Wb/Wr$$

The Eta is then calculated as

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

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

LGP calculation

LGP refers to the number of days when average daily temperature is above 5 °C (LGP_{t5}) and ETa of this reference crop exceeds a specified fraction of ETm. In the current GAEZ parameterization, LGP days are considered when Eta ≥ 0.4 × ETm, which aims to capture periods when sufficient soil moisture is available that would allow the establishment of the reference crop.

$$LGP = total\ number\ of\ days\ when\ ETa/ETm \geq\ 0.4$$

LGP equivalent

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

A quadratic polynomial is used to express the relationship between the number of growing period days and the annual humidity index. Parameters were estimated using data of all grid cells with essentially year-round temperature growing periods, i.e. with LGP_{t5} = 365.

$$LGP_{eq} = \begin{cases} 14.0 + 293.66 \times (P/ETo) - 61.25 \times (P/ETo)^2, & when\ (P/ETo) \leq 2.4 \\ 366\ , & when\ \ P/ETo) > 2.4 \end{cases}$$

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.

In PyAEZ, the LGP, LGP classification, and LGP equivalent are obtained through the following function,

```
# Length of Growing Period (LGP)
lgp = clim_reg.getLGP(Sa=100, D=1)
# Classification of LGP
```

```
lgp_class = clim_reg.getLGPClassified(lgp)
# LGP Equivalent
lgp_equv = clim_reg.getLGPEquivalent()
```

Function arguments	
Sa	A single value or A 2D NumPy array, corresponding to available soil moisture holding capacity (mm = m). Usually, this value varies with soil texture. Hence, Sa can be provided as single value for entire area or 2D NumPy array that represent variation of soil moisture holding capacity depending on soil texture. Default value is 100 mm/m. This is an optional argument
D	A single value, corresponding to corresponding rooting depth in meters. Default value is 1. This is an optional argument.
Function returns	
lgp	2D NumPy arrays of LGP [days]

Table 8. Kc values used in Module 1 for the calculation of the maximum evapotranspiration (Etm)

Daily temperature condition	Remarks	Kc
Areas with year-round temperature growing period - LGP_{t5} = 365 days		
Daily Ta ≥ 5 °C; LGP_{t5} = 365 days	In areas with year-round LGP_{t5}, the Kc value stays at 1	1.0
Areas with dormancy period or cold break - LGP_{t5} < 365 days		
Daily Ta ≤ 0 °C; Tmax < 0 °C	Precipitation falls as snow and is added to snow bucket	0.0
Daily Ta ≤ 0 °C; Tmax ≥ 0 °C	Snowmelt takes place (water balance = precipitation + snow melt); minor evapotranspiration	0.1
0° C < Daily Ta < 5 °C; Ta trend upward	Some biological activities before the start of the growing period	0.2
Daily Ta ≥ 5 °C; LGP_{t5} < 365 days; Case 1	Kc used for the days prior the start of the growing period	0.5
Daily Ta ≥5 °C; LGP_{t5} < 365 days; Case 2	Kc increases from 0.5 to 1.0 during the first month of LGP	0.5–1.0
Daily Ta ≥5 °C; LGP_{t5} < 365 days; Case 1	Kc = 1 until the daily Ta falls below 5 °C	1.0
0 °C < Daily Ta < 5 °C; Ta trend downward	Reduced biological activities before dormancy	0.2

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

Multiple cropping zones classification

Multiple cropping zones classification (Table 9) is an additional agro-climatic indicator, which relates to the possibility of cultivating multiple sequential crops under rain-fed and irrigated conditions.

The PyAEZ's core modules perform calculation for single cropping systems. Additionally, several potential multiple cropping zones have been defined through matching the growth cycle with the temperature requirements based on thermal climate, length of growing period, thermal growing period (LGP_{t0} and LGP_{t10}), and the accumulated temperature summations ($Tsum_{t0}$, $Tsum_{t10}$). For more details on the multiple cropping zones classification please refer to the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).

```
# Multiple Cropping Zones classification
multi_crop_zone = clim_reg.getMultiCroppingZones(tclimate, lgp, lgpt5, lgpt10,
tsum0,tsum10)
```

Function arguments	
tclimate	2D NumPy array, thermal climate classes
lgp	2D NumPy array, length of growing period
lgpt5	2D NumPy array, thermal LGP of Ta > 5˚C
lgpt10	2D NumPy array, thermal LGP of Ta > 10˚C
tsum0	2D NumPy array, temperature summation for Ta ≥ 0˚C
tsum10	2D NumPy array, temperature summation for Ta ≥ 10˚C
Function returns	
multi_crop_zone	Python List of 2D NumPy arrays, as [multi_crop_rainfed, multi_crop_irrigated].

Table 9. Delineation of multiple cropping zones

Pixel values	Zone	Description
1	A	Zone of no cropping (too cold or too dry for rain-fed crops)
2	B	Zone of single cropping
3	C	Zone of limited double cropping (relay cropping; single wetland rice may be possible)
4	D	Zone of double cropping (note, in Zone D sequential double cropping including wetland rice is not possible)
5	E	Zone of double cropping with rice (sequential double cropping with one wetland rice crop is possible in Zone E)
6	F	Zone of double rice cropping or limited triple cropping (may partly involve relay cropping. A third crop is not possible in case of two wetland rice crops)
7	G	Zone of triple cropping (sequential cropping of three short-cycle crops; two wetland rice crops are possible in Zone G)
8	H	Zone of triple rice cropping (sequential cropping of three wetland rice crops is possible)

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

Fallow period requirements

Fallow is an agricultural technique that consists of not sowing the arable land during one or more growing seasons. In AEZ framework, the fallow factors have been established by main crop groups and environmental conditions. The crop groups include cereals, legumes, roots and tubers, and a miscellaneous group consisting of long-term annuals/perennials. The fallow factors are expressed as percentage of time during the fallow-cropping cycle the land must be under fallow. PyAEZ determines the fallow requirements using thermal zones. For further information on the fallow period requirement, please refer to Appendix 6-10 of the *GAEZ v4 Model Documentation* (Fischer *et al.*, 2021).

```
# Fallow period requirements
fallow = clim_reg.TZoneFallowRequirement(tzone)
```

Function arguments	
tzone	2D NumPy array, corresponding to thermal zone
Function returns	
fallow	2D NumPy array, corresponding to thermal zone for fallow requirements

Permafrost evaluation

Occurrence of continuous or discontinuous permafrost conditions are used in the suitability assessment. Permafrost areas are characterized by sub-soil at or below the freezing point for two or more years. In this section, PyAEZ utilizes the air frost index (FI) which is used to characterize climate-derived permafrost condition into 4 classes: (i) Continuous permafrost; (ii) Discontinuous permafrost; (iii) Sporadic permafrost; and (iv) No permafrost. For detailed calculations for air frost index please refer to Chapter 3 of the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).

```
# Permafrost Evaluation
permafrost = clim_reg.AirFrostIndexandPermafrostEvaluation()
```

Function arguments	
None	

Function returns	
permafrost	Python List of 2D NumPy arrays, as [frost index, permafrost class]

Agro-Ecological Zones classification

The Agro-Ecological Zoning (AEZ) methodology provides a framework for establishing a spatial inventory of land resources compiled from global/national environmental data sets and assembled to quantify multiple spatial characteristics required for the assessments of land productivity under location-specific agro-ecological conditions.

The inventory combines spatial layers of thermal and moisture regimes with broad categories of soil/terrain qualities. It also indicates locations of areas with irrigated soils and shows land with severely limiting bio-physical constraints including very cold and very dry (desert) areas as well as areas with very steep terrain or very poor soil/terrain conditions. For further information on the classification criteria, please refer to Chapter 10 of the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).

```
# AEZ classification
aez_class = clim_reg.AEZClassification(tclimate, lgp, lgp_equv, lgpt_5,
soil_terrain_lulc, permafrost)
```

Function arguments	
tclimate	2D NumPy array, thermal climate classes
lgp	2D NumPy array, length of growing period
lgp_equv	2D NumPy array, LGP equivalent
lgpt5	2D NumPy array, thermal LGP of Ta > 5°C
soil_terrain_lulc	2D NumPy array, soil/terrain/special land cover classes (8 classes) • 1: Dominantly very steep terrain; • 2: Dominantly hydromorphic soil; • 3: No or few soil/terrain limitations;

	• 4: Moderate soil/terrain limitations; • 5: Severe soil/terrain limitations; • 6: Irrigated soils; • 7: Water; • 8: Built-up/artificial.
permafrost	2D NumPy array, permafrost classes
Function returns	
aez_class	2D NumPy array, 57 classes of AEZ

Module 2: Crop simulation

Introduction

This key module simulates all the possible crop cycles to find the best crop cycle that produces maximum yield for a particular grid (Module 2 overview is shown in Figure 4. During the simulation process for each grid, 365 crop cycle simulations are performed. Each simulation corresponds to cycles that start from each day of the year (starting from Julian date 0 to Julian date 365). Similarly, this process is performed by the program for each grid in the study area.

