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Climate Change Vulnerability Assessment in Highlands

A Guidance Manual

AIT Asian Institute of Technology

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TEAM GROUP

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Abbreviations

A	Adaptive Capacity
ADB	Asian Development Bank
AET	Actual Evapotranspiration
AI	Artificial Intelligence
AIT	Asian Institute of Technology
CBA	Community Based Adaptation
CBDRM	Community Based Disaster Risk Management
CC	Climate Change
CDF	Cumulative Distribution Function
CIESIN	Center for International Earth Science Information Network
E	Exposure
FAO	Food and Agriculture Organization
GAEZ	Global Agroecological Zones
GCMs	General Circulation Models
GHGs	Greenhouse Gases
HI	Harvest Index
HKH	Hindi Kush Himalaya
IAM	Integrated Assessment Modelling
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
PET	Potential Evapotranspiration
PRA	Participatory Rural Appraisal
PWM	Probability Weighted Moment
RCMs	Regional Climate Models
RID	Royal Irrigation Department
S	Sensitivity
SEDAC	Socioeconomic Data and Applications Center
SPEI	Standardized Precipitation-Evapotranspiration Index
SSP	Shared Socioeconomic Pathway
TMD	Thai Meteorological Department
UN	United Nations
UNEP	United Nations Environment Program
VA	Vulnerability Assessment
VI	Vulnerability Index
WCMC	World Conservation Monitoring Centre

1. Introduction

1.1 About this guidance manual

Climate change is a generational issue that humanity is facing today, and all countries are vulnerable to climate change irrespective of their developmental state. One may have noticed that completing the first sentence of this section itself is difficult without using the word ‘vulnerable’. This shows that vulnerability is at the center of why humanity and nature experience the adverse impacts of climate change and hence it is an essential element of addressing climate change. One of the important reasons why climate change impacts vary from location-to-location stems from the fact that the factors that underline the vulnerability of elements at risk or elements exposed vary from location to location. The other factor is the hazard itself, which has intrinsic variability in terms of duration and intensity.

Considering the importance of understanding and addressing the vulnerability of society and the environment to climate change, several approaches have been developed. These approaches often tend to take the shape of the local context and needs. It’s an important ability for the vulnerability assessment (VA) methods to be able to be applied to location-specific contexts as methods that are designed for a different context may not contribute to the full understanding of local contexts if used elsewhere. Hence, the objective of this guidance manual is to elicit a VA methodology that applies to highlands. This ability stems from the fact that the methodology presented in this manual was tested under highland conditions in Thailand.

The terms guidance manual, guidelines, technical manual etc. has often been interchangeably used with little or no difference. Irrespective of such interchangeable use of these terms, in this manual we consider a guidance manual as a documentation aid that helps a user to start from the beginning to the end of an objective assessment in a structured manner. Hence, this guidance manual is designed for users to get to know the VA and to be able to carry out the VA. For the user to be able to use this manual effectively, this manual must be used along with the analytical booklet on “**Climate Change Vulnerability of Highland Agriculture–Insights from Nan Province, Thailand**” that has been developed to provide deeper insights into the technical aspects of climate change projections, crop modelling and finally calculation of vulnerability index (VI).

This manual provides well-structured step-by-step guidance on how to conduct VA. It briefly discusses the science behind VA, especially keeping in view the users and the end-use, and keeping in view the tools/software/equipment to be used. This manual has a very clear scope and context in terms of users and what it should be used with. The treatment of language in the manual is different from those used in peer-reviewed scientific literature, without losing the meaning and intent, making this manual more accessible to a wide range of users. It is expected that the manual will have a high speed of use for low-skill and low-knowledge users, and they are expected to benefit immensely from this manual. This manual is not prescriptive in nature. It only provides the necessary broad guidance needed to conduct VA while still leaving room for the reader to use their innovation.

1.2 Target users

The typical user of this manual has a basic to mid-level understanding of climate change, vulnerability, climate change risks, and climate adaptation. The users may or may not have direct working experience on climate change issues including VA and intends to enter into the field of VA and develop the necessary skill to conduct VA. We expect that the user of this manual may be working in a government department (e.g., agriculture department), an NGO, a research institution, or a developmental organization that is mandated to conduct VA with an end goal of developing some kind of risk reduction intervention including that of climate change adaptation plans.

Because of the sectoral focus of this manual, we expect that the user of this manual has in-depth domain expertise in the field of agriculture and allied fields. Such an understanding is essential to be able to use the modelling tools described in the manual. In addition, since the manual heavily relies also on participatory methods, we expect that the user can work with farming communities in agriculture and rural development. Finally, the assessing entity or professional must be tasked to develop agriculture plans or programs targeting vulnerable farmers/regions/societies focusing on rural agricultural areas and production centers. The reader of this manual is expected to have an end-use or user in view as it is essential for the VA conducted and the VA outputs generated are useful.

1.3 The flow of the guidelines

These guidelines are prepared in such a way as to take the users through a sequence of steps necessary towards developing final VA outputs. The flow of this guidelines document is explained below.

Underlying concepts: First, the concepts underlying the VA are discussed. Since there are multiple stakeholders engaged in VA and each stakeholder may have a different understanding of VA, it is essential that a common understanding is developed before actual VA is conducted.

Vulnerability assessments in highlands: Subsequently, the guidelines present the highland conditions, constraints, and opportunities for conducting VA in highland conditions. Highland ecosystems are one of the meagerly understood ecosystems and there are very few VAs available to suit highlands. These guidelines aim to appeal to stakeholders from the highlands, not just limited to the highlands of Thailand. Further, these VAs benefit from the experiences generated from the VAs conducted in Thailand. Efforts were made to ensure that the steps involved are also applicable to highlands elsewhere.

Setting the stage: VAs are resource intensive, both in terms of financial and human resources, and they demand multi-stakeholder engagement due to the multi-user and multi-disciplinary nature of the VAs. Even if VAs are designed for a specific sub-sector, this basic nature of VAs remains. Hence, elaborate planning is involved for an effective VA exercise.

Goal and use case scenarios: Since VAs involve multiple stakeholders and since these stakeholders may have different objectives for assessing VA, it is essential that a common understanding is achieved among the users of VA. A common understanding is necessary on the goal of VA and various use case scenarios in which the VA results may be used.

Data preparation: VAs involve the use of multiple data points representing various socio-economic and bio-physical elements. Since these data points originate from different sources, measured using different methods that vary in their precision and accuracy, the VA conducted using these data points can suffer from errors. Data errors are even more important in highland conditions where the data is sparsely available. Hence, it is important to understand the data types, data sources, types of errors, sources of errors and means to address these errors so that a VA can be conducted with high repeatability and reliability.

Understanding uncertainty in VAs: In addition to errors in data used for VA, VAs can also suffer from uncertainty. These uncertainties largely stem from the basic nature of climate change projections. This inherent uncertainty can limit the use of VAs for future decisions. The users must be well aware of these limitations and be able to make appropriate decisions based on the VA.

Hazard, exposure, sensitivity, and adaptive capacity: VAs involve three basic elements i.e., hazard, exposure, sensitivity and adaptive capacity. Each of these elements is discussed in detail in the respective sections of the guidelines even though the tools used may not have separate workflows for assessing these elements. By separating these, the guidelines provide conceptual clarity to the user while conveying the operational requirements for conducting VA.

Vulnerability assessment: Generating the final output of VA involves bringing together the elements of hazard, exposure, sensitivity and adaptive capacity. Generating the VA output needs to take into consideration the use case scenario in view and the objective of the users. Hence, the section also discusses presenting the VA information appropriately to the user's needs.

Using the VA for decision-making: Once the VA output is generated, its use can follow the use case scenario identified at the beginning of the VA exercise. One of the common use case scenarios for VA is to develop community-level climate change action plans including community-based climate change adaptation plans for the agriculture sector in highland conditions.

2. Understanding Climate Change

Understanding of climate change starts with understanding of "**Climate**" itself and how it differs from its mostly commonly known counterpart "**Weather**".

2.1 Weather versus climate

Weather is the state of atmosphere for a given instant of time. It can be described using atmospheric state variables such as precipitation, temperature, pressure, wind velocity, humidity, solar radiation etc. Weather is described for a relatively short period of time: sub-daily, daily to few days or month. Hence, one can define daily weather as sunny, cloudy, rainy, hot, cold or so on.

On the other hand, Climate is the long-term pattern of weather conditions prevailing in an area. In simple words it is the average of weather for a long period time, 30 years by convention. Hence climate change can be described as a change in weather pattern over a longer period of time for a given area. We can understand such changes by analyzing aforementioned atmospheric state variables (also called climate variables) at long-term. For historical analysis, observed data or physical evidence based estimated values are used whereas, future climate projection is made based upon numerical model simulation.

2.2 Terminologies in climate change

There are several terminologies used in climate change which are described hereafter.

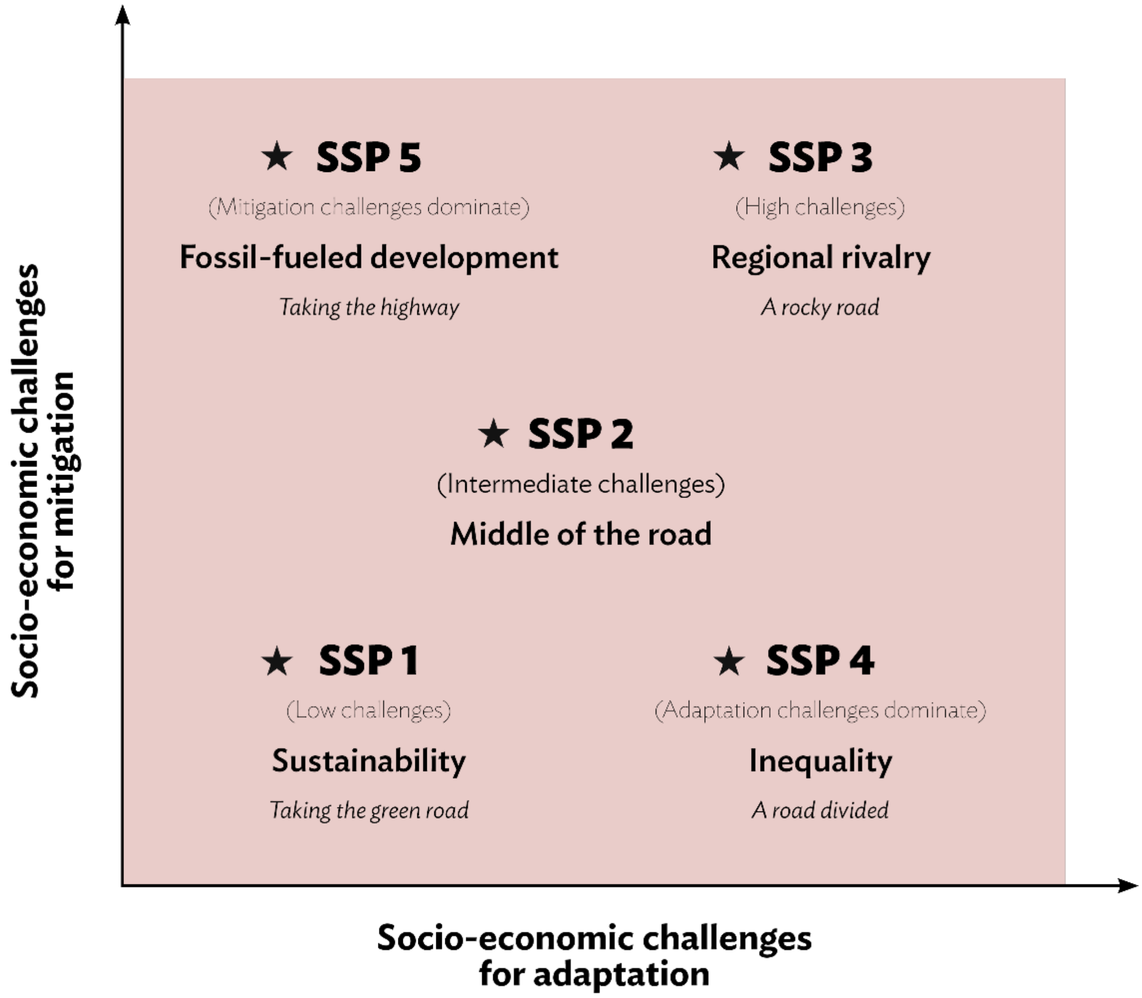
2.2.1 General Circulation Models (GCMs)

General Circulation Models (GCMs) are numerical models which try to simulate the behavior of earth's atmosphere and/or ocean over a period of time. These models consider earth as a sphere with horizontal and vertical grids representing the atmosphere, ocean and land surface. Each 3D grid is the computational point. Once the model parameters are set with initial and boundary conditions, Navier-Stokes equation on a rotating sphere is used to simulate the oceanic and atmospheric processes. Thus, GCMs are able to simulate earth's climatic conditions. For historical period we can easily simulate the climatic conditions providing observed initial conditions (for example: atmospheric temperature and pressure, wind speed and direction, moisture content, sea surface temperature, sea ice coverage, land surface characteristics at starting time step) and boundary conditions (for example: sea surface temperature, sea ice coverage, land surface characteristics, solar radiation, greenhouse gas concentrations at model boundaries such as ocean and land surface, land and atmosphere, atmosphere and space). However, for future we need to create some plausible scenarios which could better describe the evolution of human societies and their interaction with the environment. Such scenarios can be used to update the boundary conditions within GCMs during future climate projection.

2.2.2 Shared Socioeconomic Pathways (SSPs)

SSPs are scenarios developed by collaborative effort among Integrated Assessment Modelling (IAM) researchers and are based on a wide range of scientific inputs, including demographic projections, economic models, and energy-economy models. These scenarios are widely accepted and has been used by IPCC sixth assessment report (AR6). There are five different scenarios based upon socio-economic challenges for mitigation and adaptation as shown in Figure 1.

Figure 1:
SSPs mapped in the challenges for mitigation and adaptation space.



Within these five SSP scenarios, there are seven different emission scenarios based upon estimation of Greenhouse Gases (GHGs) emission as described in Table 1. Although the likelihood of the scenarios is not described by IPCC, SSP2–4.5 is considered as most likely and SSP5–8.5 as highly unlikely. GCMs are used to simulate future climate conditions upon all the scenarios to have an idea on different possibilities of evolution of future climate.

Table 1:
Summary of SSP scenarios (source: IPCC AR6).

SSP	SSP scenarios description	Emission scenarios	Emission scenarios description	Warming range (ÁC) (2081ï 2100)
SSP1	**Sustainability**: Low economic growth, low energy use and low greenhouse gas emissions.	SSP1ï 1.9	**Very low GHG emissions**: CO2 emissions cut to net zero around 2050	1.0 ï 1.8
		SSP1ï 2.6	**Low GHG emissions**: CO2 emissions cut to net zero around 2075	1.3 ï 2.4
SSP2	**Middle of the Road**: Average economic growth, energy use and emissions, reflecting a "business-as-usual" scenario.	SSP2-4.5	**Intermediate GHG emissions**: CO2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.1 ï 3.5
SSP3	**Regional Rivalry**: High economic growth, high energy use and high emissions, with a focus on regional competition and conflict.	SSP3ï 70	**High GHG emissions**: CO2 emissions double by 2100	2.8 ï 4.6
SSP4	**Inequality**: Rapid economic growth, high energy use and high emissions, with growing income and wealth disparities	SSP4ï 3.5	**High GHG emissions**: Limiting global warming to 3.5ÁC above pre-industrial levels	<3.5
		SSP4ï 6.0	**High GHG emissions**: Limiting global warming to 6.0ÁC above pre-industrial levels	<6.0
SSP5	**Fossil-fuelled development**: Rapid economic growth, very high energy use and very high emissions, based on a heavily fossil-fuel-based energy system.	SSP5ï 8.5	**Very high GHG emissions**: CO2 emissions triple by 2075	3.3 ï 5.7

2.2.3 Downscaling

GCMs are used to simulate the historical and future climate at much coarser resolution because of high computational requirement and much needed representation of large scale oceanic and atmospheric circulation. Thus, results from GCMs cannot be used directly in most instances. Downscaling is the process of deriving high-resolution climate variables from available low-resolution GCM data. Downscaling of climate variables at local scale can provide local climatic conditions in future to evaluate the potential impacts due to climate change. There are two available methods for downscaling.

Dynamic downscaling

Dynamic downscaling is done through use of GCM like model but at regional scale known as Regional Climate Models (RCMs). RCMs can be imagined as a zoom in lens embedded within GCMs. They use boundary conditions from a GCM (also known as driving GCM) and consider regional scale climate variables at much finer grid cells to simulate climate at high resolution.

Although RCMs use GCM data to simulate the climate, output from RCMs are not further fed into the GCM for continuous simulation due to demanding computational capacity.

Statistical downscaling

Since dynamic downscaling is quite resource hungry (technical skill and computational resources), we can't rely on it all the time. On contrary, statistical downscaling method derives statistical relationship between large-scale climate variables and local-scale climate variables during historical period which is applied during the future period to simulate high resolution climate data. The statistical downscaling method assumes that the relationship between large-scale climate variables and local variables will remain the same during future periods.

2.2.4 Bias correction

Simulations from GCMs/RCMs often have bias when compared with the observed dataset during the historical period. Such a discrepancy is the product of imperfect conceptualization, discretization and spatial averaging within the grid cells of GCMs/RCMs (Teutschbein and Seibert, 2010). Such discrepancy in the GCMs/RCMs result can be removed by using several bias correction techniques such as:

(1) Linear scaling method
(2) Local intensity scaling (LOCI) of precipitation
(3) Power transformation method
(4) Variance scaling (VARI) of temperature
(5) Quantile mapping method

Complexity of these techniques vary widely whereas their ability might not be directly proportional to the complexity and each method is likely to produce different result. It is best to know the techniques involved and select appropriate method based upon use case scenario.

Empirical quantile mapping

In this manual we propose to use Empirical quantile mapping (a type of quantile mapping) technique since it can effectively correct bias in mean, standard deviation and wet-day frequency as well as quantiles. Compared to other methods quantile mapping is a rather complex method of bias correction. Moreover, it can be used with grided observed dataset to statistically downscale the GCMs/RCMs data.

Table 2:
Equations used for Empirical Quantile Mapping technique.

$$P_{his}(d)^* = F^{-1}_{obs,m}\left[F_{his,m}\left(P_{his,m}\right)\right] \quad (1)$$

$$P_{fut}(d)^* = F^{-1}_{sim,m}\left[F_{sim,m}\left(P_{sim,m}\right)\right] \quad (2)$$

$$T_{his}(d)^* = F^{-1}_{obs,m}\left[F_{his,m}\left(T_{his,m}\right)\right] \quad (3)$$

$$T_{fut}(d)^* = F^{-1}_{sim,m}\left[F_{sim,m}\left(T_{sim,m}\right)\right] \quad (4)$$

Where, P = Precipitation, T = Temperature, d = daily, m = monthly* = bias corrected, his = Raw GCM data, obs = observed data, fut = Raw GCM future data, F = Cumulative Distribution Function (CDF), F^(-1) = inverse of CDF.

Cumulative distribution function (CDF) of a real-valued random variable X at x, is defined as the probability of X ≤ x as described in equation (5) .

$$F_X(x) = P(X \le x) \quad (5)$$

Where, $F_X(x)$ is the CDF and P is the probability of random variable X at point x.

We can use a variety of software or programming language to conduct empirical quantile mapping. Here, we have chosen "qmap" package in R programming language. A sample of the code is provided in Section **15.2**.

2.2.5 Performance evaluation metrics

The performance of Bias correction, and statistical downscaling should be justified with evaluation metrics. Indeed, any perturbation of data or estimation of measurement, for example crop modelling calibration and validation (refer section: Exposure) can be evaluated using such metrics. Here, we have selected four different evaluation metrics based upon their ability to measure discrepancy between observed and estimated value or pattern between them. Also, some of the metrics are standardized such that they can be used to evaluate performance across variables.

Root Mean Square Error (RMSE)

RMSE, as the name suggest is the square root of average squared errors between observed and estimated value (equation (6)). Since it uses square of errors it is quite sensitive to outliers. A few large errors can disproportionately affect RMSE. The unit of RMSE is same as of measured quantity and it can range from 0 to infinity, zero being the ideal value. RMSE can never be negative.

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(O_i - E_i)^2}{n}} \tag{6}$$

Where, O_i and E_i are observed and estimated values respectively.

RMSE to Standard deviation Ratio (RSR)

Although it is commonly accepted that, lower the RMSE, better is the performance, only Singh et al. (2005) has published a guideline to qualify what is considered a low RMSE based on the observed standard deviation. Based on the recommendation by Singh et al., (2005) an evaluation statistic, named the RMSE-observations standard deviation ratio (RSR), was developed (equation (7)). RSR standardizes RMSE using observed standard deviation, and it combines both error indices along with additional information as recommended by Legates and McCabe Jr. (1999). RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect, to a large positive value. The lower the RSR, lower will be the RMSE, and better the performance.

$$\boldsymbol{RSR} = \sqrt{\frac{\sum(\boldsymbol{O_i} - \boldsymbol{E_i})^2}{\sum(\boldsymbol{O_i} - \boldsymbol{E_{mean}})^2}} \tag{7}$$

Where, O_i and E_i are observed and estimated values respectively and E_{mean} is the estimated mean.

Coefficient of Determination (RSQ)

Coefficient of determination (R^2) (equation (8)) is just the squared of correlation coefficient and is usually used rather than correlation coefficient due to its flexibility as it eradicates the negative value and can measure the dispersion of the estimated values (Krause et al., 2005). The Pearson's correlation coefficient is defined as the ratio of covariance between two variables to their standard deviation (Korn and Korn, 2000). Coefficient of determination measures how difference in one variable is explained by difference in second variable. Thus, it can be taken as ability of predictor (observed value) to estimate predictand (estimated value). Also, it can be taken as measure of match in pattern between observed and estimated values. The range of R^2 is between 0 and 1 with 1 being the perfect fit and 0 referring to no relation between estimated and observed value. R^2

should not be used alone where discrepancy matters because the metric can be perfect (i.e., 1) if the observed and estimated variables are separated by constant discrepancy.

$$R^2 = \left(\frac{\sum(\boldsymbol{O_i} - O_{mean})(E_i - E_{mean})}{\sqrt{\sum(\boldsymbol{O_i} - O_{mean})^2 \sum(E_i - E_{mean})^2}} \right)^2 \quad (8)$$

Where, O_i and E_i are observed and estimated values. O_{mean} and E_{mean} are the observed and estimated mean.

Mean Absolute Error (MAE)

MAE is the average of absolute discrepancy between observed and estimated value (equation (9)). It is the simplest form of metric and easy to understand. Its value ranges from 0 to infinity, 0 being the perfect. MAE can never be negative as it uses absolute discrepancy. Just like RMSE, MAE is also sensitive to outliers.

$$MAE = \frac{\sum_{i=1}^{n} |O_i - E_i|}{n} \quad (9)$$

Where, O_i and E_i are observed and estimated values respectively and n is the total number of observations.

2.2.6 Period of analysis

Periods in climate change analysis can be confusing at times. Hence, it’s better to follow the convention to have uniformity. The following are the definitions of periods used in climate change analysis.

Historical period: It is the past time period defined during GCMs/RCMs’ simulation. It’s usually defined as 1950–2014 for CMIP6 and 1950–2005 for CMIP5. CMIP5 and CMIP6 refer to Climate Model Intercomparison Project Phase 5 and 6 respectively. Phase 6 is the latest phase of the project.

Baseline period/Reference period: It is the past time period we (researchers/data analyst/climate scientist/any other concerned person) define as a datum/reference to compare with future climate. It’s usually determined based on availability of data. Here, we consider it between 1985 and 2014.

Future period/s: It is the time horizon in future we (researchers/data analyst/climate scientist/any other concerned person) define when future climate variables are evaluated for analysis. The future periods are usually divided into nearly 30-year intervals from the time of analysis. Here we consider three-time horizons:

(1) Near Future (2020–2046)
(2) Mid Future (2047–2073)
(3) Far Future (2074–2100)

3. Understanding Vulnerability

Climate change adaptation discussions and actions revolve around understanding the concepts of vulnerability, risk, resilience, and adaptation. The definitions of key terms involved in vulnerability and adaptive capacity are provided in Annexure I: Important Glossary of Terms. However, here an effort has been made to discuss these concepts coherently to provide a lucid picture to the reader.

These scenarios are defined by the Intergovernmental Panel on Climate Change (IPCC) based on global socio-economic development trends. Among the five contrasting scenarios we have chosen the most likely scenario: SSP245 and the most pessimistic scenario: SSP585.

Incorporation of six GCMs, alongside optimistic and pessimistic scenarios, empowers us to comprehensively understand the uncertainties among different GCMs and scenarios.

3.1 Theoretical underpinnings of vulnerability

There is a diversity in the way vulnerability has been conceptualized. The diverse definitions of vulnerability can be broadly grouped into categories, i.e., engineering-based definitions and social definitions. An example of an engineering-based vulnerability definition is that provided by Wisner et al. (2005) who stated that vulnerability is "… a measure of the damage suffered by an element at risk when affected by a hazardous process". An example of a social definition of vulnerability could be that of Adger (2000) who espoused vulnerability as "the presence or lack of ability to withstand shocks and stresses to livelihood".

In the engineering-based definitions, the vulnerability is considered as a damage-based outcome, and it follows the hazard and impact approach i.e., the role of the system in affecting impact is considered almost negligible. Whereas, in the social-based definitions, we observe that the impacts are considered as a function of the interaction of the inner state of a system (i.e., vulnerability) before it meets hazard, with that of the hazard that produces the impact. Here, the inner state of the system receives greater attention than engineering-based definitions. Both these definitions are not wholistic in nature and don't convey the complete picture of vulnerability.

What IPCC has done was integrate both these understandings into an easy-to-use definition that can inform the operational aspects of climate change adaptation. Consequently, IPCC defined vulnerability as "The degree to which a system is susceptible to damage, or unable to cope with, adverse effects of climate change, including climate variability and extremes." Here, vulnerability is considered as a function of the character, magnitude, and rate of climate variation which represents the hazard and impact and combines it with the inner state of the system espoused by the social scientists.

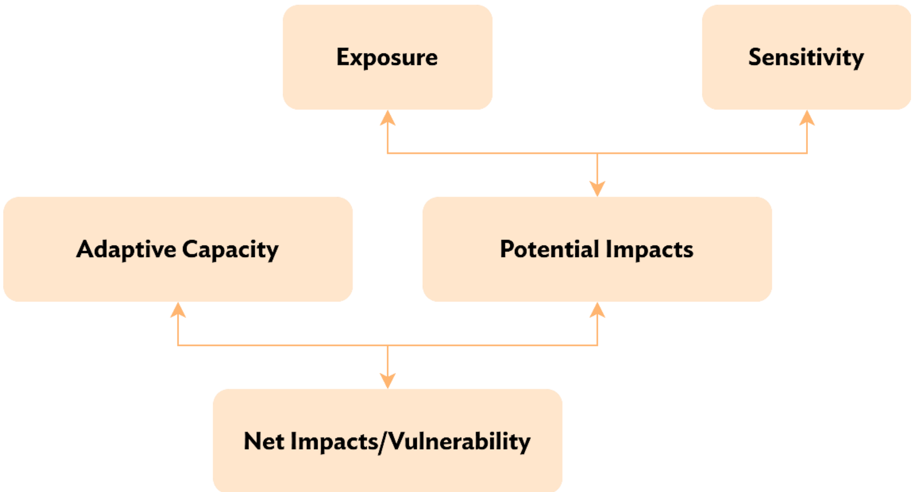
The idea of vulnerability has often been applied at two levels – social and biophysical vulnerability (Adger et al., 2004). Social vulnerability represents an internal state of a system concerning its susceptibility to external hazards (Allen, 2003), where outcomes (impacts) are determined by a combination of the social vulnerability and the external hazards to which a system is exposed (Brooks and Adger, 2003). Biophysical vulnerability, on the other hand, represents the outcomes (impacts) a system incurs and is typically defined as a function of exposure and sensitivity. According to Smit and Pilifosova (2001), vulnerability is a function of exposure, sensitivity and adaptive capacity, and this definition has come to stay with most climate change practitioners and researchers.

$$V = f(E_{xt}, S_{xt}, A_{xt})$$

where V= current vulnerability (damage a system will incur if it experiences climatic hazard in its present state);
S= Sensitivity of system x at time t;
E= Exposure of system x at time t, and
A = Adaptive capacity of system x at time t.

Figure 2 depicts the relationship between vulnerability, exposure, sensitivity and adaptive capacity. It signifies that the actual impacts that are felt by society in the aftermath of a climatic hazard are the result of a series of processes that take place momentarily. When a hazard interacts with the elements of exposure, it is their sensitivity characteristic that makes the elements affected by the hazard. However, the real impacts felt in the aftermath of hazard or climatic stimuli are resultant of the action of adaptive capacity that tries to mitigate the impacts while the process of hazard and exposure elements are interacting with each other.

Figure 2:
Relation between vulnerability, adaptive capacity, and net impacts (based on Marshall, et al. 2010).



The element of exposure is defined differently by different domains of the risk management community. Within the climate change community, exposure is considered as the intensity of the hazard that is experienced by the elements within the path of the hazard. It is the extent to which an element experiences climate change (IPCC 2007). On the contrary, the disaster risk reduction community defines exposure as all elements that are within the path of the hazard. Accordingly, all elements in the path of hazard are considered equally exposed to the hazard. Exposure is often not altered by most of the interventions within a reasonable time scale and hence may not constitute the object of interventions under most circumstances. However, it is the sensitivity aspect of the exposure element that can be altered in an external intervention.

Sensitivity is the underlying factor of the exposed element that predisposes the exposed elements to be damaged/affected by climatic stimuli. Sensitivity is the intrinsic characteristic of the exposure element, and it is determined by the underlying condition of the elements within the path of the hazard. These underlying conditions could include social, economic and environmental conditions. Social conditions include inequality, gender, age, health, access to services, governance, policies, institutions, and networks. Economic conditions could include poverty, livelihoods, and access to markets. Environmental conditions could cover a range of characteristics of land, water, forests and biodiversity and ecosystem services.

On the contrary, adaptive capacity includes the combination of all the strengths and resources available within a community, society or organization that can reduce the level of risk or the effects of a climatic event. Capacity has an indirect relationship with vulnerability. Examples of capacity could include skills, financial services, institutions, relief, response and rehabilitation plans.

Vulnerability is often determined by multiple factors and hence factors contributing to vulnerability in one location may be different from another location. For this reason, VAs must consider location and context-specific factors, and VAs conducted at one location may not be applicable for decision-making for another location.

3.2 The significance of vulnerability in adaptation

From the foregone discussion, it may have come to the fore that vulnerability is at the center of adaptation. A simplistic definition of adaptation could include any response, autonomous or planned, to climate change, current or future. These responses could be manifested by human society or by nature itself. For these guidelines, we consider only the responses of human society to climate change while there is a need to understand and guide the natural response to climate change as well, to guide our human responses which is another important discussion altogether.

Adaptation could be autonomous or planned adaptation. Autonomous adaptation indicates that human societal responses occur spontaneously as the impacts of climate change are experienced. Hence, autonomous adaptation could mean experiencing certain losses before responses and adjustments are even made. Societies evolve through a series of autonomous adaptations and hence human evolution itself could be constructed as an output of autonomous adaptations. As a result of this autonomous adaptation, practices are formed and adopted over the years. Understanding these autonomous adaptations is important to gain a perspective on how societies responded, what capacities helped in those responses, what worked and why, and what has limited their responses. Approaches such as indigenous and local knowledge revolve around understanding past adaptations to a large extent. These insights are valuable for designing a better-planned adaptation as well.

In planned adaptation, responses are designed based on a perspective on current and future climate change impacts. The reason why planned adaptation is important is that it helps society to be prepared in advance for climate change impacts are felt. By doing so, society can avoid facing losses from climate change. Hence, most of our climate change adaptation discussions and actions are largely focused on planned adaptation. Unless stated otherwise, adaptation in these guidelines refers to planned adaptation for the current and future climate change impacts.

Adaptation can take two broad approaches, one by understanding and addressing vulnerabilities (hence vulnerability-based approaches) and the other through understanding and addressing risks (hence risk-based approaches). These two approaches have some contrasting differences. In the case of risk-based approaches, the stress is on mitigating the risks. A typical example of a risk-based approach could include the construction of a dyke against sea level rise or high tides. Here, the dyke mitigates the impacts of the hazard by acting as a physical barrier between the hazard and the elements of exposure. It may not directly modify the characteristics of the elements of exposure such as the nature of houses constructed or the socio-economic characteristics of the population living near the dyke. Due to this, there is a possibility that the elements of exposure develop hidden vulnerabilities that may resurface only aftermath of a catastrophic event such as a typhoon. In contrast, a vulnerability-based approach promotes actions that can address the underlying vulnerabilities of the society and environment even before the exposure elements interact with a climatic stimulus. Such an approach could be ideal for dealing with extreme events which were never experienced before. Hence, it is often considered that understanding and addressing vulnerabilities is a robust and important aspect of adaptation planning.