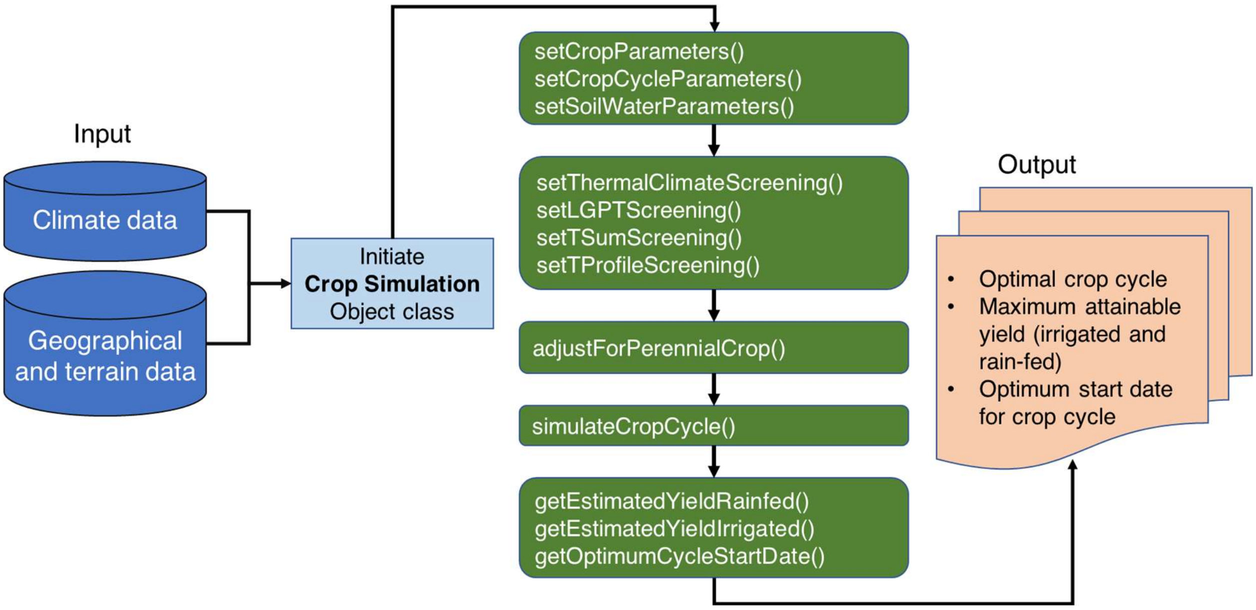
Schematic representation of this process is shown in Figure 5. The attainable yields under irrigated and rain-fed conditions, during each crop cycle, are calculated with the help of several deterministic and empirical models as follows.

- **Total biomass** (de Wit, 1965): This model calculates total biomass produced by photosynthesis activities of plants under radiation condition of each grid. For more detailed calculations, refer to Chapter 4 of the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).
- **Crop yield from total biomass**: Crop yield is obtained as a portion of useful harvest from the total biomass. This portion is defined by an index call Harvest Index (HI). Harvest index is defined as the amount of useful harvest divided by the total above ground biomass. For more detailed calculations, refer to Chapter 4 of the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).
- **Effects of water limitation on the crop yield**: This component is carried out for the rain-fed yield calculation only. In the case of irrigated conditions, this component is abandoned, as we are assuming that the water is not a limiting factor for crop growth. To address the water limitation on the crop yield, two major models are considered:
    - reference Evapotranspiration - the Penman-Monteith equation (Doorenbos and Pruitt, 1977). A description of the implementation of the Penmann-Monteith equations is provided in Appendix 3-1 of Fischer *et al.* (2021);
    - water balance calculation, together with applying the yield reduction factors based on water limitation (Smith, 1992).
- **Effects of temperature during crop cycle** and screening of crop cycles based on temperature requirements (termed *Thermal Screening*).

Similar to Module 1, we have to import and initiate the class for the crop simulation module.

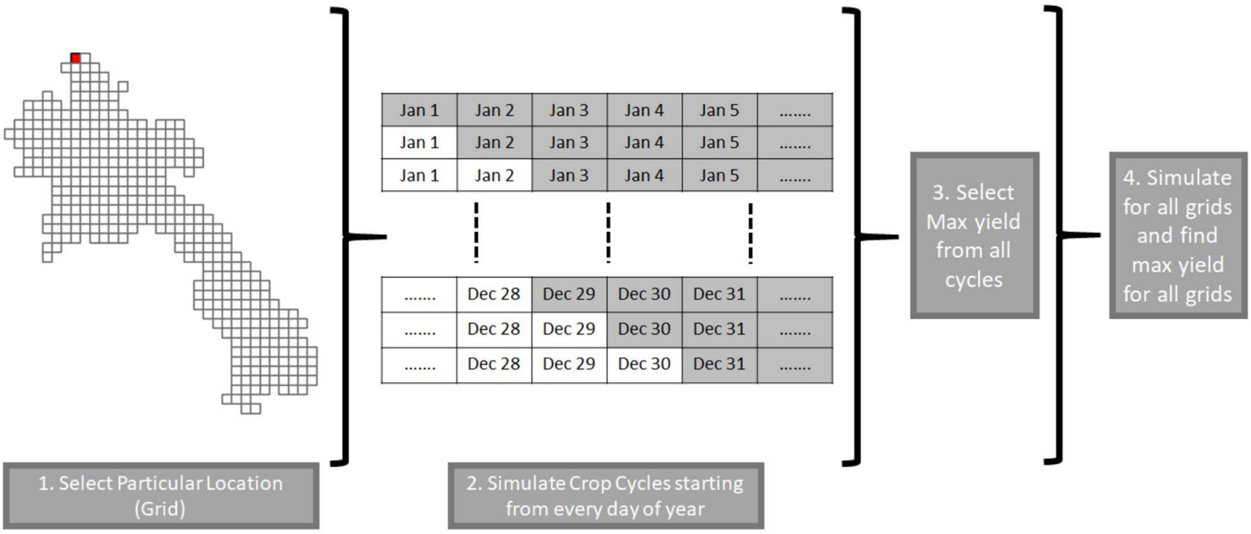
```
# import Module 2 Class
import CropSimulation
# create an instance - initiate the Class
aez = CropSimulation.CropSimulation()
```

Figure 4. Overview of Module 2 (crop simulation) workflow



Source: Authors' own elaboration

Figure 5. Overview of crop simulation routine



Source: Authors' own elaboration.

Setting up inputs for Module 2

Geographical and terrain input

```
# Load geographical location and elevation data into the object class
aez.setLocationTerrainData(lat_min, lat_max, elevation)
```

Function arguments	
`lat_min`	a single value corresponding to the minimum latitude (decimal degrees) of the study area
`lat_max`	a single value corresponding to the maximum latitude (decimal degrees) of the study area
`elevation`	2D NumPy array, elevation of the study area in metres
Function returns	
None	

Climate data input

First, we have to read and load the climate data into Module 2 Class before proceeding with any calculations.

```
# Use the line below if MONTHLY data are used
aez.setMonthlyClimateData (min_temp, max_temp, precipitation, short_rad,
wind_speed, rel_humidity)
# Use the line below if DAILY data are used
aez.setDailyClimateData (min_temp, max_temp, precipitation, short_rad,
wind_speed, rel_humidity)
```

Function arguments	
min_temp	3D NumPy array, daily or monthly minimum temperature (°C)
max_temp	3D NumPy array, daily or monthly maximum temperature (°C)
precipitation	3D NumPy array, daily or monthly total precipitation (mm/day)
short_rad	3D NumPy array, daily or monthly solar radiation (W/m2)
wind_speed	3D NumPy array, daily or monthly windspeed at 2 m elevation (m/s)
rel_humidity	3D NumPy array, daily or monthly relative humidity (percentage decimal, 0–1)
Function returns	
None	

Setting study area inputs (optional)

This function is set up as an optional step which set up the mask layer as input which reduces the computation time outside the pixels of considerations.

```
# Set up mask for the study area (country, regional, or local)
clim_reg.setStudyAreaMask(admin_mask, no_data_value=0)
```

Function arguments	
admin_mask	2D NumPy array, extracted only region of interest (Binary 0/1)
no_data_value	A single value, pixels equal to this value will be omitted during calculation
Function returns	
None	

Crop parameters input

This function allows users to set up the main crop parameters necessary for PyAEZ. This step is mandatory for Module 2 calculations.

```
# Set crop paramaters input for Module 2
aez.setCropParameters(LAI, HI, legume, adaptability, cycle_len, D1, D2)
```

Function arguments	
LAI	A single value, Leaf Area Index
HI	A single value, Harvest Index
legume	A single binary value, Is the crop is legume? No = 0, Yes = 1
adaptability	A single value, corresponding to adaptability class of the crop. Hence, value must be either 1, 2, 3, or 4 corresponding to adaptability class of the crop.
cycle_len	A single value, corresponding length of crop cycle [days]
D1	A single value, corresponding rooting depth in metres at the beginning of the crop cycle
D2	A single value, corresponding rooting depth in metres after maturity (D1 and D2 can also be same value. In this case, interpolations will not be applied, and same rooting depth will be applying for the entire crop cycle)
Function returns	
None	

Soil water parameter input

This function allow user to set up the parameters related to the soil water storage.

```
# Set soil water parameter
```

```
aez.setSoilWaterParameters(Sa, pc)
```

Function arguments	
Sa	A single value or a 2D NumPy array, corresponding to available soil moisture holding capacity [mm/m]. Usually, this value varies with soil texture. Sa can be provided as single value for entire area or 2D NumPy array that represents variation of soil moisture holding capacity depending on soil texture
pc	A single value between 0 and 1, corresponding to soil water depletion fraction below which
Function returns	
None	

Crop cycle parameter input

This function allow user to set up the parameters related to the crop cyles.

```
# Set crop cycle parameter
aez.setCropCycleParameters(stage_per, kc, kc_all, yloss_f, yloss_f_all)
```

Function arguments	
stage_per	A 4-element numerical list, corresponding to percentage of each 4 stages of a crop cycle, namely initial (d1), vegetative (d2), reproductive (d3), and maturation stage (d4). Example: stage per = [10, 30, 30, 30]
kc	A 3-element numerical list, corresponding crop water requirements for initial, reproductive, the end of the maturation stage. Example: kc = [1.1, 1.2, 1]
kc_all	A single value, corresponding to crop water requirements for entire growth cycle.
yloss_f	A 4-element numerical list, corresponding to yield loss factors of each 4 stages of a crop cycle, namely initial (d1), vegetative (d2), reproductive (d3), and maturation stage (d4). Example: yloss_f = [1,2,2.5,1]
yloss_f_all	A single value corresponding to yield loss factor for entire growth cycle
Function returns	
None	

Thermal screening input

The functions in this section will screen the suitability of grid-cells for the possible presence of individual LUTs. The crops' temperature requirements will be matched with the prevailing thermal conditions (thermal Rregime characteristics calculated in Module 1.

Thermal climate

PyAEZ ‘s screening of crop/LUTs about thermal climate results in a ‘yes/no’ filter for further calculations.

Thermal growing period

Growth cycle lengths of crop/LUTs are matched with LGP_{t5}. The result of the matching provides optimum match when the growth cycle can generously be accommodated within LGP_{t5}. Otherwise, the match is considered not suitable.

Accumulated temperature sum

The matching of the crop LUT heat unit requirements with the prevailing temperature sum is:

- optimum, when the requirements are within the specified optimum Tsum range;
- not suitable, when prevailing Tsum range are too high or too low.

Temperature profile

Potential crop calendars of each LUT are tested for the match of crop/LUT temperature profile requirements and grid-cell temperature profiles, while considering growth cycle starting days within the length of the growing period for rain-fed conditions, and separately within the year for irrigated conditions.

For all feasible crop calendars within the LGP (rain-fed) or within the year (irrigated), the temperature profile conditions are tested against optimum and suboptimum crop temperature profile requirements and in each case an “optimum” or “not suitable” match is established.

```
# Set parameters for Thermal Screening
aez.setThermalClimateScreening(tclimate,no_tclimate)
aez.setLGPTScreening(no_lgpt, optm_lgpt)
aez.setTsumScreening(no_Tsum, optm_Tsum)
aez.setTProfileScreening(no_Tprofile, optm_Tprofile)
```

Function arguments	
tclimate	2D NumPy array, corresponding to thermal climate (an output of Module 1)
no_tclimate	A numerical list, corresponding to pixel values of “not suitable” thermal climate zones
no_lgpt	3-elements numerical list, “not suitable” 3 LGPt conditions (as in Module 1)
optm_lgpt	3-elements numerical list, “optimum” 3 LGPt conditions (as in Module 1)
no_Tsum	3-elements numerical list, “not suitable” 3 Tsum conditions (as in Module 1)
optm_Tsum	3-elements numerical list, “optimum” 3 Tsum conditions (as in Module 1)
no_Tprofile	18-elements numerical list, “not suitable” 18 Tprofile conditions (as in Module 1)
optm_Tprofile	18-elements numerical list, “optimum” 18 Tprofile conditions (as in Module 1)
Function returns	
None	

Adjustment for perennial crop (optional)

If a perennial crop is introduced, PyAEZ will perform adjustment on the Leaf Area Index (LAI) and the Harvest Index (HI) based on the effective growing period. For detailed calculates and adjustment values, please refer to Chapter 4 of the *GAEZ v4 Model Documentation* (Fischer *et al.*, 2021).

```
# Set parameters for adjusting for Perennial Crop
aez.adjustForPerennialCrop(aLAI, bLAI, aHI, bHI)
```

Function arguments	
aLAI	A single value, corresponding to αLAI . Example: Arabica coffee αLAI = 0
bLAI	A single value, corresponding to βLAI . Example: Arabica coffee βLAI = 270
aHI	A single value, corresponding to αHI . Example: Arabica coffee αHI = 120
bHI	A single value, corresponding to βHI . Example: Arabica coffee βHI = 120
Function returns	
None	

Calculations and outputs

Crop cycle simulation

After setting up all of the related parameters, we can now run the crop cycle simulations/calculations by executing the function below:

```
# Crop cycle simulation
aez.simulateCropCycle(start_doy=1, end_doy=365, step_doy=1, leap_year=False)
```

Function arguments	
start_doy	A single value, corresponding to crop simulations starting Julian date. This is an optional argument. Default value is 0
end_doy	A single value, corresponding to crop simulations ending Julian date. This is an optional argument. Default value is 365
step_doy	A single value, corresponding to spacing (in days) between 2 adjacent crop simulations. This is an optional argument. Default value is 1

leap_year	• True or false, depending on whether the simulating year is a leap year or not. This allows handing leap and non-leap year differently • This is only relevant for monthly climate data because this value will be used in interpolation processes • In case of daily climate data inputs, length of daily climate data vector will be taken as number of days in a year This is an optional argument, and the default value is false
Function returns	
None	

Estimated maximum yield

These functions return the maximum attainable yield under the provided climate conditions in both rain-fed and irrigated conditions. The result's unit is in kilograms per hectare (kg/ha) (Figure 6).

```
# Estimation of Maximum Yield for Rainfed scenario
yield_map_rain = aez.getEstimatedYieldRainfed()
# Estimation of Maximum Yield for Irrigated scenario
yield_map_irr = aez.getEstimatedYieldIrrigated()
```