What communities undergo after a climatic event such as floods or drought is resultant of the combination of vulnerability and adaptive capacity, and hence adaptive capacity plays a vital role in buffering the shocks. Designing adaptation interventions should not only be based on assessing sensitivities but also based on an objective assessment of capacities that exist within communities and those that could be readily mobilized within a short span.

It can be considered that vulnerability can arise as a result of a loss of resilience in a system. Resilience is about people's capacity far beyond the minimum of being able to cope. A resilient community can bounce back or return from a shock and remain unchanged. The concept of resilience helps to obtain a complete understanding of vulnerability. A good understanding of vulnerability and resilience is very crucial to the development of sustainable adaptation strategies.

From the foregone discussion, it became clear that the actual impacts of climate change can be reduced by:

(1) promoting resilience to reduce system sensitivities
(2) increasing adaptation capacity and effectiveness of adaptation responses and
(3) improving the adaptation-planning processes (Grafton, 2009).

Figure 3 below illustrates vulnerability, resilience and adaptation in the context of climate change for a better understanding of these concepts.

Figure 3:
Vulnerability, resilience, and adaptation (Source: Ilori And Prabhakar, 2014).

A drought, for example, could decrease the well-being of a poor household or community. In some cases, it makes no difference (e.g., graph 3 above) and in others, it may lead to a long-term reduction in well-being (graph 1 above). A resilient community will be able to bounce back from an unexpected climate disaster (graph 2 above).

The first graph is typical of a vulnerable household or community that is prone to the risk of climate change. Any perturbation in the climate system would lead to a decline in overall well-being in an irreversible manner. This denotes the vulnerable situation, where the communities impacted by climate change will not be able to go back to a previous condition without external intervention.

The second graph depicts the behavior of a resilient household or community. The household or community could return more quickly to the original well-being level. This resilience is an important asset as climate changes. An occurrence of drought only leads to a temporary decline. The system can adjust after some time and return to normal.

The third graph is typical of a household or community that has moved beyond resilience to be able to adapt fully to a new climate. The well-being does not change in the course of the drought.

They are fully adapted to the drought perhaps through the use of drought-resisting crops for farming or through an early warning system that would alert them that drought is coming so they can prepare for it. This situation also typifies anticipatory/planned adaptation.

3.3 Vulnerability assessment methodologies

The vulnerability concepts discussed earlier in this section have been applied differently in different contexts leading to several applied forms of vulnerability assessment methodologies. The following conclusions can be drawn from the perusal of the methodologies:

(1) All the methodologies, irrespective of whether qualitative or quantitative, have used the exposure, sensitivity and adaptive capacity model for vulnerability assessment.
(2) Most of the vulnerability assessment methodologies have utilized participatory approaches involving communities at the local level.
(3) A variety of participatory tools were employed within the participatory approaches.
(4) Vulnerability assessments were mostly qualitative and hence it was difficult to understand how vulnerabilities were assessed at one location compared with the other location. Developing a quantitative vulnerability assessment methodology is of high priority for suiting the needs of the decision-makers.
(5) The lack of simple quantitative methods makes it difficult to prioritize the nature and severity of vulnerabilities.
(6) Most methodologies tend to identify vulnerabilities through indicators though they end with identifying the indicators and don't often quantify them.
(7) Though most methodologies have tried to identify both biophysical and socio-economic vulnerability indicators, the distinction and the nature of the use of these two forms of vulnerability are not apparent.
(8) Most methodologies suffered from the weak linkage between the identification of vulnerabilities, quantification and use of this information for the identification of climate change adaptation options. Hence, adaptation options tend to appear isolated from the rest of the methodology and outcomes of vulnerability assessment.
(9) Indicators used for exposure were mostly limited to general climatic parameters such as temperature and precipitation whereas some methodologies didn't identify change as an indicator.
(10) There is a wide variation in indicators representing sensitivity and capacity. Most indicators employed in these were restricted to broad indicators such as demographics and socioeconomic factors such as income and education levels which can be obtained from village level and other census data.

Most climate change vulnerability assessment methodologies stress the need to take into consideration the future projected climate change impacts in carrying out VAs. However, one needs to be cautious about the overemphasis on future projections-based VAs as an overemphasis on future climate projections could potentially make the interventions narrow-based and such a narrow-focused approach may have higher chances of failure due to the uncertainty associated with the future climate projections. Instead, it has been advised to focus on the processes of adaptation and recognizing the capacities that the communities already have to eventually build upon these capacities. With this as a starting point, the inclusion of future projections could happen once stakeholders understand the language of climate projections and the involved uncertainties.

3.4 Indicator-based approach to assess vulnerabilities

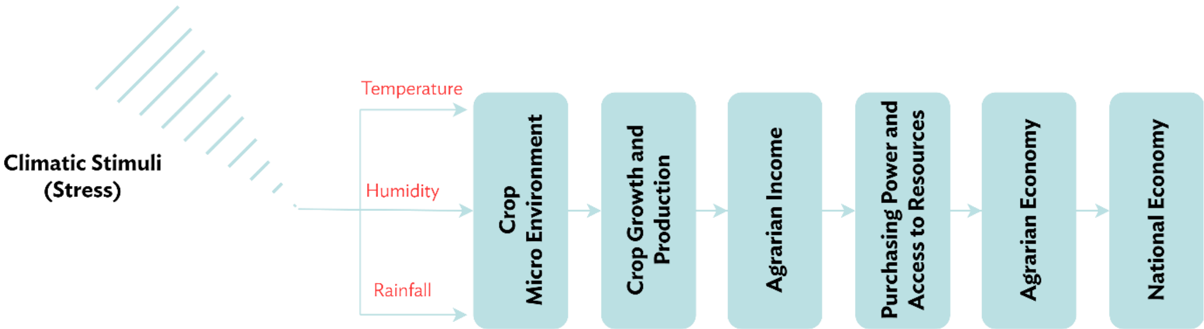
As discussed before, identifying and quantifying vulnerability indicators has assumed an important approach among various vulnerability assessment methodologies. This is for the reason that the indicators provide an easy way to grasp different components of vulnerability, be able to better represent how they relate to each other and help with the effective communication of output. Most multi-lateral developmental agencies such as the World Bank, Asian Development Bank and UN agencies and most global assessments, e.g., Human Development Index, and Sustainable Development Goals, employ indicators for tracking progress in development and this familiarity of approach and sources of data plays an important role in the way VAs are conducted and communicated. Indicators also help disaggregate the vulnerability in such a way that it is appealing to a range of stakeholders representing different occupations, sectors and technical backgrounds. This methodology also provides certain flexibility that certain types of indicators for which the data is not available can be obtained through measurements, estimations or by using proxy indicators where the data is not available.

The need for using indicators in vulnerability assessments is supported by scholars such as Vincent and Cull (2014) who stated that “In social, or context vulnerability, vulnerability is a potential state that determines whether hazard exposure will translate into adverse impacts. It is, therefore, necessary to rely on indicators that best represent the complex underlying processes.”

The VA methods that have employed indicators have identified these indicators either through inductive or deductive approaches wherein in the inductive approach the vulnerability indicators are selected from a wide variety of indicators; whereas in the deductive approach the indicators are often chosen based on a theoretical framework that is constructed to explain the underlying vulnerabilities. Inductive approaches are often intensive and data-driven.

Figure 4 shows the path in which climate change impacts the local agriculture economy and subsequently the larger economy, which could provide a valuable basis for identifying vulnerability indicators. The figure shows how vulnerabilities along the line of impact pathway would exacerbate the climate change impacts.

Figure 4:
Climate change impact pathway on agriculture and its macro-economic linkages.



The concept of impact pathway provides us with the following understanding that helps in identifying appropriate vulnerability indicators:

(1) Addressing all kinds of vulnerabilities is important as environmental vulnerabilities could lead to individual vulnerability of those who depend on natural resources;
(2) Individual vulnerabilities can result in social vulnerability;
(3) The vulnerability assessments should consider the boundary of influence of the adaptation project since the impact pathways are consolidated within that boundary;
(4) The very nature of vulnerability determines that the community-based approaches take precedence in vulnerability reduction interventions; and
(5) Vulnerabilities are highly location-specific in nature and vulnerability assessment efforts should aim to provide the location-specific information where the adaptation interventions need to be implemented.

4. Vulnerabilities of Highlands

Highland ecosystems are characterized by high elevation, often accompanied by low mountain ranges. These are unique ecosystems with distinct weather and climate patterns requiring special understanding and differentiation from other geographical regions. Highlands are also often called uplands. However, the word uplands are also interchangeably used with a type of crop where flooded irrigation is not followed as in the case of 'upland rice'. Highlands are characterized by high insolation (high solar radiation), low temperatures, and high precipitation. The daily temperature fluctuations tend to be higher than in the lowlands with much cooler nights and warmer days. In highlands, the climatic conditions are highly influenced by the elevation. Hence, an understanding of the vertical elevation of the highlands is essential to understanding highlands.

Asia is the home of highlands and highland people. Asia accounts for 36% of the global highlands (FAO 2015) and this amounts to nearly half of the world's mountain populations. A large portion of Asia's highlands falls under Class 6 of elevation classes of UNEP-WCMC which indicates that these highlands are mostly in the elevation range of 300–1000m. Southeast Asian highlands have the third largest vulnerable populations in the world. Nearly 41% of mountain people in Southeast Asia are estimated to be highly vulnerable to food insecurity. This signifies the need to focus on Asian highlands as a hotspot of climate change vulnerability.

4.1 Climate change in highlands

The rapidly changing climate in the highlands is also an important aspect that is aggravating the vulnerabilities of the highlands. Climate change impacts hydrology, biodiversity, and ecosystem services in highlands. Globally highlands are rapidly changing their climatic characteristics than the lowlands. The rapid changes were also observed in the Hindu Kush Himalayan (HKH) region which is reported to be warming three times faster than the global average with debilitating impacts on the region's glaciers, glacier-fed rivers, and dependent national and regional economies. Increasing water scarcity is a real threat to most highlands. The decline in freshwater in the highlands will have a serious impact on the agricultural productivity of the highlands. A decline in agricultural productivity will in turn have food security implications downstream in the river basins these highlands feed.

By 2050, mean annual temperatures for the Asian Highlands (averaged over all upper basins) are projected to increase from 2.5°C to 3.1°C. Highland plateau regions especially may face higher warming than other highlands (as in the case of HKH and the Tibetan plateau). A slight to substantial increase in precipitation in major highlands in Asia on an average of 39-48mm has been projected by 2050. At the same time, the average potential evapotranspiration (PET) and actual evapotranspiration (AET) increases as much as 11% by 2050, indicating a high-water demand in the highlands. Hence, an increase in precipitation is compensated for by the increased PET. Soil moisture content may be drastically affected, with an average decline of 5% due to increased PET and AET. A shift in bioclimatic zones was also projected across Asian highlands. These changes will have a compounding impact on the traditional agricultural systems followed in the highlands with severe food security implications.

4.2 Unique socio-economic context

Asian highlands are highly vulnerable because of the unique socio-economic characteristics of the highland populations. The highlands are characterized by poor overall development due to physical isolation, poor infrastructure development and employment opportunities. As a result, the highlands have one of the lowest urbanizations in the world. Food insecurity in the highlands is on the rise. Food insecure people in mountain areas rose 30 percent over 12 years to nearly 330 million (FAO, 2015). This number could grow in the future due to climate change impacts in the highlands. This is making populations from the highlands migrate to the plains seeking employment opportunities.

There has also been rapid environmental degradation in many parts of Asian highlands. The rapid environmental degradation is related to deforestation, and other forms of resource extraction that many local communities may not benefit from. The natural resource extraction from highlands is an alarming problem that not only affects the long-term livelihoods of highland communities but will also affect the ecosystems and ecosystem services that are essential for populations beyond these highlands. As a cumulative effect, over the past several decades, highlands are slowly depleting human resources, leaving behind aged and vulnerable populations. This has a cascading and debilitating effect on how institutions have developed in highland contexts. Poor institutional development often does not protect local populations, depriving them of access to various services and facilities. Political and social marginalization is an important issue in most Asian highlands.

4.3 Unique agricultural context

Unlike lowlands and plains, the highlands are characterized by high heterogeneity in vertical and horizontal planes in terms of microclimate, geographical, and other factors that determine the nature of agriculture practiced. Highland agriculture is distinctly characterized compared to lowland agriculture due to its distinct weather and climate patterns and different socioeconomic conditions. Shallow soils and depletion of nutrients due to runoff and leaching make highland soils poor in fertility. Landholding sizes are often smaller due to the small areas possible to cultivate on slopes. Agriculture in the highlands is often characterized by low input intensification compared to the lowlands, considered low per capita fertilizer and pesticide use.

Due to the physical isolation of the highlands, access to markets is often challenging and long-distance transportation under difficult conditions contributes to high marketing costs. These factors make highlands often unsuitable for mass and commercial agricultural production. However, efforts are being made globally to make the highlands centers of production for high-value crops by utilizing the unique climatic conditions of the highlands. These changes are especially being driven by the growing urban demand for high-value agricultural produce. As a result, traditional agriculture that has been developed over years is slowly changing in the highlands and this can be detrimental to the local ecosystems. Due to the fragile nature of mountain ecosystems, one has to preserve the traditional and low-input agriculture systems while addressing the local socio-economic development challenges. There is a need to strengthen institutions in the highlands to adapt highland agriculture to rapid climate change in highlands.

However, the highlands also provide some unique opportunities. High reliance on animal husbandry makes highland agriculture suitable for the promotion of resource circulation models. Climate change also provides new opportunities in highlands due to vertical warming that provides a potential for growing new crops. There is a need to identify these new opportunities, and new crops, and prepare well in time which is one of the objectives of highland development in the face of climate change.

4.4 Challenges of the highlands in Thailand

The Thai highlands is a mountainous natural region in the north of Thailand. The region of the Thai highlands encompasses the nine administrative provinces of northern Thailand, based on the six-region system, as well as parts of the Tak and Sukhothai Provinces. The Thai highlands are undergoing rapid changes in agriculture and socio-economic conditions that could be detrimental to the sustainability of the highland ecosystems. The expansion of upland maize cultivation is believed to have played a key role in deforestation and environmental problems in these highland areas. Unsustainable farming practices and over-exploitation of natural resources in the area have led to severe resource degradation, low productivity, adverse health impacts, and unstable incomes.

Some of the key challenges of agriculture in Thai highlands include severe soil degradation and erosion, chemical contamination in the environment, and climate change. 19,461 ha of the primary forest was lost in highland provinces between 2002–2020. The lost forest areas were converted to maize monocropping. These issues are reportedly affecting the food quality and safety in the highlands. A 1.4 to 1.8°C increase in mean annual temperature by the 2060s and a 3.0 to 3.8°C increase by the 2090s were projected in Thai highlands. Climate change, manifested through rising temperatures and a greater frequency of extreme weather events such as droughts, is exacerbating agricultural problems.

Similar issues could be observed in the highlands of the Nan province. The province is experiencing an increase in maize cultivation, and it is significantly correlated with an increased deforestation rate in the province. Deforestation and other unsustainable practices are deteriorating soils, and soil erosion and the extensive application and subsequent leaching of agri-chemicals are contaminating critical water sources. Monoculture farm practices, especially maize production, have led to increased household debt burdens, as indicated by the income-to-debt ratio reaching 0.89 by 2032. The deterioration of soil fertility and soil health is leading to increased and chronic debt among farmers. All these factors are increasing the economic burden on the households and the environmental burden on the Nan highlands.

4.5 Challenges of vulnerability assessments

As discussed previously, the highlands offer unique socio-economic, climatic and geographical conditions. They are also one of the highly vulnerable regions to climate change impacts. Despite these reasons, the vulnerability assessments in the highlands are yet to be developed fully. Some of the factors contributing to the lack of development in vulnerability assessments could be attributed to the slow and limited focus of governments on these fragile ecosystems as the highlands have been seen as an economic opportunity only recently.

High spatial variability in local characteristics of highlands means the need to have high granular/high resolution and quality data on all bio-physical and socio-economic conditions which is largely lacking in highlands. There is a scarcity of homogenous and disaggregated data in most highlands. This pushes researchers to make assumptions that drive the analysis and interpretation of the analysis a challenging one to the local conditions. Most vulnerability studies are focused on lowlands and plains. Vulnerability indicators are often location specific and hence the available literature from other regions cannot be readily used for the highland conditions. In addition, since vulnerability studies are also focused on hazard-specific conditions, the nature and degree of difference between hazards of highlands and lowlands often mean limited suitability for application and relevance to highland conditions. Even within the highlands, spatial extrapolation of vulnerabilities is faced with a challenge due to high spatial, both vertical and horizontal, heterogeneity in the highlands.