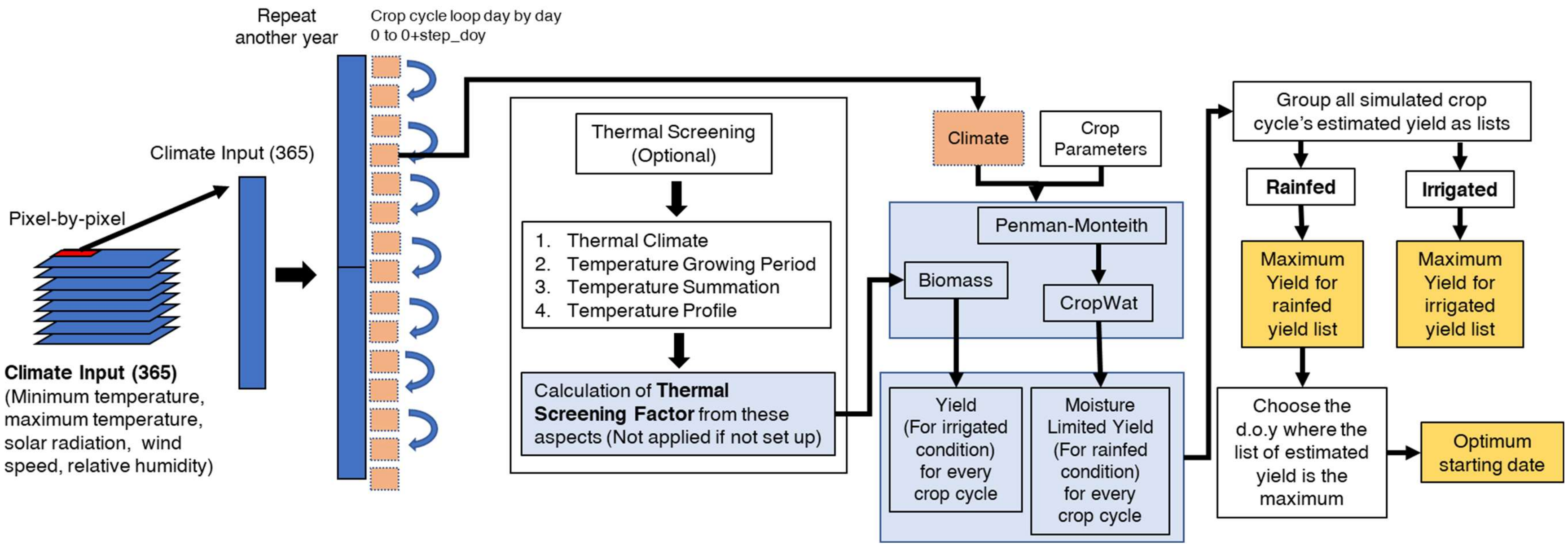
Function arguments	
None	
Function returns	
yield_map_rain	2D NumPy arrays, the maximum attainable yield under the provided climate conditions, under rain-fed conditions [kg/ha]
yield_map_irr	2D NumPy arrays, the maximum attainable yield under the provided climate conditions, under irrigated conditions [kg/ha]

Optimum crop calendar

```
# Optimum starting date for crop cycle
starting_date = aez.getOptimumCycleStartDate()
```

Function arguments	
None	
Function returns	
starting_date	2D NumPy arrays. Each pixel value corresponds to the Julian day of the optimum crop cycle starting date

Figure 6. Estimation of maximum attainable yield (rain-fed and irrigated) and optimum starting date (Module 2)



Source: Authors' own elaboration.

Module 3: Climate constraints

Introduction

In this module, various yield reduction factors will be applied to the maximum attainable yield estimated from Module 2 to consider the constraining effects which are difficult to simulate during the crop cycle simulation (Figure 7). For example, climatic effects can be pests, diseases, and poor workability due to excess soil moisture. These effects, in turn, depend on the different levels of inputs and LGP Equivalent.

All of the reduction factors used in Modules 3, 4, and 5 are located in 2 parameter files corresponding to irrigated and rain-fed conditions. These files MUST be edited with the reduction factors values corresponding to each crop and input level. Users are strongly encouraged to advise to use specific reduction factors based on national research for national-level analysis.

This module considers types of agro-climatic constrains:

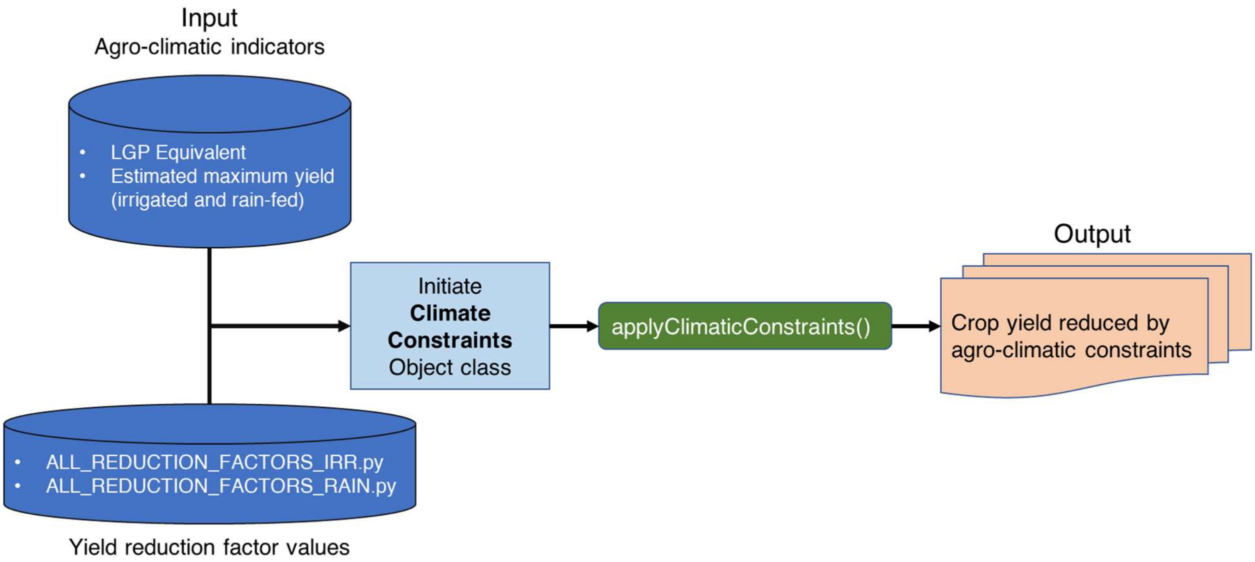
- long term limitation to crop performance due year-to-year rainfall variability;
- pests, diseases, and weeds damages on plant growth;
- pests, diseases, and weeds damages on produce's quality;
- climatic factors affecting the efficiency of farming operations.

See the *GAEZ v4 Model Documentation* for further details on the climate constraints (Fischer *et al.*, 2021).

Similar to the previous modules, this module starts with importing and initiating the class.

```
# Import and create a Class instgance
import ClimateConstraints
obj_constraints = ClimaticConstraints.ClimateConstraints()
```

Figure 7. Overview of Module 3 (climate constraints) workflow



Source: Authors' own elaboration.

Setting up parameter files

The following two parameter files contains the reduction factors values to be used in Module 3, 4, and 5.

File	Remark
ALL_REDUCTION_FACTORS_IRR.py	Reduction factors for irrigated conditions
ALL_REDUCTION_FACTORS_RAIN.py	Reduction factors for rain-fed conditions

Within the two parameter files, the values related to climatic constraint are input as:

```
'''-------------------------------------------------------'''
'''Reduction Factors for Climatic Constraints'''
'''-------------------------------------------------------'''
#defining yield reduction factors based of LGP Equivalent class
lgp_eq_class = [[0,29],[30,59],[60,89],[90,119],[120,149],
                [150,179],[180,209],[210,239],[240,269],
                [270,299],[300,329],[330,366]]

lgp_eq_red_fr = [[25,25,25,25,25,25,25,50,50,50,75,75],
                 [100,100,100,100,100,100,100,100,100,100,100,100],
                 [50,50,50,50,50,75,75,100,100,100,100,75],
                 [100,100,100,100,100,100,100,100,100,100,100,75]]
```

Function arguments	
None	

Parameters	
lgp_eq_class	2D List, corresponding to the LGP Equivalent classes [days]
lgp_eq_red_fr	2D List, corresponding to reduction factors. The rows are corresponding to 4 types of agro-climatic constraints which are mentioned in the above section and columns are corresponding to LGP Equivalent classes as in lgp eq class

Applying climate constraints

This function applies the climate-related yield reduction factors to produce the reduced yield:

```
# Apply climate constraints
yield_out = obj_constraints.applyClimaticConstraints(lgp_eq,yield_in,irr_or_rain)
```

Function arguments

lpg_eq	2D NumPy array, corresponding to LGP Equivalent
yield_in	2D NumPy array, corresponding to the yield before applying the climatic reduction factors
irr_or_rain	A single character (string), indicating whether yield_in is under irrigated(I) or rain-fed condition(R)
Function returns	
yield_out	2D NumPy array. The yield reduced by climatic factors [same unit as yield_in]

Module 4: Soil constraints

Introduction

After applying the agro-climatic constraints onto the maximum attainable yield, we will now apply the soil constraints (Figure 8).