However, highlands provide us with a unique opportunity of gaining a deeper understanding of various elements of vulnerability that may not be necessarily obtained from other regions. High dependency on natural resources for social resilience and the role of biodiversity and ecosystem services in the highlands provide us with an important opportunity to understand highland natural resources and ecosystem services. Experiences suggest that animal husbandry plays an important role in the resilience of highlands and there is a need to promote animal husbandry to strengthen resource circulation/closed-loop agricultural systems in highlands that can improve agricultural resilience. Highlands also provide greater opportunities for crop diversification due to vertical warming. The traditional farming practices that evolved over the ages following local ecosystems and traditions in highlands can help conserve the local ecosystems.

5. Setting the Stage

Vulnerability is multi-faceted and multi-disciplinary in nature. Assessing vulnerabilities also require multi-stakeholder engagement since vulnerabilities are transitive and cumulative in nature i.e., individual vulnerabilities can become societal vulnerability and vice versa. Due to the complex nature of the vulnerability, it is essential that thorough planning is required to undertake VA.

5.1 Language first

The first and foremost necessity before undertaking the VA is that all the team members engaged in VA have a common understanding of the vulnerability and concepts underlying vulnerability as different understandings could lead to a lack of agreement on the approach to be taken for VA. This understanding should also percolate to the extent of various vulnerability frameworks used both conceptually and in an operational sense. This also includes the language, and meaning is uniformly understood among the team members. The members also would want to refer to the already existing guidance documentation available at the superior administrative structure such as national governments that may clarify the vulnerability, nature and purpose of vulnerability assessments etc. as they can provide an easy way to agree on the common meaning of vulnerability in the VA team.

5.2 Boundaries matter

Identifying geographical and administrative boundaries for assessing vulnerability is important, especially for addressing a specific problem or for targeting the VA to a specific decision-making body such as a local government or a provincial government. The team may also want to identify the sections of society as well as the specific sector and or sub-sector of the economy whose vulnerability needs to be assessed. Tasks like identifying specific vulnerable groups such as indigenous people, and inclusion of specific demographic groups such as gender, and age should be considered at this stage.

5.3 Ensure ownership

Ensuring the ownership of VA is essential for the effective uptake of results and their use for decision-making hence using a participatory approach is at the center of the VAs. There are at least two components to that participatory approach, the first is setting up a core interdisciplinary team of experts and the second is setting up a stakeholder group.

Setting up an interdisciplinary team is an essential requirement for conducting VAs due to the interdisciplinary and multi-faceted nature of vulnerability. The nature and composition of the teams depend on the objective and the sectoral focus of the VAs. VAs typically require experts with socioeconomics and bio-physical backgrounds. For example, a VA conducted for the agriculture sector typically require core experts from agricultural economics, hydrology or agricultural irrigation, climatology, agronomy, and rural sociology or rural development. Additional experts may be chosen based on the specialized nature of the VAs. While these experts organize the VAs, the information required for VA comes from various sources and stakeholders.

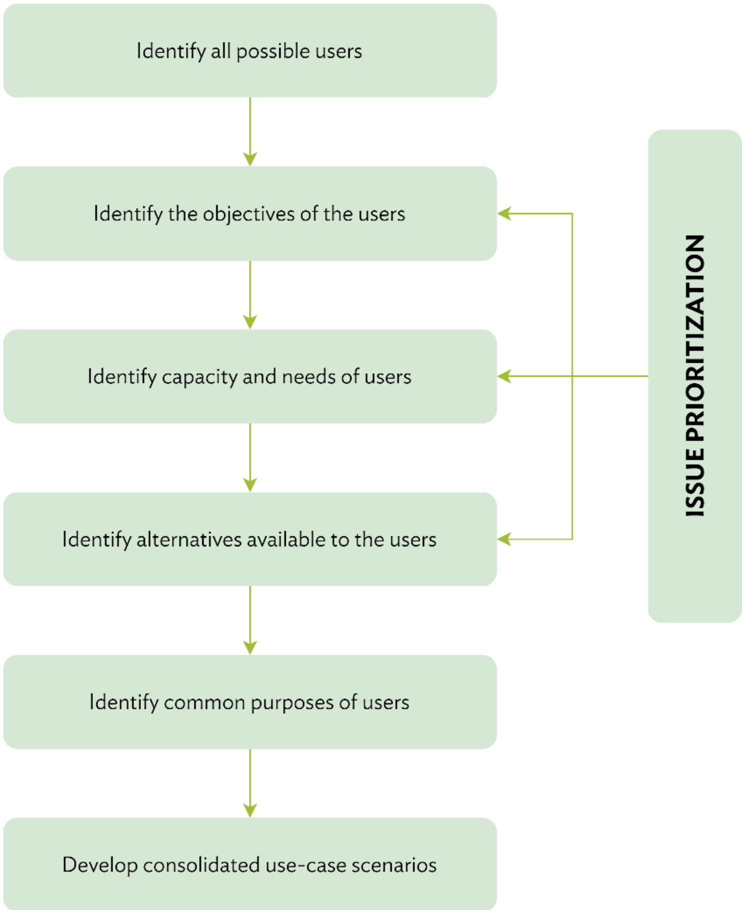
For operational benefit, it is advised that a stakeholder group may also be formed that performs the function of advising the VA process and be able to supply required data for the VA. The composition of the stakeholder group could consist of local governments, climate change adaptation specialists, development practitioners, farmer organizations, NGOs, private sector representation etc. The stakeholder group would be able to ensure the VA is location-specific, objective and need-driven and keep it targeted to a specific outcome. The stakeholder group would also play a key role in obtaining necessary permissions for conducting VAs, financing the VA activity, linking it to a policy process such as formulation of an adaptation strategy or plan, and communicating the results to wider sections of the society that help in the dissemination and effective uptake of VA results by appropriate actors.

6. Goal and Use Case Scenarios

Identifying a collective goal and use case scenarios for VA is an essential aspect of conducting VAs. VA goal and use case scenarios are interlinked wherein the goal serves as an outcome that the VA should contribute to, and the use case scenarios are subservient to achieving the goal.

A use case in general can be defined as a series of steps required to reach a specific goal. It could also be understood as the purpose and context in which VAs will be used. The purpose for which vulnerabilities are assessed determines the way the vulnerabilities are assessed and this linkage between the purpose and method of assessment is an important consideration in VA.

Figure 5:
The flow of steps in organizing a use case scenario exercise (Source: Authors).



For example, when a VA is conducted by an agriculture department, the department would want to evaluate the vulnerability of current agriculture production systems to future climate change impacts intending to develop comprehensive community-based bottom-up adaptation plans to address agriculture-related vulnerabilities. The department may also want to bring a systems perspective in designing the solutions for which they would like to obtain some hints from the VA. Similarly, when a VA is conducted by a roads and buildings department, the use case here could be to identify the vulnerability of current building stock to the projected climate change or to design infrastructure that can withstand future climate change shocks. Since use case scenarios vary from user to user, it is important that the users first arrive at a use case scenario for which they want to use the outputs of VA. Depending on the purpose of VA, there could be several use cases one may consider and when all these use cases refer to a single goal e.g., climate change vulnerability reduction then each of these use cases can be considered as use case scenarios. It is advised to conduct a thorough use case scenario mapping exercise as a part of VA to guide the VA process in a robust and output-oriented manner. Use case scenario mapping exercises takes the shape of multi-stakeholder consultation workshops where the participants provide their inputs to the process of identifying the use cases of VAs. A use case scenario designing workshop in a highland context should ideally seek participation from local governments, agricultural departments, rural development, water resources, land, farmer representatives, and private sector stakeholders engaged in marketing farm produce and input supply. The process involved in the use case scenario workshop is shown in Figure 5.

A use-case scenario development exercise typically consists of six steps. In the first step, the participants begin by identifying all users of VA. Not all participants listed in the previous paragraph may not use the VAs regularly or as a main resource to carry out their daily tasks. Hence, it is important to ask a key question to identify users of VA which takes the shape of "whose work will not be complete without referring to VA". Since there is a possibility of identifying the users to only those who attended the workshop, the VA coordinating team must do a thorough desk study and prior key informant interviews to identify an exhaustive list of users and ensure the participation of all potential users of the VA in the exercise. Once all users of VA are identified, the exercise moves to the stage of specifying the objective of each user i.e., for what purpose the user needs VA.

Listing all the objectives on a chart and identifying linkages between these objectives is essential at this stage. This ensures that all objectives of users are recognized and possible synergies among objectives are identified. When most users have a similar objective with a few outliers, the group may want to discuss how these outliers can be addressed by identifying alternative means of achieving these objectives. The purpose here is to see if a common objective can be agreed upon so that a focused VA can be developed. Even if the objectives are matching, the users may differ in terms of the capacities that they have to use the VA. Hence, the discussion should identify possible capacity constraints and if these constraints will limit the effective use of VA in delivering a specific objective. Since it may not be possible to develop a VA that is compatible with all capacity limitations, the group must identify certain resources or follow-up capacity-strengthening activities to develop the capacity of users in key areas so that the VA can contribute to all users to a maximum extent.

In preparation for the exercise, the coordinating team should present the necessary information to develop a deep understanding of the agricultural context of the region, underlying vulnerabilities and climate change so that this information brings all the participants to a common understanding of the issues. Issue prioritization is an important element of the use case scenario workshop. Issues can be prioritized using simple techniques such as ranking exercises.

Some examples for use cases of VAs are listed below:

(1) Assess the climate change vulnerability of current crops grown in highlands to future climate change
(2) Assess the climate change vulnerability of alternative crops suitable for highland agriculture in the future
(3) Identify the climate change vulnerability reduction potential of agronomic practices in highland agriculture

7. Data Preparation

This section provides an in-depth understanding of:

(1) what kind of data is necessary for conducting VA
(2) how to prepare the necessary data for all stages of the VA
(3) kinds of data treatment to be carried out
(4) data quality issues, source of data quality issues, and how to address/improve the data quality.
(5) implications of data quality on the output and usability of VA.
(6) how to ensure data quality

7.1 Data used in VA

Several types of data are being used in VA. In general, these data can be grouped into two categories:

(1) Primary data
(2) Secondary data

The primary data comes from direct observations from field and by questionnaire survey. The secondary data comes from different sources which include the data provided by national and local government agencies and from openly accessible global data sources. Specific data used in VA is given in Table 3.

Table 3:
Data used in VA.

SN	Data	Duration	Spatiotemporal resolution	Source
Climate data (observed)				
1	Minimum Temperature	1985ï 2014	Point/Daily	TMD
2	Maximum Temperature	1985ï 2014	Point/Daily	TMD
3	Rainfall	1985ï 2014	Point/Daily	TMD, RID
4	ERA5 (Min/Max Temperature, Rainfall)	1985ï 2014	0.25Ã 0.25Á/ Daily	https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset
Climate data (GCMs)				
1	CMCC-ESM2	1985ï 2100	1Ã 1Á/Daily	CCCMA
2	EC-Earth3	1985ï 2100	1Ã 1Á/Daily	EC-Earth Consortium, Rossby Center, SMHI
3	EC-Earth3-CC	1985ï 2100	1Ã 1Á/Daily	
4	GFDL-ESM4	1985ï 2100	1Ã 1Á/Daily	NOAA
5	NorESM2-MM	1985ï 2100	1Ã 1Á/Daily	NCC
6	TaiESM1	1985ï 2100	1Ã 1Á/Daily	RCEC
Crop data				
1	Crop type (land-use)	28/12/2018	1:4,000/25,000/ 50,000	LDD
2	Planting method (Transplant/sowing)	-	-	Baseline survey & literature
3	Cropping period (Planting and Harvest Date)	-	Farm scale	

SN	Data	Duration	Spatiotemporal resolution	Source
4	Maximum canopy cover (CC_x)	-	-	FAO database & literature
5	Crop yield	2012ï 2019 1984ï 2019	District/Annual Province/Annual	RID, OAE, DOAE
6	Cropping intensity	Cropping period	Farm scale/Per annum	Baseline survey & literature
Soil data				
1	Soil textural class (sand/silt/ clay/loam etc.)	2018	1:25,000	LDD
2	No. of soil horizons	-	Farm scale	Baseline survey & literature
3	Thickness of soil horizons	-	Farm scale	
4	Soil properties: • Soil moisture content (θ) at saturation, Field capacity and Permanent wilting point • Saturated hydraulic conductivity • Depth of layer restricting/limiting root deepening • Soil organic matter • Soil pH	Cropping period	Farm scale	A hydraulic properties calculator (Saxton and Rawls, 2006) is available to estimate θ_s and K_{sat} from soil texture. From θ_{sat}, θ_{fc}, θ_{pwp} and K_{sat}, FAO Harmonised World Soil Database (Fisher et al., 2008) *(AquaCrop derives other physical parameters governing soil evaporation, internal drainage, deep percolation, surface runoff and capillary rise)*
Field management practices				
1	Soil fertility (Indication of maximum relative dry above ground biomass)	Cropping period	Farm scale	Baseline survey & literature
2	Practices affecting soil evaporation and/or surface runoff: • Mulches • Tied ridges • Soil bunds • Cover and type of soil mulches • Height of soil bunds • Adjustment of surface runoff when affected by crop type and planting	Cropping period	Farm scale	
3	Rainfed/Irrigation	Cropping period	Farm scale	DOAE, RTG, Baseline survey
Socio-economic data				
1	Human development index	1985ï 2014	Village/Annual	Baseline Survey, CIESIN (2018), literature
2	Population density	1985ï 2014	Village/Annual	
3	Literacy rate	1985ï 2014	Village/Annual	
4	Livestock density	1985ï 2014	Village/Annual	

Note: ERA5: ECMWF Reanalysis Version 5; DOAE: Department of Agricultural Extension; RTG: Royal Thai Government; LDD: Land development Department; OAE: Office of Agricultural Economics, FAO: Food and Agriculture Organization. GCM data portal: (https://esgf-node.llnl.gov/projects/cmip6/). Data collection might vary according to consideration of indicators for VI calculation.

7.2 Data quality issues in VA

The data or information is the base of VA. The certainty of VA is purely dependent on the certainty of data used in VA. A proper understanding on the data used, data quality, and data quality related issues is therefore required before they are used in VA. Basically, the most common data quality issues can be grouped into five categories:

(1) Duplicate data
(2) Unstructured data
(3) Inaccurate data
(4) Data formats, and
(5) Data accessibility.

7.2.1 Duplicate data

Multiple copies of same record are duplication in the data. This is one of the very common issues in data management. This issue mainly occurs due to manual error when someone accidentally enters the same value multiple times. Sometimes it also happens when the algorithm goes wrong. Merging different data formats and standardizing the data are also other possible reasons for data duplication. It is therefore inevitable in identifying duplicate data for improved reliable, and trusted data for VA.

7.2.2 Unstructured data

The structure of the data is altered when data is entered incorrectly, or some files are corrupted which leads to missing or unstructured information. For example, weather station records for rainfall and temperature have missing location information such as latitude, longitude and altitude. Likewise, the address of the questionnaire respondent is missing from the questionnaire survey data is another example of unstructured data. The unstructured data or partially missing information could sometimes be a serious hindrance to move forward in data analysis, data processing and VA.

7.2.3 Inaccurate data

One of the most common and biggest challenges in data quality is inaccurate or incomplete data. When data is partially available and the data itself is inaccurate, there is no point in analysing and processing the data for decision making purposes. The inaccuracy in data mainly arise due to human errors, typos and systematic errors in the algorithms. The decision making in scientific planning and management projects is therefore purely dependent on the quality of data used in the process thus inaccurate data in VA leads to inconsistent results.

7.2.4 Inconsistent data formats

Data stored in different formats for the convenience of storing might result in inconsistent data formats. When data is compiled from different formats to a homogenous format, there may be chances of missing information in the resultant data. Data quality is therefore highly linked with integrating different data formats to a homogenous data format. This data quality issue is very well associated with VA analysis as different data sources with different data formats are integrated in the VA analysis.

7.2.5 Multiple units and languages

Differences in the units, scripts and language create serious problems with data processing and interpreting the results. For example, in VA, several climatic variables are used in deriving certain output quantities such as evaporation and evapotranspiration. The consistency in the units determine the proper output values hence unit consistency is inevitable in the VA. Similarly, the language in which the data is written is also an important factor to be considered as it could mislead some important information if not properly translated.

7.2.6 Data accessibility

Some data sources restrict access to specific data depending on the nature and sensitivity of the datasets. For example, local and national governments-based online data portals have some restrictions in accessing data directly from web servers. Often the users of the data need special permission to access sensitive data from the respective web portals. However, most of the global data sources, remote sensing-based data products, assimilated data products, land surface model simulated datasets are most of the time accessible freely from the respective web servers.