The combination of 7 soil qualities (SQ), which are based on the soil characteristics of each soil unit, and the input level gives us a single yield reduction factor - *Soil Rating*, which will be applied to the remaining yield. For more details on this calculation, please refer to the *GAEZ v4 Model Documentation* (Fischer *et al*., 2021).

- SQ1: Nutrient availability;
- SQ2: Nutrient retention capacity;
- SQ3: Rooting conditions;
- SQ4: Oxygen availability to roots;
- SQ5: Excess salts;
- SQ6: Toxicity;
- SQ7: Workability (constraining field management).

The soil characteristic of each soil unit must be prepared as outlined in Table 3. The two .csv files of the topsoil and subsoil characteristics are:

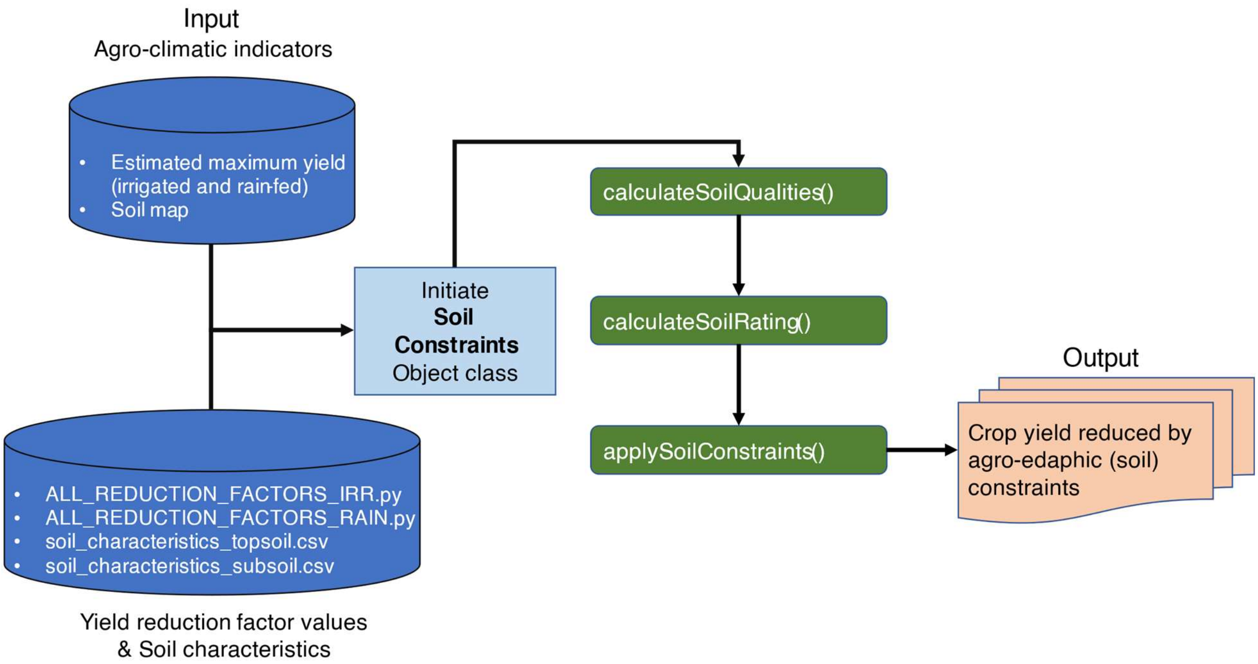
- soil_characteristics_topsoil.csv;
- soil_characteristics_subsoil.csv.

These two files are located in `./input_data/csv/` folder.

First, we must import Module 4 class:

```
import SoilConstraints
soil_constraints = SoilConstraints.SoilConstraints()
```

Figure 8. Overview of Module 4 (soil constraints) workflow



Source: Authors' own elaboration.

Setting up parameter files

The following two parameter files contains the reduction factors values to be used in Module 3, 4, and 5.

File	Remark
ALL_REDUCTION_FACTORS_IRR.py	Reduction factors for irrigated conditions
ALL_REDUCTION_FACTORS_RAIN.py	Reduction factors for rain-fed conditions

```
'''Reduction Factors for Soil Constraints'''
# Value - values of soil characteristics (mush be ascending order)
# Factor - yield reduction factors corresponding to each value

# Soil texture for SQ1
TXT1_value = ['Fine', 'Medium', 'Coarse']
TXT1_factor = [90, 70, 30]

# Soil texture for SQ2
TXT2_value = ['Fine', 'Medium', 'Coarse']
TXT2_factor = [90, 70, 30]

# Soil texture for SQ7
TXT7_value = ['Fine', 'Medium', 'Coarse']
TXT7_factor = [90, 70, 30]

# Soil organic carbon
OC_value = [0, 0.8, 1.5, 2]
```

```
OC_factor = [50, 70, 90, 100]

# Soil pH
pH_value = [3.6, 4.1, 4.5, 5, 5.5, 6]
pH_factor = [10, 30, 50, 70, 90, 100]

# Total exchangeable bases
TEB_value = [0, 1.6, 2.8, 4, 6.5]
TEB_factor = [30, 50, 70, 90, 100]

# Base saturation
BS_value = [0, 35, 50, 80]
BS_factor = [50, 70, 90, 100]

# Cation exchange capacity of soil
CECsoil_value = [0, 2, 4, 8, 10]
CECsoil_factor = [30, 50, 70, 90, 100]

# Cation exchange capacity of clay
CECclay_value = [0, 16, 24]
CECclay_factor = [70, 90, 100]

# Effective soil depth
RSD_value = [35, 70, 85]
RSD_factor = [50, 90, 100]

# Soil coarse material (Gravel)
GRC_value = [10, 30, 90] # %
GRC_factor = [100, 35, 10]

# Drainage. VP: very poor, P: Poor, I: Imperfectly, MW: Moderately well, W:
Well, SE: Somewhat Excessive, E: Excessive
DRG_value = ['VP', 'P', 'I', 'MW', 'W', 'SE', 'E']
DRG_factor = [50, 90, 100, 100, 100, 100, 100]

# Exchangeable sodium percentage
ESP_value = [10, 20, 30, 40, 100] # %
ESP_factor = [100, 90, 70, 50, 10]

# Electric conductivity
EC_value = [1, 2, 4, 6, 12, 100] # dS/m
EC_factor = [100, 90, 70, 50, 30, 10]

# Soil phase rating for SQ3
SPH3_value = ['Lithic', 'skeletic', 'hyperskeletic']
SPH3_factor = [100, 50, 30]

# Soil phase rating for SQ4
SPH4_value = ['Lithic', 'skeletic', 'hyperskeletic']
SPH4_factor = [100, 50, 30]

# Soil phase rating for SQ5
SPH5_value = ['Lithic', 'skeletic', 'hyperskeletic']
SPH5_factor = [100, 50, 30]

# Soil phase rating for SQ6
```

```
SPH6_value = ['Lithic', 'skeletic', 'hyperskeletic']
SPH6_factor = [100, 50, 30]

# Soil phase rating for SQ7
SPH7_value = ['Lithic', 'skeletic', 'hyperskeletic']
SPH7_factor = [100, 50, 30]

# Other soil depth/volume related characteristics rating
OSD_value = [0]
OSD_factor = [100]

# Soil property rating - vertic or not
SPR_value = [0, 1]
SPR_factor = [100, 90]

# Calcium carbonate
CCB_value = [3, 6, 15, 25, 100] # %
CCB_factor = [100, 90, 70, 50, 10]

# Gypsum
GYP_value = [1, 3, 10, 15, 100] # %
GYP_factor = [100, 90, 70, 50, 10]

# Vertical properties
VSP_value = [0, 1]
VSP_factor = [100, 90]
```