7.3 Steps to ensure data quality in VA

Data quality is to be ensured before proceeding with VA analysis. Various measures for ensuring data quality are as follows:

7.3.1 Data deduplication

Data duplication is one of the common problems in the time series data for variables such as precipitation, temperature, wind speed, solar radiation, relative humidity, evaporation etc. Data deduplication is the solution to data duplication issues. Data deduplication is the process of identifying duplicate records by human intuition, computer algorithms and data visualization and data analysis. Computer based algorithms or Artificial Intelligence (AI) effectively identifies the exact match or close match of the duplicate records. Data with duplicate records are trimmed with algorithms and visual inspection to ensure data quality in VA.

7.3.2 Data integration tool

Unstructured data is partially due to missing information. These issues can be effectively addressed by data integration tools where unstructured data can be converted to structured data. Data integration tools also help convert different formatted data into a required format without losing any critical information.

7.3.3 Automation tools

Inaccurate data is of no use for any decision-making purpose. Most of the time human error leads to inaccuracies thus minimizing human engagement in the data entering monitoring and analysis process. Automation tools can reduce significant time of manual data processing which also reduce the inaccurate data issues.

7.3.4 Translation tools

Data stored in multiple languages needs to be translated with appropriate content before it is used in VA. Translating tools and with the help of local people, these multilanguage issues in the data can be rectified effectively.

8. Understanding the Uncertainty Involved in VA

This section introduces the user to the concept of uncertainty in VA, how it affects the VA output and the usability of VA for decision making. It also describes the sources and types of uncertainty in VA and identify the means to reduce it.

8.1 What is uncertainty in VA?

Uncertainty in general can be described as a degree to which a value is unknown. Uncertainty arises from lack of information or from the fact that is not known or from disagreement on what is known. Uncertainty in climate change VA is relatively higher than any other related fields such as vulnerability to natural hazards etc. This is primarily because climate change projection itself has high range of uncertainty alongside vulnerability to highland agriculture involves several physiographic and socio-economic factors which increases spatiotemporal variability thus increasing uncertainty in the measured indicators. Secondly, it involves modelling the process over a much longer time in the future. The uncertainties arising from several input data, model parameters and model structure, if severe, affect the decision-making process in the VA.

8.2 Sources of uncertainty in VA

The source of uncertainty extends from quantifiable error in the data used in VA, mis-concepts/terminologies, human error, and uncertainty in climate projection. Therefore, both quantitative and qualitative assessments are required to quantify the uncertainty in VA. Quantitative uncertainty is estimating the range of values calculated by the models while the qualitative uncertainty is reflecting on the judgements from a group of experts on qualitative or subjective interpretations. As for as the uncertainty with respect to VA, the main aim should be to use the best available information to assess vulnerability and make the decisions while the iteration approach in assessing the vulnerability and associated uncertainty is strongly recommended as and when the new information is available.

8.3 Interpreting VA outputs with uncertainty

Decision makers are required to have a clear understanding on climate change VA outputs and associated uncertainties for effective decision making. The uncertainty assessment is therefore vital both for the best estimate of vulnerability to climate change system and the potential range of vulnerabilities under given uncertainties. The VA synthesizes scientific information from modelling studies, experimental studies, field studies, technical reports and experts' knowledge therefore the output of VA is a combination of multiple data sources and experts' opinion. The output of VA should be synthesized in such a way that the uncertainty is clearly communicated across the vulnerability assessment.

8.4 Precautions for reduction of the uncertainty

Several precautions for reduction of the uncertainty in VA can be practiced for effective decision making. The first and foremost practice is to use multiple sources for the same kind of data. Uncertainty in the input data can be reduced when multiple sources of data and its ensemble is used. Multiple sources of data capture all possible variability in the variable considered and the ensemble of multi-source data signify a representative value of the variable which greatly reduces the uncertainty in the input values. For example, future climate change projection from multiple

GCMs or RCMs can be averaged across to obtain an ensemble of climate variables (precipitation and temperature) which are likely to reduce the model uncertainty. Secondly, parameter uncertainty also significantly contributes to the overall uncertainty therefore minimizing parameter uncertainty improve the certainty in the VA decision making. A global optimizer algorithm for calibrating model parameters should be used in the model calibration process. Several advanced, sophisticated, and robust parameter estimation algorithms can be used to avoid the local minima problems in the model parameter estimation during VA process. Interval-based parameter estimation also reduces the uncertainty during the model calibration process. Such advanced techniques are necessary to reduce the uncertainty in the VA process. Thirdly, uncertainty can be reduced in selecting the most appropriate and representative model structure to conceptualize and model the components of VA process. Certain models are lumped in nature which simplifies the complex process into a simple process. On the other hand, fully physically based models are more complex in nature which demands more data and extensive parameterization and computation. Therefore, selection of the best model with respect to the study area and other factors is necessary not only to model the complete process but also to reduce the uncertainty arising from misrepresentation during process modelling.

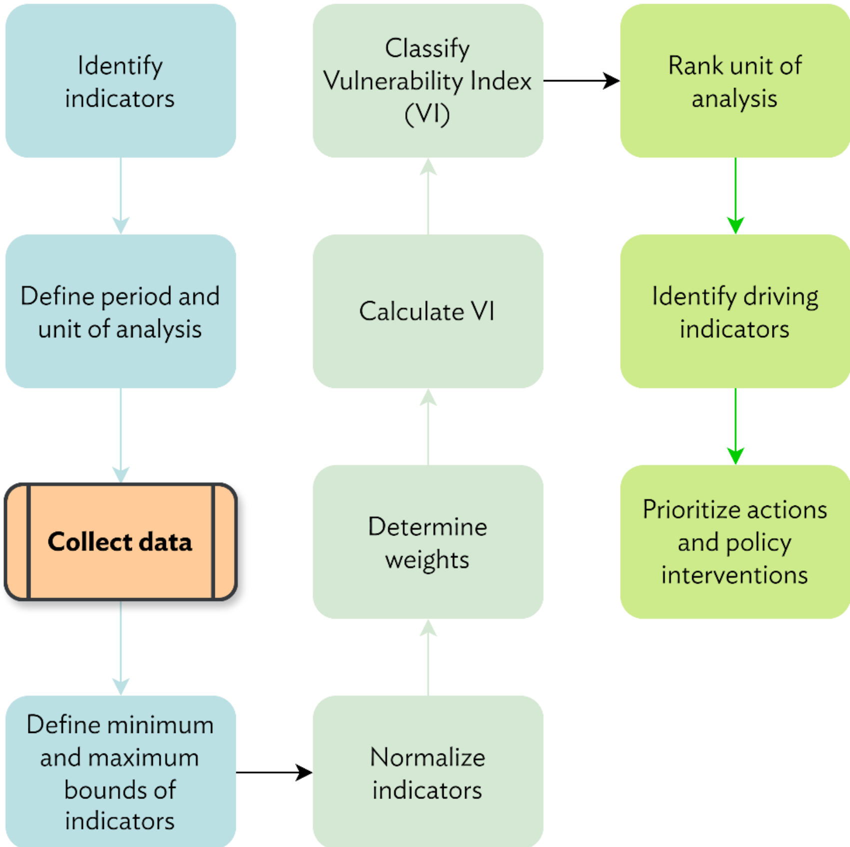
9. Vulnerability Assessment

This section discusses the stepwise process of vulnerability assessment. Only sample calculations are provided in this manual. For detailed results from the calculations please refer to KP2.

9.1 Steps of VI Calculation

Figure 6 shows the overall steps involved in vulnerability assessment which usually starts with the identification of indicators from each element: **Exposure, Sensitivity and Adaptive Capacity**.

Figure 6:
Steps of vulnerability assessment.



Unit of analysis: Villages and Periods: Baseline (1985–2014), Near Future (2020–2046), Mid Future (2047–2073) and Far Future (2074–2100)

9.1.1 Step 1: Identify indicators

The list of identified indicators under each component of vulnerability is given in Table 5 to Table 11. All the selected indicators represent the highland agriculture farming community in Bua Yai subdistrict, Nan province, Thailand. The sources of data are both primary (baseline survey) and secondary (climate change projection, crop modelling and geospatial analysis). The secondary data are collected from local and national government agencies, global open-source data and literature review. All the identified indicators are discussed under respective elements' in the **Exposure**, **Sensitivity** and **Adaptive Capacity** chapters.

9.1.2 Step 2: Define period and unit of analysis

In this project, we have considered villages of Bua Yai district as unit of analysis considering the project interest, location of demonstration sites, and availability of data. Whereas periods of analysis are considered coherent to climate change projection: Baseline (1985–2014), Near Future (2020–2046), Mid Future (2047–2073) and Far Future (2074–2100).

9.1.3 Step 3: Collect data

The sources of data are both primary (baseline survey) and secondary (climate change projection, crop modelling and geospatial analysis). The secondary data are collected from local and national government agencies, global open-source data and literature review.

9.1.4 Step 4: Define minimum and maximum bounds of indicators

Minimum and maximum bound play vital role during normalization process as the indicators' values are normalized between 0 and 1 in reference to these values. For a single period of analysis, we can simply consider minimum and maximum values across unit of analysis (villages). However, if we want to compare vulnerability across periods then it is essential to consider indicators' value across both villages and periods (baseline and future). While doing so, we need to be careful about indicators which are considered constant over the period of time. Since the lower range (minimum and maximum bound) of indicator contribute to higher fluctuation in vulnerability index within minimal change. To prevent such phenomena, it's better to present indicators within known range such as percentage (0 to 100% in most cases). In our case most of the indicators which are likely static throughout the period are either changed to percentage or some known range following survey data and literatures as presented in Table 5 to Table 11.

9.1.5 Step 5: Normalize indicators

The term 'normalization' refers to the transformation of indicator values measured on different scales and in different units into unit-less values on a common scale. For example, the different units of measurement: household income in Baht, land ownership in hectare or rai, literacy rate in percentage, soil organic matter in percentage, crop water productivity in kg/m^3 – and many more. These different units cannot be aggregated without normalization. They will be normalized using a minimum-maximum transformation approach to fit them between 0 to 1 scale. Here, we define '0' as 'lowest' and '1' as 'highest'.

For example, an annual precipitation of 1000mm/year may be '0 i.e., lowest vulnerability', while a precipitation of 200 mm may be '1 i.e., highest vulnerability'. Indicators measured are normalized by applying the min-max method. This method transforms all values to scores ranging from 0 to 1 by subtracting the minimum value and dividing it by the range of the indicator values.

Each indicator under three main components (E, S and A) were calculated at specific village level and specific crop conditions using the present and future period datasets. As different indicators are calculated at different spatiotemporal scales, the normalization on the indicators is applied depending upon whether the indicator is positively or negatively correlated as follows. The following formula (Equation 1 and 2) will be used.

If increase in indicator values increases vulnerability:

$$X_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}} \tag{10}$$

If increase in indicator values decreases vulnerability:

$$X_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}} \tag{11}$$

Where, X_{max} and X_{min} are the maximum and minimum bounds respectively while X_{ij} represents all the values for j^{th} indicator for the i^{th} village.

9.1.6 Step 6: Determine weights

The next step is to determine the weightage. If certain factors are more important than others, different weights should be assigned to corresponding indicators. This means that indicators that receive a greater (or lesser) weight thus have a greater (or lesser) influence on the respective vulnerability element and on overall vulnerability index. The different weights assigned to indicators can be derived from various methods such as existing literature, stakeholder information, expert opinion or statistical variance method. If the same weight is considered, we can simply take weight as one divided by number of indicators.

Here, both equal and different weight methods are tested first, and equal weight method was chosen based on the result. Different weights are calculated based on variance of indicator across the villages using equation (12), where weights are assumed to vary inversely with standard deviations (SD) to ensure that large variation in any one of the indicators would not unduly dominate the contribution of the rest of the indicators and distort interunit comparisons. During comparison of results between equal and different weight methods we found that different weight methods take off spatial variation of indicators resulting in small to no difference in vulnerability index within the space. Hence, we stick to the equal weight method.

$$w_j = \frac{1}{\left(SD_i \times \sum_{i=1}^{n} \frac{1}{SD_i}\right)} \tag{12}$$

Where w_j is the weight of the j^{th} indicator and Xij is the normalized value of Xij and SD is the standard deviation.

9.1.7 Step 7: Calculate Vulnerability Index (VI)

After determining weight, we simply multiply the normalized values of indicator with their respective weight and sum up to evaluate Vulnerability Index (VI) at each village as shown in equation (13). Similarly, the sum of the product between normalized exposure indicators and their respective weights give exposure component of VI and so on and so forth for sensitivity and adaptive capacity as depicted in equation (14), (15) and (16).

$$\text{VI} = \sum_{i=1}^{n} \left(w_j \times X_{ij}\right) \tag{13}$$

$$\text{E} = \sum_{i=1}^{n} \left(w_j \times E_{ij}\right) \tag{14}$$

$$\text{S} = \sum_{i=1}^{n} \left(w_j \times S_{ij}\right) \tag{15}$$

$$\text{AC} = \sum_{i=1}^{n} \left(w_j \times AC_{ij}\right) \tag{16}$$

Where VI is vulnerability index, w_j is the weight of the jth indicator, Xij , E_{ij}, S_{ij} and AC_{ij} are the normalized values of Xij indicator, exposure, sensitivity and adaptive capacity indicators.

Finally, the baseline and future agricultural vulnerability indices for each village are determined by repeating the aforementioned steps. However, the minimum and maximum bounds and weights remain same across different periods.

9.1.8 Step 8: Classify Vulnerability Index:

Vulnerability Index (VI) lies between 0 and 1, with 1 indicating maximum vulnerability and 0 no vulnerability at all. To interpret the level of vulnerability, a percentile-based vulnerability classes can be prepared like the one shown in Table 4. Henceforth villages can be classified into five percentile-based classes: Very High Vulnerability, High Vulnerability, Moderate Vulnerability, Low Vulnerability and Very Low Vulnerability.

Table 4:
Percentile-based vulnerability classes.

Percentiles	Vulnerability class
80 – 100	Very High Vulnerability
60 – 80	High Vulnerability
40 – 60	Moderately Vulnerability
20 – 40	Low Vulnerability
0 – 20	Very Low Vulnerability

9.1.9 Step 9: Rank unit of analysis

The overall objective of calculating VI is to prioritize vulnerable units and act upon them, hence, it is evident to rank villages in the order of vulnerability index. Based on the VI score, m units (8 villages) can be ranked from 1 to 8; 1 representing the village with highest vulnerability and the 8th as the lowest. The indicator values may infer extent of intervention needed to improve the situation of vulnerable units.

9.1.10 Step 10: Identify driving indicators

The VI range and interpretation may vary depending upon the scale, type of system or sector under consideration, and set of vulnerability indicators selected. Hence, simple ranking or units won't be sufficient. It's better to identify the driving indicators based on their percentage contribution to the VI.

To determine the percentage contribution of each indicator, the product of normalized value and weight is divided by VI of respective village and multiplied by 100. These contributions can be sorted out to determine top driving indicators. This helps us to prioritize indicators to act on and decide prioritized actions at each unit. In line with these actions, we can recommend policy interventions.

9.1.11 Step 11: Prioritize actions and policy interventions

Village level vulnerability maps provide information on critical villages where adaptation actions are of immediate priority to tackle the climate change impact. Similarly, driving indicators provide information on which indicator to act on. Combining this information together will provide us with an idea of which village to act on and on what indicators. However, policy interventions are likely to affect all villages hence it's recommended to derive action plans for all the villages.

While developing such action plans, it's best to consider the physiography of the region, Local knowledge, available resources, community culture, on-going agricultural practices, community organizations, research and academic institutions, public private partnership and so on. Considering these facts a sample priority action plan for the most critical unit, i.e., Tabman village (village 4) is presented in Table 5.

Table 5:
Priority actions and policy interventions for Tabman village.

V4: B. Tabman		
Indicators	**Actions/practices**	**Policy Interventions**
Change in annual rainfall (mm/yr)* (6.6%)	**Development of alternative irrigation facilities:** (1) On-farm reservoirs (2) Rainwater harvesting **Shift to efficient irrigation systems:** (1) Solar Irrigation (2) Keyline water management (3) Drip irrigation (4) Subsurface irrigation (5) Vertical farming and hydroponics	**Demonstration projects:** Establish demonstration projects where farmers can observe and learn about the benefits and effectiveness of efficient irrigation systems, alternative irrigation facilities and use of water efficient crops. **Technical assistance program:** Establish programs that offer technical assistance to farmers, helping them assess their irrigation needs, select suitable crops, select suitable technologies, and provide guidance on system design, installation, and maintenance. **Information and Extension Services:** Improve access to information and extension services for farmers, providing them with up-to-date knowledge and resources.
Soil organic matter in topsoil (% of cultivable land with moderate fertile soil) (6.6%)	**Enhance soil management practices** (1) Addition of organic matter such as biochar, compost (2) Crop rotation helps break disease cycles, improve soil structure, and enhance nutrient availability (3) Conservation tillage to minimize soil erosion and disturbances	**Soil health monitoring and assessment programs:** Establish soil health monitoring and assessment programs to track soil quality and provide feedback to farmers. **Incentives for organic and regenerative Agriculture:** Certification support, market access assistance and premium prices for organic or regenerative products
Soil acidity (% of cultivable land with medium to neutral soil) (6.5%)	**Enhance soil management practices:** (1) Addition of organic matter such as biochar, compost prevent pH fluctuations (2) Liming for Acidic Soils (3) Mulching such as wood chips or pine needles, can gradually acidify the soil over time (4) Use of crops suitable to the soil pH type	**Soil health monitoring and assessment programs:** Establish soil health monitoring and assessment programs to track soil quality and provide feedback to farmers. **Technical assistance program:** Establish programs that offer technical assistance to farmers, helping them select suitable crops as per soil pH and provide appropriate solutions on increasing or decreasing soil pH
Crop water use efficiency (kg/m³)^^ (5.6%)	(1) Shifting to water efficient crops (2) Cover cropping, Mulching	**Demonstration projects:** Establish demonstration projects where farmers can observe and learn about the benefits and effectiveness of efficient irrigation systems, alternative

V4: B. Tabman		
Indicators	**Actions/practices**	**Policy Interventions**
		irrigation facilities and use of water efficient crops. **Technical assistance program:** Establish programs that offer technical assistance to farmers, helping them assess their irrigation needs, select suitable crops, select suitable technologies, and provide guidance on system design, installation, and maintenance. **Information and extension services:** Improve access to information and extension services for farmers, providing them with up-to-date knowledge and resources.
Proportion of off-farm median income to total income (%) **(5.3%)**	(1) Increasing farm income (2) Value-added processing of agricultural products (3) Direct Marketing and Community Supported Agriculture (Farm-to-Restaurant) (4) Climate Smart Agriculture (Use of drought tolerant crops, shifting to high value crops) (5) Access to Improved Inputs (seeds, fertilizers, agricultural tools and equipment) (6) Creating alternative occupation (7) Agritourism (farm tours, farm stays, educational workshops, or hosting events like farm-to-table dinners or festivals)	**Market diversification, value addition, linkages and, value chain development:** Promote diversification and support farmers in adding value to their agricultural products through processing, packaging, branding, and marketing initiatives. Facilitate market linkages between farmers and non-farm sectors, such as agribusinesses, processors, retailers, and service providers. **Access to agriculture inputs:** Input subsidies, quality control and certification of agricultural inputs, farmer cooperatives and group purchasing **Access to credit and financial services:** Improve access to credit and financial services for farmers seeking to establish or expand non-farm businesses. **Rural employment programs:** Create job opportunities for farmers in sectors such as rural services, public works projects and infrastructure development.
31%		

10. Exposure

Definition of Exposure (E) has been different in context of climate risk assessment and vulnerability assessment. It has been defined as damage level caused by climate hazards or extent of coverage of hazard. But to start with let's understand what hazard is.

In general, hazards are considered as process or phenomenon that may cause loss of life, injury or leave other negative impacts such as property damage, socio-economic disruptions, or environmental degradation. As far as climate change vulnerability to highland agriculture is concerned, the hazards are predominantly climate hazards such as temperature extremes, rainfall extremes, floods and droughts. It is measured in terms of magnitude, duration and frequency. Alongside, hazard has a spatial extent that the selected system or number of people, special infrastructure or any other important resources can be exposed to. These two components of hazard has been considered differently in climate risk and vulnerability assessment frameworks.

During climate risk assessment, hazard and exposure both are considered as separate elements with hazard indicating damage level and exposure indicating the spatial extent that the system is exposed to. Whereas, during climate vulnerability assessment framework of IPCC, (2007) hazard is incorporated within exposure element and described as magnitude, duration and frequency of hazard over the unit of analysis. In this manual, we follow the latter definition where exposure incorporates hazard within itself.

Table 6 shows all the indicators considered within the study which are described later on.

Table 6:
Indicators derived from the reviewed indices of exposure and their functional relationship to agricultural vulnerability.

Index	Indicators (unit)	Calculation	Relation	Reference
E1	Drought severity for wet/primary season (unitless)*	-Sum SPEI <= -1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E2	Drought severity for dry/secondary season (unitless)*	-Sum SPEI <= -1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E3	Drought duration for wet/primary season (Month)*	Count SPEI <= -1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E4	Drought duration for dry/secondary season (Month)*	Count SPEI <= -1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E5	Flood severity for wet/primary season (unitless)*	Sum SPEI <= 1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E6	Flood severity for dry/secondary season (unitless)*	Sum SPEI <= 1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E7	Flood duration for wet/primary season (Month)*	Count SPEI <= 1.5	Positive	Wang et al. (2020); Duong et al. (2017)
E8	Flood duration for dry/secondary season (Month)*	Count SPEI <= 1.5	Positive	Wang et al. (2020); Duong et al. (2017)

Index	Indicators (unit)	Calculation	Relation	Reference
E9	Change in annual temperature (°C/year)*	Slope of annual temperature	Positive	Neset et al. (2019); Gbetibouo et al. (2010)
E10	Change in annual rainfall (mm/year)*	Slope of annual rainfall	Negative	Neset et al. (2019); Gbetibouo et al. (2010)

* : Min and max bounds are evaluated based on indicator values across unit of analysis (villages) during baseline and future periods.

Floods and droughts are mostly defined using Standardized Precipitation Evapotranspiration Index (SPEI) which is calculated based upon observed data for baseline period while future values are calculated using bias corrected GCMs/RCMs data.

10.1 Standardized Precipitation Evapotranspiration Index (SPEI)

SPEI is a standardized measure of water availability based on precipitation and potential evapotranspiration (PET). It is an extension of Standardized Precipitation Index (SPI) and accounts for the effect of temperature unlike SPI. Calculation of SPEI starts with calculation of water surplus or deficit (D_i) as shown in equation (17).

$$D_i = P_i - PET_i \tag{17}$$

Here, D_i, P_i, and PET_i are water surplus or deficit, precipitation and potential evapotranspiration for the i^{th} month respectively. With limited data, PET can be calculated using Thornthwaite method where only temperature data is required. Whereas if data on solar radiation, wind speed and relative humidity are also available, then more sophisticated PET estimation methods such as Penman-Monteith equation can be used. However, it should also be noted that more sophisticated methods are also related to more uncertainty. D_i is then fitted into log-logistic distribution to calculate SPEI ultimately as shown in equation (18) given by Abramowitz and Stegun (1965).

$$SPEI = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 W^2 + d_3 W^3} \tag{18}$$

$$W = -2\ln(P) \tag{19}$$

Where P is the probability of exceeding a determined value of D. For $P \leq 0.5$,

$$P = 1 - F(x) \tag{20}$$

For P > 0.5, P is replaced by 1−P and the sign of the resultant SPEI is reversed. The constants are:

(1) $C_0 = 2.515517$
(2) $C_1 = 0.802853$
(3) $C_2 = 0.010328$
(4) $d_1 = 1.432788$
(5) $d_2 = 0.189269$
(6) $d_3 = 0.001308$

F(x) is determined using equation

$$F(x) = \left(1 + \left(\frac{\alpha}{x - \gamma}\right)^{\beta}\right)^{-1} \tag{21}$$

Where, α, β and γ are scale, shape and origin parameters, respectively for D values in the range (γ > D < ∞).

These parameters can be estimated using different methods such as unbiased Probability Weighted Moments (ub-PWM), plotting position PWM and maximum likelihood method. The unbiased PWM method is selected (equation (22) to (25)) due to its ability to find solution for all the regions and comparability across space.

$$\beta = \frac{2w_1 - w_0}{6w_1 - w_0 - 6w_2} \tag{22}$$

$$\alpha = \frac{\beta(w_0 - 2w_1)}{\Gamma(1 + \frac{1}{\beta})\Gamma(1 - \frac{1}{\beta})} \tag{23}$$

$$\gamma = w_0 - \beta(w_0 - 2w_1) \tag{24}$$

$$w_s = \frac{1}{N}\sum_{i=1}^{N} \frac{\binom{N-i}{s} D_i}{\binom{N-1}{s}} \tag{25}$$

Where, $\Gamma(\beta)$ is the gamma function of β, N is the number of data points and ws are PWM for different values of s.

Using equations (17) through (25), SPEI can be calculated on the range of time scales from 1 – 48 months. The wet, normal and drought events can be categorized based on the SPEI values as shown in Table 7.

Table 7:
SPEI values corresponding to wet, normal and dry events.

SPEI	Condition	Probability
≥2	Extreme wet	0.02
1.50 to 1.99	Severe wet	0.06
1.00 to 1.49	Moderate wet	0.10
-0.99 to 0.99	Normal	0.65
-1.49 to -1.00	Moderate drought	0.10
-1.99 to -1.50	Severe drought	0.05
≤2	Extreme drought	0.02

SPEI value above 1 is considered as wet conditions. Therefore, the flood hazard threshold is considered as SPEI more than 1.

Please refer to the R script in Annexure III for the calculation process of SPEI, drought and flood characteristics along with temperature and rainfall slopes and crop water demand.

10.2 Drought

Drought is a prolonged dry period in a given climate cycle. Drought causes shortage of water for drinking water supply, crop growth, hydro power generation and other environmental needs thus it greatly impacts on health, agriculture, energy, and environment in the affected region. Drought is characterized in terms of a state of deficit in the water availability. Therefore, SPEI is one of the standard indicators to represent droughts in a given region and at a given time scale. Table 2 provides different drought conditions and corresponding SPEI values. The threshold for drought conditions, therefore, is considered as SPEI lower than -1.

10.3 Drought severity, duration and intensity

Drought severity is the cumulative sum of all SPEI values less than or equal to -1. The wet and dry season drought severity are similarly computed corresponding to the specific seasons during the baseline and future periods. Here we have considered severe droughts hence drought is defined as the sum of SPEI values less than or equal to -1.5.

Drought duration is the number of months with SPEI values less than or equal to -1. Here we have considered severe droughts hence drought duration is the number of months with SPEI values less than or equal to -1. Drought intensity is nothing but the ratio of drought severity to drought duration. Its unit is per month.

10.4 Flood

Floods occur due to extreme heavy precipitation when natural watercourses lack the capacity to carry the excess water. The flood hazard events often correlated and identified with several climate-based indicators such as Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). Future flood hazard is calculated from future SPEI values. SPEI values for future times are calculated from future projected precipitation and temperature datasets from bias corrected GCMs.

10.5 Flood severity, duration and intensity

Flood severity is the cumulative sum of all SPEI values greater than 1. Different season flood severity is computed from corresponding season SPEI values. The wet season is considered from April through September while the dry season is considered from October through March. The wet and dry season specific flood severity is the corresponding cumulative sum of SPEI values during these specific seasons for both the baseline and future periods. Here we have considered severe floods hence flood is defined as the sum of SPEI values greater than or equal to 1.5.

Flood duration is the number of months with SPEI values greater than or equal to 1. Here we have considered severe flood hence flood duration is the number of months with SPEI values greater than or equal to 1.5. Flood intensity is nothing but the ratio of flood severity to flood duration. Its unit is per month.

Note: we haven't used intensity as an indicator to avoid redundancy

10.6 Rate of change in annual precipitation/temperature

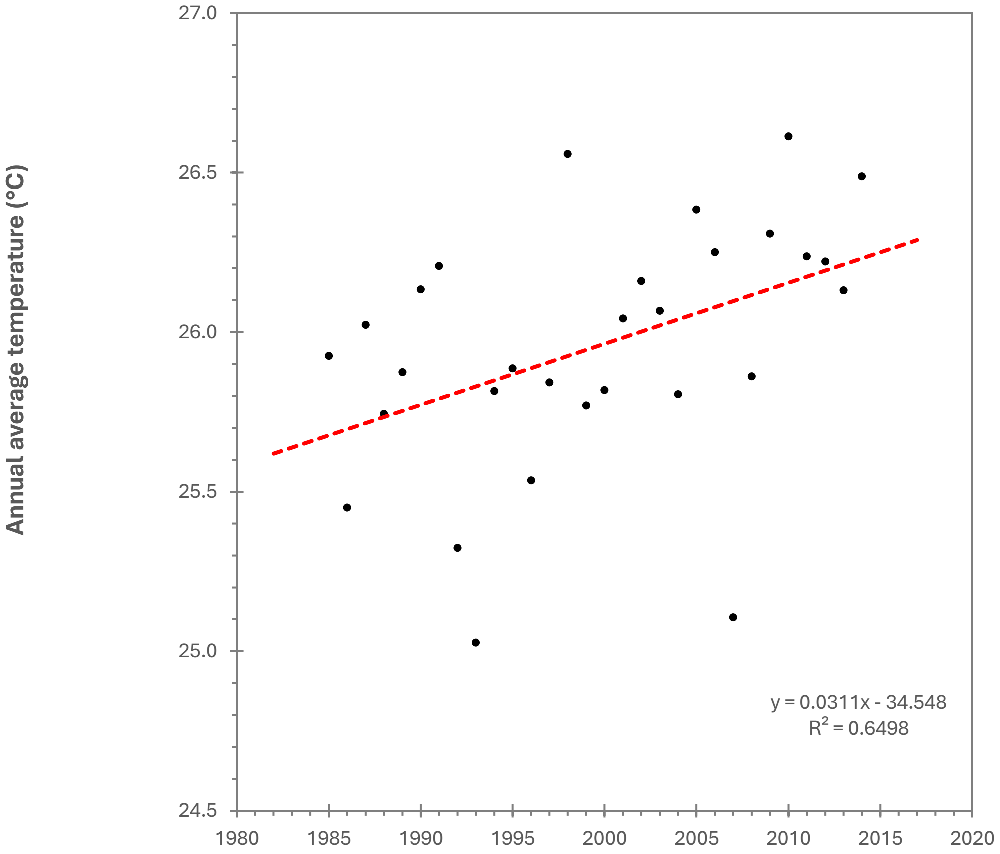
Rate of change in annual precipitation is calculated by calculating the slope parameter of a linear regression fit between annual precipitation/temperature and time in years. Positive value of rate of change in annual precipitation/temperature implies the increase in the precipitation over the period of time while the negative value implies the decrease in the precipitation/temperature over the period of time.

10.7 Linear regression of temperature in Bua Yai

Regression is a statistical method to model the relationship between a dependent variable (precipitation/temperature in our case) and one or more independent variable (year in our case). Depending upon the number of dependent variables it can be simple linear regression or multiple linear regression.

Figure 7 shows that the annual average temperature at Station ID: 48333 is changing at the rate of 0.03211ºC/year between 1985 and 2014. The slope of the regression line is the coefficient of the “x” variable presented in the graph, and it can be obtained by adding trendline in scatter plot in MS-Excel with check mark on “Display Equation on chart”.

Figure 7:
Linear regression fit of annual average temperature (station 48330) during 1972–2020.



11. Sensitivity

The Sensitivity (S) component of vulnerability indicates how a system is likely to react to climate hazards when disaster occurs. For example, how the crop production system is affected due to change in climate. Several factors can be considered under sensitivity component. In the context of climate change vulnerability to highland agriculture, the list of sensitivity indicators considered here is provided in followed by description of all the indicators. Yield gap and crop water use efficiency are derived from crop modelling; hence they are discussed at the end followed by the process of crop modelling.

Table 8:
Indicators derived from the reviewed indices of sensitivity and their functional relationship to agricultural vulnerability.

Index	Indicators (unit)	Calculation	Relation	Reference
S1	Yield gap (%)	Yield Gap = [Potential Yield (Y_p) – Water-limited Yield (Y_w)] / Potential Yield (Y_p)	Positive	Wang et al. (2020)
S2	Erosion risk (% of respondents believing in erosion risk)	No. of respondents believing in erosion risk/Total respondents*100	Positive	Brien et al. (2003); Carter et al. (2010); Parker et al. (2019)
S3	Soil organic matter in topsoil (% of cultivable land with moderate fertile soil)	Area of cultivable land with moderate fertile soil/Total area of cultivable land*100	Negative	Brien et al. (2003); Carter et al. (2010); Parker et al. (2019)
S4	Soil acidity (% of cultivable land with medium to neutral soil)	Area of cultivable land with medium to neutral soil/Total area of cultivable land*100	Negative	Brien et al. (2003); Carter et al. (2010); Parker et al. (2019)
S5	Proportion of arable land to agricultural land (%)	Area of cultivated land/Total area of agricultural land*100	Positive	Wiréhn et al. (2015); Neset et al. (2019)
S6	Crop water use efficiency (Kg/m^3)^^	Crop yield/Water applied	Negative	
S7	Crop water demand (mm/year)^^	Evapotranspiration - Effective rainfall	Positive	Duong et al. (2017)
S8	HH living on farm income only (%)	Number of households/Total households*100	Positive	Duong et al. (2017)
S9	Deforestation rate (% of forest area destroyed/30 years)	-Slope of annual forest area percentage*30 years	Positive	Hagenlocher et al. (2018)
S10	Human population density (Person/HH)^	Number of person/HH	Positive	Gbetibouo et al. (2010)
S11	Crop rotation (% of HH with crop rotation)	No. of HH with crop rotation/Total number of HH*100	Negative	Swami & Parthasarathy (2021)

Index	Indicators (unit)	Calculation	Relation	Reference
S12	Crop diversity (crops/100 rai)*	Number of crops grown*Total area of cultivation/100	Negative	Gbetibouo et al. (2010); Neset et al. (2019); Bhatia (1965)

^ : Min and max bounds are evaluated from baseline survey
^^ : Min and max bounds are evaluated based on literatures
* : Min and max bounds are evaluated based on indicator values across unit of analysis (villages) during baseline and future periods

11.1 Erosion risk

Soil erosion is a phenomenon where topsoil is eroded due to combined effect of looseness in soil and intensive rainfall and unmanaged irrigation drainage system. Erosion of topsoil causes loss in fertile soil subsequently increasing use of chemical fertilizers to maintain soil fertility. Soil erosion is essentially a physical quantity derived from erosion modelling. However, here we have accounted erosion risk as perceived vulnerability towards by the respondents of the baseline survey.