Parameters	
Soil texture	
TXT1_value	List of strings, corresponding to soil texture types for SQ1
TXT1_factor	List of numerical values, corresponding to respective reduction factors to TXT1 value
TXT2_value	List of strings, corresponding to soil texture types for SQ2
TXT2_factor	List of numerical values, corresponding to respective reduction factors to TXT2 value
TXT7_value	List of strings, corresponding to soil texture types for SQ7
TXT7_factor	List of numerical values, corresponding to respective reduction factors to TXT7 value
Soil organic carbon	
OC_value	List of numerical values, corresponding to soil organic carbon. Values must me in ascending order
OC_factor	List of numerical values, corresponding to respective reduction factors to OC_value
Soil pH	

Parameters	
pH_value	List of numerical values, corresponding to soil pH. Values must me in ascending order
pH_factor	List of numerical values, corresponding to respective reduction factors to pH_value
Total exchangeable bases	
TEB_value	List of numerical values, corresponding to total exchangeable bases. Values must me in ascending order
TEB_factor	List of numerical values, corresponding to respective reduction factors to TEB_value
Base saturation	
BS_value	List of numerical values, corresponding to base saturation. Values must me in ascending order
BS_factor	List of numerical values, corresponding to respective reduction factors to BS_value
Cation exchange capacity of soil	
CECsoil_value	List of numerical values, corresponding to cation exchange capacity of soil. Values must me in ascending order
CECsoil_factor	List of numerical values, corresponding to respective reduction factors to CECsoil_value
Cation exchange capacity of clay	
CECclay_value	List of numerical values, corresponding to cation exchange capacity of clay. Values must me in ascending order
CECclay_factor	List of numerical values, corresponding to respective reduction factors to CECclay_value
Effective soil depth	
RSD_value	List of numerical values, corresponding to effective soil depth. Values must me in ascending order
RSD_factor	List of numerical values, corresponding to respective reduction factors to RSD_value
Soil coarse material (gravel)	
GRC_value	List of numerical values, corresponding to soil coarse material (Gravel) content as percentage. Values must me in ascending order
GRC_factor	List of numerical values, corresponding to respective reduction factors to GRC_value
Drainage class	
DRG_value	List of strings, corresponding to drainage class (VP: very poor, P: Poor, I: Imperfectly, MW: Moderately well, W: Well, SE: Somewhat Excessive, E: Excessive)

Parameters	
DRG_factor	List of numerical values, corresponding to respective reduction factors to DRG_value
Exchangeable sodium percentage	
ESP_value	List of numerical values, corresponding to exchangeable sodium percentage. Values must me in ascending order
ESP_factor	List of numerical values, corresponding to respective reduction factors to ESP_value
Electric conductivity	
EC_value	List of numerical values, corresponding to electric conductivity. Values must me in ascending order
EC_factor	List of numerical values, corresponding to respective reduction factors to EC_value
Soil phase rating - stagnic or gleyic, present or not	
SPH3_value	List of strings, corresponding to soil phase class for SQ3
SPH3_factor	List of numerical values, corresponding to respective reduction factors to SPH3_value
SPH4_value	List of strings, corresponding to soil phase class for SQ4
SPH4_factor	List of numerical values, corresponding to respective reduction factors to SPH4_value
SPH5_value	List of strings, corresponding to soil phase class for SQ5
SPH5_factor	List of numerical values, corresponding to respective reduction factors to SPH5_value
SPH6_value	List of strings, corresponding to soil phase class for SQ6
SPH6_factor	List of numerical values, corresponding to respective reduction factors to SPH6_value
SPH7_value	List of strings, corresponding to soil phase class for SQ7
SPH7_factor	List of numerical values, corresponding to respective reduction factors to SPH3_value
OSD_value	List of numerical values, corresponding to other soil depth/volume related characteristics rating
OSD_factor	List of numerical values, corresponding to respective reduction factors to OSD_value
Soil property rating - vertic or not	
SPR_value	List of numerical values, corresponding to soil property rating. Values in the list can be either 0 or 1 depending on availability of particular soil phases. Values must me in ascending order

Parameters	
SPR_factor	List of numerical values, corresponding to respective reduction factors to SPR_value
Calcium carbonate	
CCB_value	List of numerical values, corresponding to calcium carbonate content as percentage. Values must me in ascending order
CCB_factor	List of numerical values, corresponding to respective reduction factors to CCB_value
Gypsum	
GYP_value	List of numerical values, corresponding to gypsum content as percentage. Values must me in ascending order
GYP_factor	List of numerical values, corresponding to respective reduction factors to GYP_value
Vertical properties	
VSP_value	List of numerical values, corresponding to vertical properties. Values in the list can be either 0 or 1 depending on availability of vertical properties. Values must me in ascending order
VSP_factor	List of numerical values, corresponding to respective reduction factors to VSP_value

Calculate soil qualities

This function calculates 7 soil qualities for each soil unit based on the input soil characteristics.

```
# Soil qualities
soil_constraints.calculateSoilQualities(irr_or_rain)
```

Function arguments	
irr_or_rain	Single character String, indicating calculations are considered under either rain-fed condition or irrigated condition. 'R' is for rain-fed condition, and 'I' is for irrigated condition

Function returns
None

Calculate soil ratings

This function calculates soil ratings for each soil unit, combining 7 soil qualities based on input level.

```
# Soil rating
soil_constraints.calculateSoilRating(input_level)
```

Function arguments	
input_level	Single character String, corresponding to input level. 'L' is for Low input level, 'I' is for Intermediate input level, and 'H' is for Hight input level
Function returns	
None	

Extracting soil qualities

This function returns 7 soil qualities calculated for each soil unit based on the input soil characteristics.

```
# Extracting soil qualities
soil_qualities = soil_constraints.getSoilQualities()
```

Function arguments	
None	
Function returns	
soil_qualities	2D NumPy array. Each row corresponds to soil units. The first column corresponds to soil unit code. Column 2–8 correspond to the 7 soil qualities

Extracting soil ratings

This function returns 7 soil qualities calculated for each soil unit based on the input soil characteristics.

```
# Extracting soil qualities
soil_ratings = soil_constraints.getSoilRatings()
```

Function arguments	
None	
Function returns	
soil_ratings	2D NumPy array. Each row corresponds to soil units. The first column corresponds to soil unit code. The second column corresponds to the soil rating of each soil unit

Applying soil constraints

This function applies all soil-related yield reduction factors.

```
# Soil Constraints
yield_out = soil_constraints.applySoilConstraints(soil_map, yield_in)
```

Function arguments	
soil_map	2D NumPy array, corresponding to soil unit. Each pixel value must be soil unit code. This code is used to match the soil rating with the input yield
yield_in	2D NumPy array, corresponding to the yield before applying the soil reduction factors
Function returns	
yield_out	2D NumPy array. The yield reduced by soil-related factors [same unit as yield_in]

Module 5: Terrain constraints

Introduction

This section introduces the yield reduction due to terrain slope, soil erosion, and Fournier index (FI) (Figure 9). The FI is based on the monthly precipitation (climate-related). These yield reduction factors will be applied to the maximum attainable yield. For detailed calculations for this section, please refer to the *GAEZ v4 Model Documentation* (Fischer *et al.*, 2021).

First, we must import Module 5 class:

```
import TerrainConstraints
terrain_constraints = TerrainConstraints.TerrainConstraints()
```

Setting up parameter files

The following two parameter files contains the reduction factors values to be used in Module 3, 4, and 5.