11.2 Soil organic matter

The organic matter content in the soil is the measurement of soil fertility. It is considered as a sensitive parameter since it directly affects the crop yield. Soil can be classified into different fertility levels based on the organic matter content. This helps to create a spatial map of soil fertility. Here, we have used soil map from the Land Development Department (LDD) to identify soil with less and moderate fertility to calculate the (% of cultivable land with moderate fertile soil.

11.3 Soil acidity

Soil acidity, also known as pH, refers to the level of acidity or alkalinity of any soil over an extent. We have used the term acidity here in coherence with soil data from Land Development Department. Fluctuation in soil acidity fluctuates the crop growth and yield attributing to sensitivity indicator. Different crops are suited to different soil acidity levels while most of them grow well in medium to neutral soil. Hence, percentage of cultivable land with medium to neutral soil is considered as our indicator.

11.4 Proportion of arable land to agricultural land

Arable land refers to all the land which is used for cultivation only whereas agricultural land includes cultivated area along with areas used for other agricultural purposes such as livestock grazing, dairy farming, poultry farming, aquaculture, orchards, vineyards etc. Proportion of arable land to agriculture land is one the indicator which defines diversity in agricultural practices. It also reflects the saturation level of the agricultural system from cultivation and provides an idea further development. Here we used the percentage of arable land to agricultural land as an indicator, and it is directly proportional to vulnerability.

11.5 Crop water demand

Crop water demand or evapotranspiration is calculated in AquaCrop model using Penman-Monteith equation. This crop water demand is the potential water demand for the crop to grow under ideal stress-free conditions. The source of water for crop growth is rainfall and irrigation. Rainfall data is provided in the climate file from which daily rainfall excess information is calculated in the AquaCrop model. Irrigation is the additional source of water for crop growth which is calculated as the difference between evapotranspiration and rainfall excess.

Please refer to the R script in Annexure III for the calculation crop water demand.

11.6 HH living on farm income only

Households living on farm income are the most sensitive households during disaster as they are likely to hit the first and directly. Here, we calculated the percentage of households as the sensitivity indicator.

11.7 Deforestation rate

Deforestation is most likely to occur due to illegal encroachment for poaching forest resources or to expand the agricultural land. Here we have considered deforestation rate since it is observed in the project site, i.e., Bua Yai for the latter purpose which signifies the inadequacy of agricultural land.

11.8 Human population density

The more densely populated the area is the more demand of resources to be fulfilled and the more difficulty in management during disaster events. Hence, we have considered person/HH as a sensitivity indicator reflecting population density in the unit of analysis.

11.9 Crop rotation

When the same crop is cultivated throughout the year, particular nutrients required for the crop replenish while others get enriched due to nutrient cycle. Such a change in nutrient cycle can be utilized in favor by cultivating different crops in sequence. This process is called crop rotation. Crop rotation not only help to grow yield but also reduce vulnerability since one crop within a season might get affected by climate change while others remain unaffected.

11.10 Crop diversity

Like crop rotation, the act of cultivating multiple crops but at different pieces of land and cropping calendar is called crop diversity. Crop diversity enhances pollination process and exchange of nutrients. Also, like crop rotation it helps in reducing vulnerability since one crop within a season might get affected by climate change while other remain unaffected.

To derive these indicators, we need to go through the process of crop modelling. Where we simulate the crop yield based upon climate, crop, management practices and soil data. The principle followed by AquaCrop model, and the process of simulation is discussed hereafter.

11.11 Principle of AquaCrop model

Crop models are a crucial tool to simulate climate change's impact on cropping system. Crop modelling is the process of conceptualizing various stages of crop growth and modelling with appropriate functions. AquaCrop is a crop model developed by FAO's Land and Water division to assess the effect of climate and environment on crop yield and crop water productivity, thereby addressing food security. The AquaCrop model is developed in such a way that it balances accuracy, simplified process of parameter estimation and robustness in decision making. The AquaCrop model can be used to model the growth and yield response of any herbaceous crops to water and different field management conditions. The AquaCrop model allows the user to simulate crop growth and development under various water availability and field management scenarios. Climate change impact can also be simulated using this crop model. AquaCrop model calculates crop yield and crop water productivity in four main steps as follows:

11.11.1 Development of green canopy cover

The crop growth and foliage development in AquaCrop is modelled with canopy cover concept. Canopy cover is the fraction of the soil surface covered by the canopy and it ranges from 0 to 1 where 0 indicates the crop is yet to develop and 1 indicates the crop is fully developed and covering the entire ground area. Soil water content in the root zone is linked with the leaf development and canopy expansion. Soil water content in the root zone is tracked on a daily basis and any shortage in the soil moisture is accounted for as water stress on the crop growth and canopy cover development.

11.11.2 Crop transpiration

Under well-watered conditions, crop transpiration (Tr) is calculated by multiplying the reference evapotranspiration (ET0) with crop coefficient (Kc). The crop coefficient is proportional to canopy cover, and it varies throughout the crop cycle. Water stress is not only affecting the canopy cover development but also affects the crop transpiration as water stress can induce stomatal closure thereby limiting the transpiration process.

11.11.3 Above-ground biomass

The quantity of above-ground biomass is proportional to the cumulative crop transpiration (ΣT_r). The proportional factor is water productivity (WP). WP is also normalized for the effect of climatic conditions thus the normalized WP (WP') is also valid for comparison across different seasons, locations and CO_2 concentrations.

11.11.4 Crop yield

The simulated above ground biomass is integration of all photosynthetic elements accumulated by a crop during the crop growth season. Crop yield is a portion of the accumulated above ground biomass which is separated using harvest Index (HI). The actual HI is adjusted from reference HI with adjustment coefficients for water stress.

11.12 AquaCrop model development

Development of crop models for any area of interest can be completed in three major steps: model set-up, calibration and validation. Before we proceed it's better to understand the model interface first.

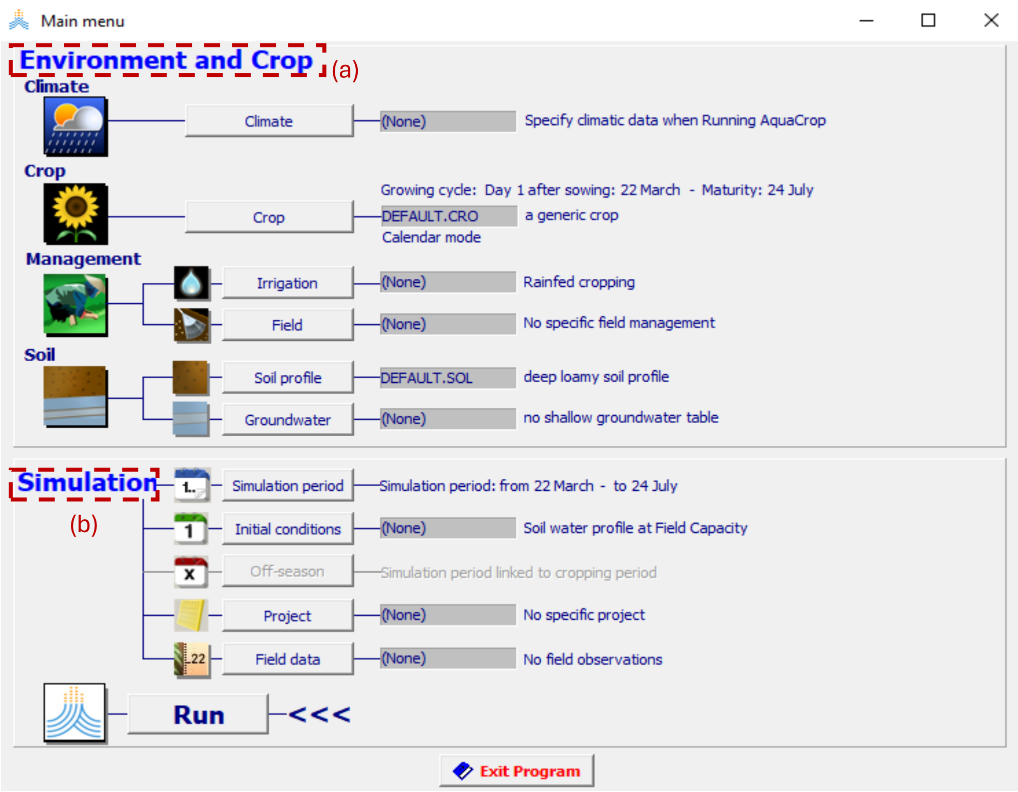
11.12.1 File Management

Main Menu

This section describes the different panels of the AquaCrop model and how the different input files are displayed in the model. There are two panels in the AquaCrop model: a) Environment and Crop and b) Simulation panel (Figure 8).

(1) **Environment and crop panel**: Users can: (1) select or create Climate, Calendar, Crop, Irrigation and Field management, Soil profile and Groundwater table files and display or update the corresponding characteristics; (2) specify the start of the growing cycle.
(2) **Simulation panel**: Users can: (3) specify the Simulation period; (4) select or create Initial conditions, Off-season conditions, Project, and Field data files and display or update the corresponding characteristics; (5) Run a simulation for the specified environment, crop and simulation setting.

Figure 8:
Main menu of AquaCrop a) Environment and Crop Panel and b) Simulation Panel



Selecting files, undoing the selection and default settings.

When AquaCrop is launched, default settings are assumed (Table 9). By means of the <Select/Create> button available in the file management panel of the Main menu we can access to the database from which input files can be selected (Figure 9). The files are stored in the default database, which is the DATA subdirectory of the AquaCrop folder. With the <Path> button the user can select another directory.

Figure 9:
(a) Main menu of AquaCrop with input data dialogue boxes opened.

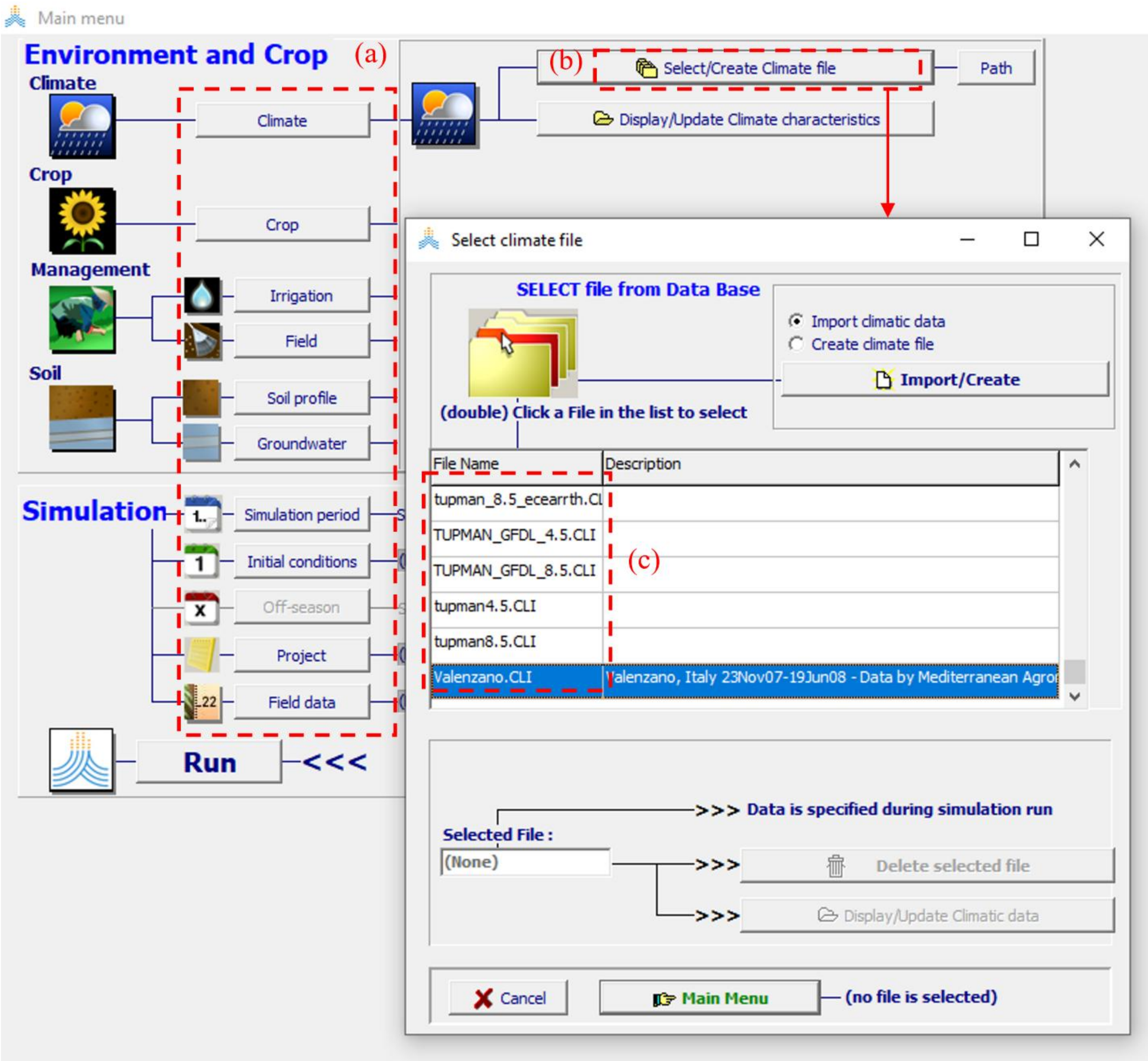


Table 9:
Default settings.