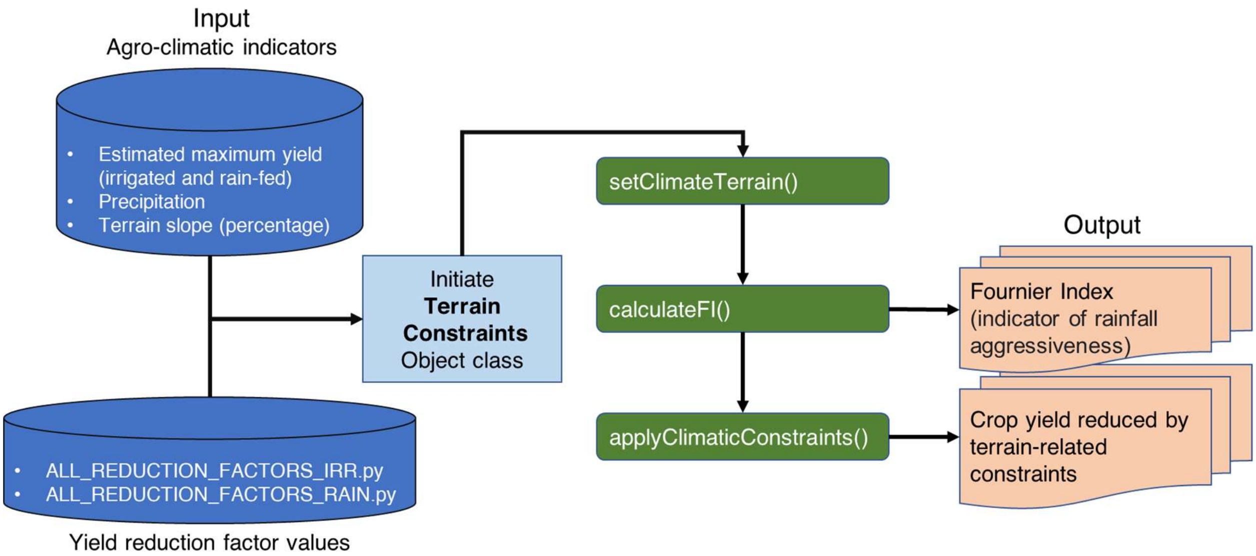
File	Remark
ALL_REDUCTION_FACTORS_IRR.py	Reduction factors for irrigated conditions
ALL_REDUCTION_FACTORS_RAIN.py	Reduction factors for rain-fed conditions

```


'''Reduction Factors for Terrain Constraints'''
'''--------------------------------------------------------'''
# Classes of slopes (Percentage Slope)
Slope_class = [[0,0.5],[0.5,2],[2,5],[5,8],[8,16],[16,30],[30,45],[45,100]]
# Classes of Fournier index
FI_class=[[0,1300],[1300,1800],[1800,2200],[2200,2500],[2500,2700],[1700,10000
0]]
# Sample data are for irrigated-intermediate input-wetland rice
# Rows corresponding to FI class and columns corresponding to slope class
Terrain_factor =[[100,   100,   75,    50,    25,    0,     0,     0],
                 [100,   100,   100,   100,   100,   75,    0,     0],
                 [100,   100,   100,   100,   75,    25,    0,     0],
                 [100,   100,   100,   100,   50,    0,     0,     0],
                 [100,   100,   100,   100,   25,    0,     0,     0],
                 [100,   100,   100,   100,   25,    0,     0,     0]]


```

Parameters	
slope_class	2D List, corresponding to slope classes. Slope unit must me percentage slope
FI_class	2D List, corresponding to Fournier index (FI) classes

Parameters	
Terrain_factor	2D List, corresponding to reduction factors. The rows are corresponding to FI classes and the columns correspond to slope classes

Figure 9. Overview of Module 5 (terrain constraints) workflow



Source: Authors' own elaboration.

Setting up inputs

Climate and terrain inputs

This function allows users to set up the monthly precipitation and terrain slope data. This is a mandatory step before executing further calculations.

```
# Set up climate and slope data
terrain_constraints.setClimateTerrainData(precipitation, slope)
```

Function arguments	
precipitation	3D NumPy array corresponding to monthly precipitation. Unit of monthly precipitation can be of any unit, since Fournier index (FI) is a ratio, unit conversion factors will be cancelled out
slope	2D NumPy array, corresponding to terrain slope. [percentage slope]
Function returns	
None	

Calculate Fournier index

This function calculates Fournier index (FI) based on the input monthly precipitation. FI is a simple index that indicates the potential of soil erosion based on monthly precipitation.

```
# Calculate Fournier index
terrain_constraints.calculateFI()
```

Function arguments	
None	
Function returns	
None	

Extract Fournier index

This function returns Fournier index (FI), which is based on the input monthly precipitation. This is an optional function. FI can be extracted with this function if required.

```
# Extract Fournier index
fi = terrain_constraints.getFI()
```

Function arguments	
None	
Function returns	
fi	2D NumPy array, corresponding to Fournier index (FI) based on the input monthly precipitation

Applying terrain constraints

This function applies the terrain-related yield reduction factors.

```
# Apply terrain constraints
```

```
yield_out = terrain_constraints.applyTerrainConstraints(yield_in, irr_or_rain)
```

Function arguments	
yield_in	2D NumPy array, corresponding to the yield before applying the terrain-related reduction factor. This can be the yield under either irrigated or rain-fed conditions from Module 4
irr_or_rain	Single character String, indicating yield in is in either rain-fed or irrigated condition. 'R' is for rain-fed condition, and 'I' is for irrigated condition
Function returns	
yield_out	2D NumPy array. The yield reduced by soil-related factors [same unit as yield_in]

Module 6: Economic suitability analysis

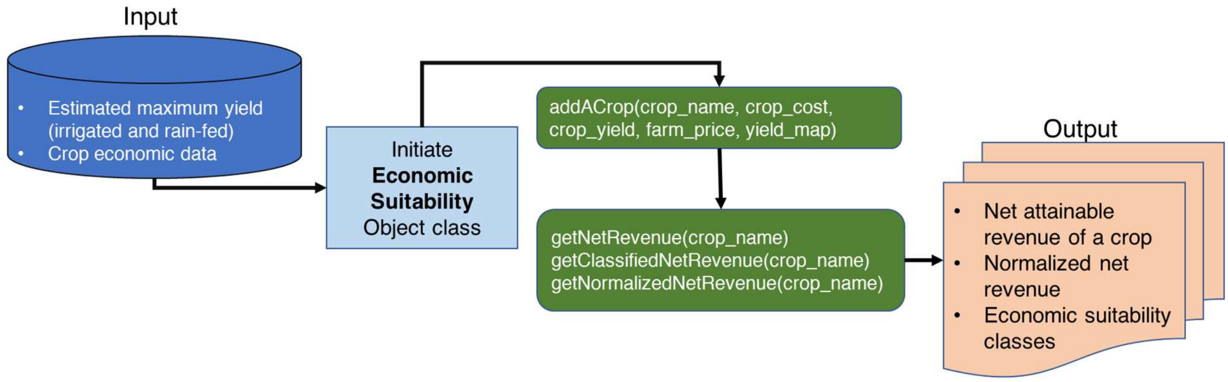
Introduction

Economical suitability analysis module is the most recent addition to AEZ framework (Figure 10). This module converts AEZ's final crop suitability (a result of the previous 5 modules) into an economic suitability. Additionally, all crops of interest are compared to the umbrella crop (crop with the highest economical potential) in order to indicate and map out its comparative advantage in terms of an attainable net revenue relative to the best available option. For more detailed calculations, refer to Module 6 chapter in national Agro-economic Zoning for major crops in Thailand (NAEZ) report (FAO, 2017a).

First, we have to import the Module 6 class and create an instance of that class as below.

```
import EconomicSuitability
econ_su = EconomicSuitability.EconomicSuitability()
```

Figure 10. Overview of Module 6 (economic suitability) workflow



Source: Authors' own elaboration.

Crop parameters inputs

This function allows users to set up the crop parameters for an economic analysis. The key inputs for Module 6 are the crop yield information generated from the previous 5 modules in PyAEZ, market prices, and the costs of the crop.

This function will be called multiple times as it performs a comparative economic analysis. This is a mandatory function to run before any further calculations.

```
# Crop parameter input
econ_su.addACrop(crop_name, crop_cost, crop_yield, farm_price, yield_map)
```

Function arguments	
crop_name	A single string value, corresponding to the crop name that you are adding. This name will be used later to extract output for each crop

crop_cost	• 1D NumPy array, corresponding to the cost of production for each yield values in crop yield variable. • Values of crop_cost and crop_yield must be corresponding to each other, and they must be in ascending order. • Units of this variable must be in cost per hectare. • All the costs and prices in this module must be in same currency.
crop_yield	• 1D NumPy array, corresponding to the yield values. • Values of crop_cost and crop_yield must be corresponding to each other, and they must be in ascending order. • Units of this variable must be in tonnes per hectare.
farm_price	• 1D NumPy array, corresponding to the historical crop price that farmers sell. • The price array is used to calculate distribution (mean) of prices. • Unit: price (same currency throughout unit per tonne).
yield_map	2D NumPy array, corresponding to yield map of the crop. Unit: tonnes per hectare
Function returns	
None	

Net revenue

This function returns net revenue from the crop identified with 'crop_name'.

```
# Get the Net Revenue
crop_rev = econ_su.getNetRevenue(crop_name)
```

Function arguments	
crop_name	A single string value, corresponding to the crop name
Function returns	
crop_rev	2D NumPy array, net revenue of the input crop_name. Unit: revenue per hectare

Classified net revenue

This function returns classified net revenue for the crop 'crop_name'. The classification scheme for crop net revenue is outlined in Table 10.

```
# Net revenue classification
crop_rev_class = econ_su.getClassifiedNetRevenue(crop_name)
```

Function arguments	
crop_name	A single string value, corresponding to the crop name
Function returns	
crop_rev_class	2D NumPy array, classified net revenue of the input crop_name

Table 10. Net revenue classification

Pixel value	Net revenue class	Description
0	Not suitable	Net revenue less than 0%
1	Very marginal	Net revenue between 0% and 10%
2	Marginal	Net revenue between 10% and 20%
3	Moderate	Net revenue between 20% and 30%
4	Medium	Net revenue between 40% and 50%
5	Good	Net revenue between 50% and 63%
6	High	Net revenue between 63% and 75%
7	Very high	Net revenue is equivalent to 75% or more than the overall maximum

Source: FAO. 2017. *National Agro-Economic Zoning for Major Crops in Thailand (NAEZ) (Project TCP/THA/3403): NAEZ model implementation and results : final report*

Normalized net revenue

This function returns the normalized net revenue for the crop 'crop_name'. The normalization is done, firstly, by assigning the highest possible net revenue, among crops passed through the module, to 1 (i.e. an umbrella crop). Secondly, the net revenue values of other crops are normalized as a portion of the umbrella crop (0–1 scale). This normalization process is performed separately for each pixel.

```
# Normalized net revenue
crop_rev_norm = econ_su.getNormalizedNetRevenue(crop_name)
```

Function arguments	
crop_name	A single string value, corresponding to the crop name
Function returns	
crop_rev_norm	2D NumPy array, normalized net revenue of the input crop_name. Output values between 0 and 1

Utility calculations

Introduction

This section will outline the additional calculation routines used throughout the PyAEZ's 6 main modules. These functions are contained within a class called 'UtilitiesCalc'.

The functions are as follows:

Functions in UtilitiesCalc	Description
interpMonthlyToDaily	Perform monthly-to-daily interpolation for climate data
averageDailyToMonthly	Aggregate daily climate data into monthly data
generateLatitudeMap	Generate latitude map as 2D NumPy array, by linearly interpolating the bottom and top latitudes of the study area
classifyFinalYield	Classify yield estimation and produce suitability map according to AEZ's classification scheme
saveRaster	Saving 2D NumPy arrays as GeoTIFF raster files
averageRasters	Averaging a list of rasters in the time-dimension
windSpeedAt2m	Convert windspeed from a particular altitude to 2 m above the surface

To use this UtilitiesCalc class, we first must import and create a class instance:

```
import UtilitiesCalc
obj_utilities = UtilitiesCalc.UtilitiesCalc()
```

Monthly-to-daily interpolation

This function performs interpolation of monthly climate data into daily climate data with quadratic spline interpolation as recommended in AEZ framework. The interpolation is performed between `cycle_begin` and `cycle_end` Julian dates.

```
# Monthly-to-daily interpolation
daily_vector = obj_utilities.interpMonthlyToDaily(monthly_vector, cycle_begin,
cycle_end, no_minus_values=False)
```

Function arguments	
monthly_vector	1D NumPy array with 12 elements corresponding to the monthly climate data
cycle_begin	A single value corresponding to the beginning Julian date of the crop cycle
cycle_end	A single value corresponding to the ending Julian date of the crop cycle
no_minus_values	True or false. If this argument is True, negative values will be forced to be zero. This helps getting rid of any unrealistic negative interpolated values in the climate

	parameters such as precipitation data. If this argument is false, then negative values are allowed. By default, this argument is set as false and it's not a mandatory argument to pass
Function returns	
daily_vector	1D NumPy array, corresponding to the output daily climate data between cycle_begin and cycle_end Julian dates

Daily-to-monthly aggregation

This function aggregates daily climate data into monthly climate data. The aggregation is done by averaging the data in each month.

```
# Daily-to-monthly aggregation
monthly_vector = obj_utilities.averageDailyToMonthly(daily_vector)
```

Function arguments	
daily_vector	1D NumPy array with 365 elements corresponding to the daily climate data
Function returns	
monthly_vector	1D NumPy array with 12 elements corresponding to the aggregated monthly climate data

Create latitude map

The latitude map is created by linearly interpolating the bottom and the top latitude values of the study area, as defined by the user's input.

```
# Generate latitude map
lat_map = obj_utilities.generateLatitudeMap(lat_min, lat_max, im_height, im_width)
```

Function arguments	
lat_min	A single value corresponding to the minimum latitude as decimal degree
lat_max	A single value corresponding to the maximum latitude as decimal degree
im_height	A single value corresponding to height of resulting latitude map as number of pixels
im_width	A single value corresponding to width of resulting latitude map as number of pixels
Function returns	
lat_map	2D NumPy array, corresponding to latitude map. The resulting dimension of the latitude map will be im_height and im_width respectively

Classify the final crop yield

This function classifies yield estimations and produces suitability maps according to classification scheme defined in AEZ framework. The classification scheme consists of 5 classes (very suitable, suitable, moderately suitable, marginally suitable, and not suitable) (Table 11).

```
# Classification of yield estimation
est_yield_class = obj_utilities.classifyFinalYield(est_yield)
```

Function arguments	
est_yield	2D NumPy array corresponding to the estimated yield
Function returns	
est_yield_class	2D NumPy array, corresponding to the suitability map after yield classification

Table 11. Yield suitability classification

Pixel value	Suitability class	Description
1	Not suitable	Yields between 0% and 20% of the overall maximum yield
2	Marginally suitable	Yields between 20% and 40% of the overall maximum yield
3	Moderately suitable	Yields between 40% and 60% of the overall maximum yield
4	Suitable	Yields between 60% and 80% of the overall maximum yield
5	Very suitable	Yields are equivalent to 80% or more of the overall maximum yield

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

Saving GeoTIFF rasters

This function allows saving 2D numpy array as GeoTIFF raster file. This function can be used to save any output of this PyAEZ package as a GeoTIFF raster file.

```
# Save 2D NumPy to GeoTIFF
obj_utilities.saveRaster(ref_raster_path, out_path, numpy_raster)
```

Function arguments	
ref_raster_path	String, locating reference raster. This must be GeoTIFF raster file. Projection information is copied from this raster to final raster. Any input GeoTIFF raster to PyAEZ package with Projection information can be passed for this argument
out_path	String, the desired location to save the output GeoTIFF file (with .tif extension)
numpy_raster	2D NumPy array, corresponding to the raster that user wants to save. Please be aware that the dimensions of this NumPy array and that of reference GeoTIFF raster must be the same in order to avoid error
Function returns	
None	

Averaging raster files

This function averages list of raster files in time dimension. Some calculations in the AEZ framework are recommended to perform with averaged climate data for 30 years. This function can be used for such calculations.

```
# Averaging raster files
avg_raster = obj_utilities.averageRaster(raster_3d)
```

Function arguments	
raster_3d	3D NumPy array, corresponding to any climate data. The averaging will be done by the time dimension (across the years)
Function returns	
avg_raster	2D NumPy array, the averaged climate data - into 'one year' worth of data

Calculate wind speed at 2 m altitude

This function converts wind speed from a particular altitude to wind speed at 2 m altitude. All of the wind speed values used in PyAEZ calculations are at 2 m altitude, however, it is common for climate data services to offer the wind speed at 10 m altitude, hence this conversion.

```
# Converting to wind speed at 2 m altitude
wind_speed_2m = obj_utilities.windSpeedAt2m(wind_speed, altitude)
```

Function arguments	
wind_speed	A NumPy array (can be 1D, 2D or 3D), corresponding to wind speed
altitude	A single value corresponding to the altitude (above ground)[m]
Function returns	

wind_speed_2m	Converted wind speed at 2 m altitude as a NumPy array. Units will be same as unit of wind_speed

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A Python package for Agro-Ecological Zoning

Agro-Ecological Zoning (AEZ) framework was developed as a tool to analyse the effect of climate on land use and agricultures, as well as helping to optimise the crop cycle to produce the best yield possible. PyAEZ is an open- source Python package which offers AEZ calculations for user to implement for their regional AEZ analyses. This technical document contains detailed descriptions of all the AEZ modules and functions in PyAEZ.

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