Subject	File	Remarks
Climate	–	A default minimum and maximum air temperature, ETo, rainfall (none), and CO2 concentration are assumed. When running a simulation, other values for ETo and rainfall can be specified.
Calendar	–	The onset of the growing period is specified by the user
Crop	DEFAULT.CRO	Generic crop data with planting date
Irrigation Management	–	Rainfed cropping is assumed. When running a simulation, irrigation characteristics (quality and amount) can be specified
Field Management	–	Optimal field management conditions are assumed
Soil profile	DEFAULT.SOL	Soil physical characteristics of a deep loamy soil
Groundwater	–	Absence of a shallow groundwater table
Simulation Period	–	Simulation period covers the growing cycle
Initial Conditions	–	Soil water content is at field capacity and salts are absent in the soil profile
Off-Seasons	–	Optimal field management conditions are assumed
Project	–	
Field Data	–	

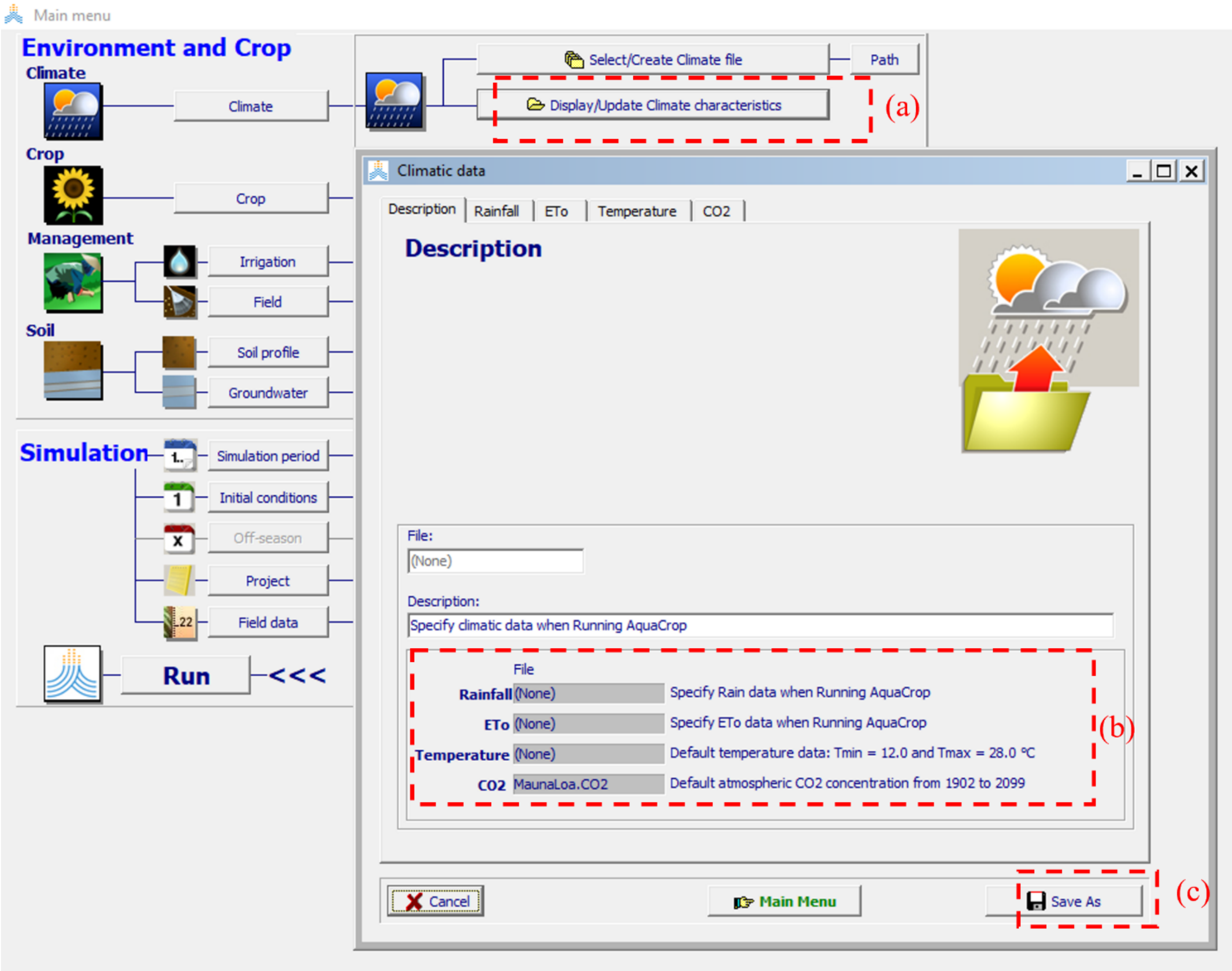
Creating Input Files

There are several options to create input files for the simulation of AquaCrop model.

(1) From the Select file menu (example in Figure 9): Create file menus becomes available by selecting the <Create file> command in the Select file menu (Option b, in Figure 9). In the files, characteristics of the climate, calendar, crop, irrigation or field management, soil profile, groundwater, initial conditions, project or field data are stored.

(2) All input files should be in **.txt** format. We can update the characteristics of input files depending on the types of crops from Display/Update Characteristics (Option a, in Figure 10). We can check and select the database updated in the model (Option b, in Figure 10). After that we can click Save As command to save the respective input files (Option c, in Figure 10).

Figure 10:
(a) Display/Update characteristics for selecting respective input files, b) Check the input file uploaded for the model (c) Choose the Save As command for saving the files.



11.12.2 Climate

Climatic data required by AquaCrop.

To simulate AquaCrop model, we need climatic data of the specific region or place. For each day of the simulation period, AquaCrop requires:

(1) Minimum (T_n) and maximum (T_x) air temperature,
(2) Reference evapotranspiration (ET_0),
(3) Rainfall data, and
(4) Mean annual atmospheric CO2 concentration. ET_0

The required climatic data are stored in respectively:

(1) Temperature files (files with extension '. TnX'),
(2) ET_0 files (files with extension '.ET_0'),
(3) Rainfall files (files with extension '.PLU') and
(4) CO_2 files (files with extension '.CO_2')

A covering climate file (file with extension ".CLI") contains the names of the Tnx, ET_0, PLU and CO_2 file. The climatic data itself is stored in the Tnx, ET_0, PLU and CO_2 files. As mentioned in creating input files, the climate data with all climatic variables are also prepared in txt format so, it can be uploaded on the model (Table 10).

Table 10:
Example of a text file containing climatic data. It consists of daily data, which are (column 1) rainfall in mm, (column 2) minimum and (column 3) maximum air temperature in °C, (column 4) hours of bright sunshine in hours/day, and (column 5) wind speed in m/sec.

0	11.1	30.8	7.8	1.71	3.9
0	10.3	31.6	8	1.43	2.7
0	11.5	31.5	8	1.29	1.4
0	10.7	32.2	8.5	2.57	2.8
0	11.5	30	8.1	1.86	3.3
0	11.9	29.2	8.3	1.14	3.2
0	11	28.6	8.5	2	3.1
0	10.6	28.7	8.4	1.43	3.4
0	11	29	8.4	1.86	3.2
0	10.5	29.9	8.1	2.5	3.1
0	10	30.9	8.1	0.88	3.1
0	9.3	30.3	8.1	3	3

The climate data can be daily or monthly climate data. The text file consists of climatic data recorded in a specific time range (ranging from a few days up to several years) or of calculated averages for a number of years.

When we select the climate file from Environment and Crop panel, we need to click select/create climate file (Option b, Figure 9). After that we need to click import/create, then we import climate txt file from the file location. While preparing climate file, we need to adjust the type and time of climate data, then we need to define climate parameters according to code, following ETo should be defined using the location of meteorological station such as Lat, Lon and elevation. We need to import each climatic variable file from the database which will be stored Tnx, ETo, PLU and CO2 files (Figure 11).

11.12.3 Crop

Import/Create Crop File

Crop file describes the crop type, crop planting time and date and different crop parameters. First, we select the crop type from the default database, or we create the crop file. While we create crop file, we need to choose crop type either the crop is fruit/grain, leafy or root crops. After that we need to select the planting method, either crops are grown using sowing or transplanting method. Finally, we need to give sowing or transplanting date which decides the length of crop growing cycle (Option b, Figure 12). The crop file is saved as CRO.

Figure 11:

Creating climate files: a) Updating data type and time b) choosing the climate parameters c) calculating ET_o and d) Import of climate data in files.

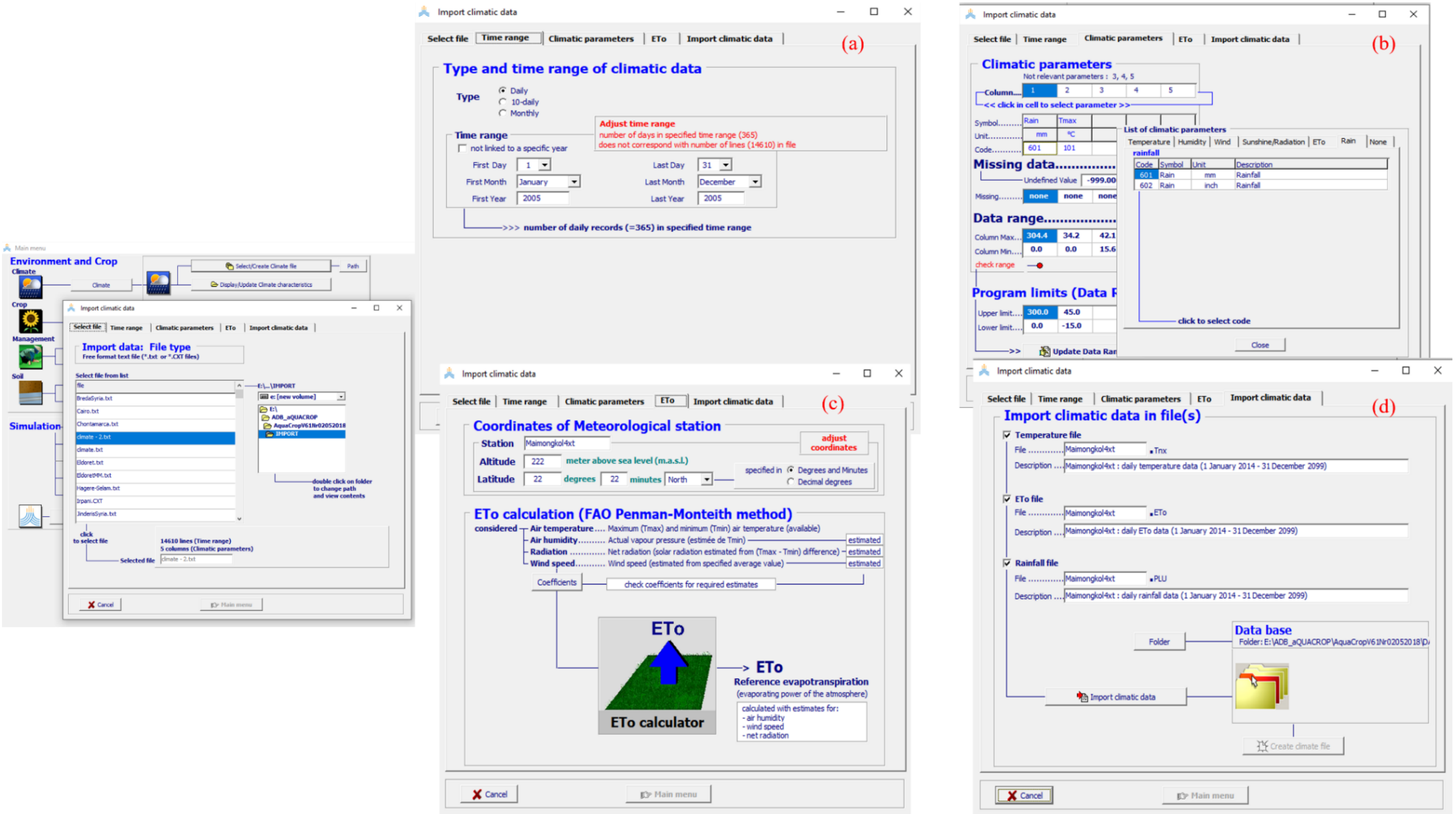
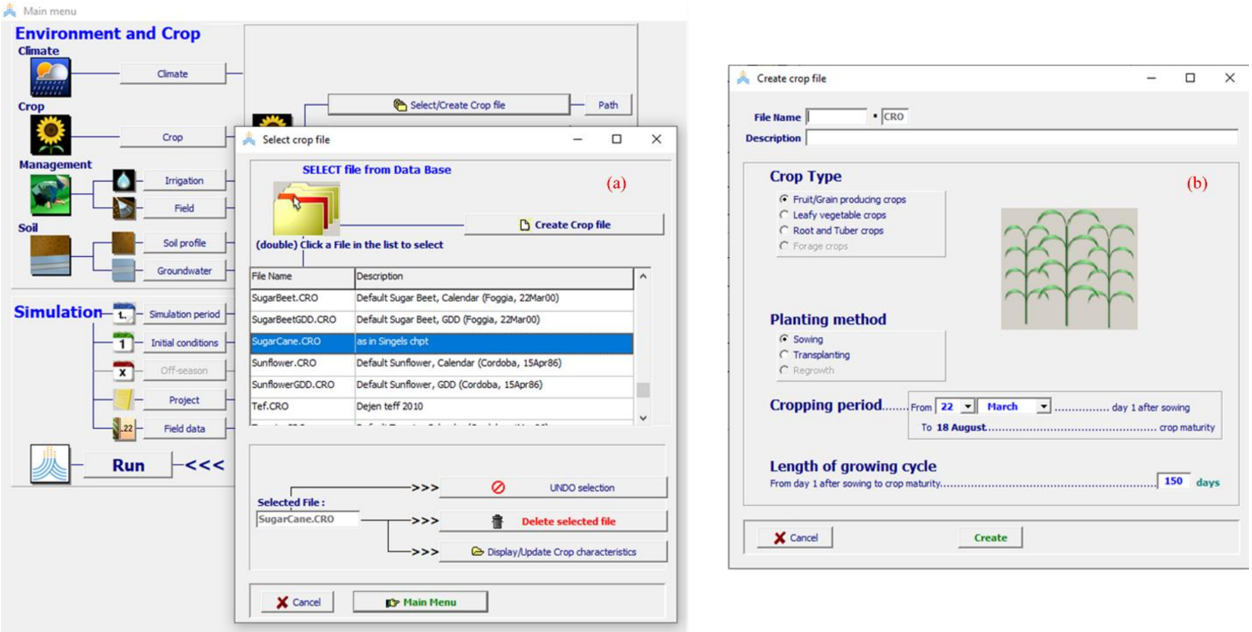


Figure 12:
Import crop file from database b) Create crop file.

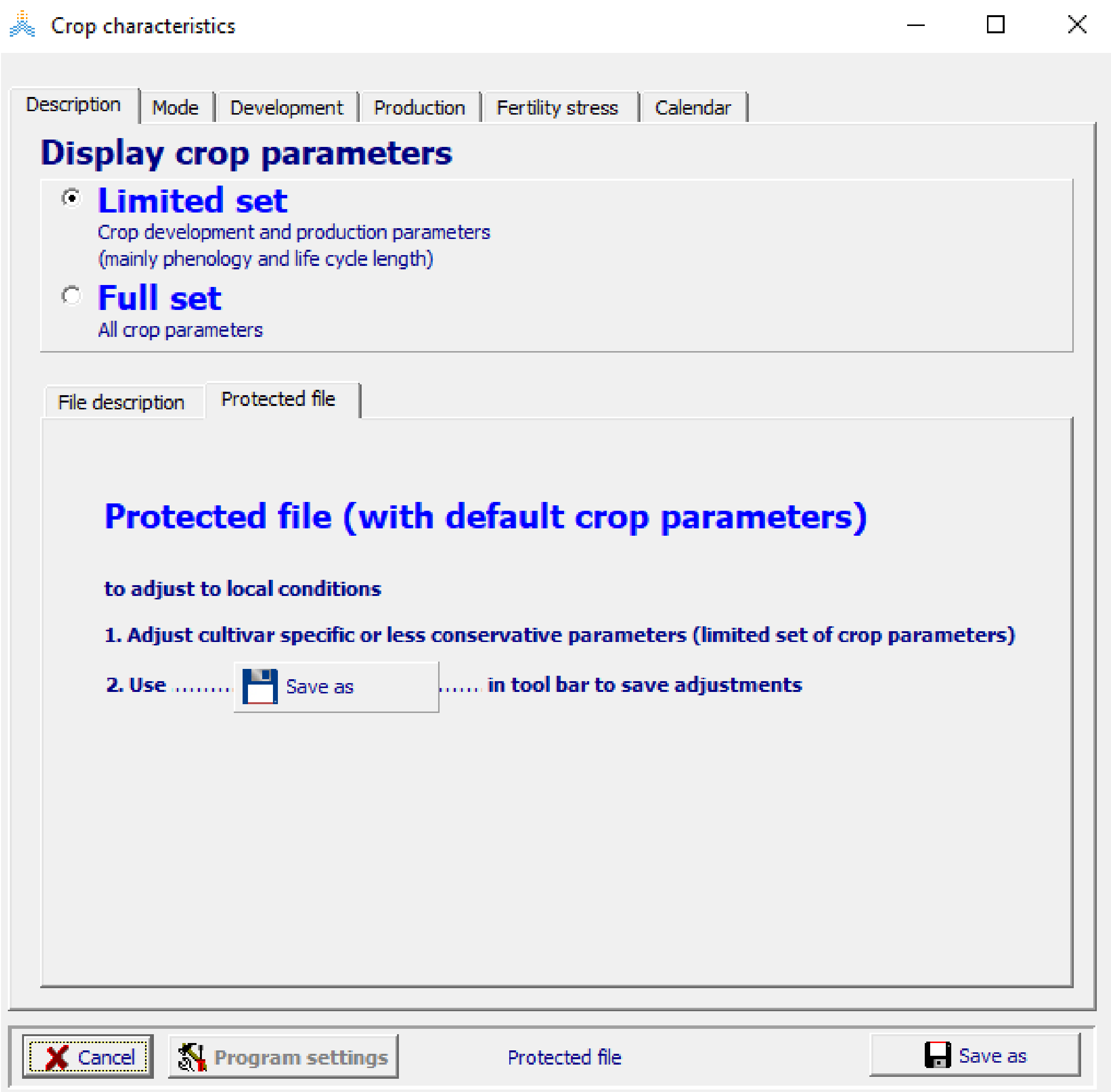


Display and update crop characteristics

After creating the crop file, we have to update the crop parameters depending upon the crop types. We need to click the display/update crop characteristics command, then we get access to the crop characteristics where we adjust crop parameters. There are different crop parameters such as mode, crop development, crop production, fertility stress and crop calendar which are as follows (Figure 13):

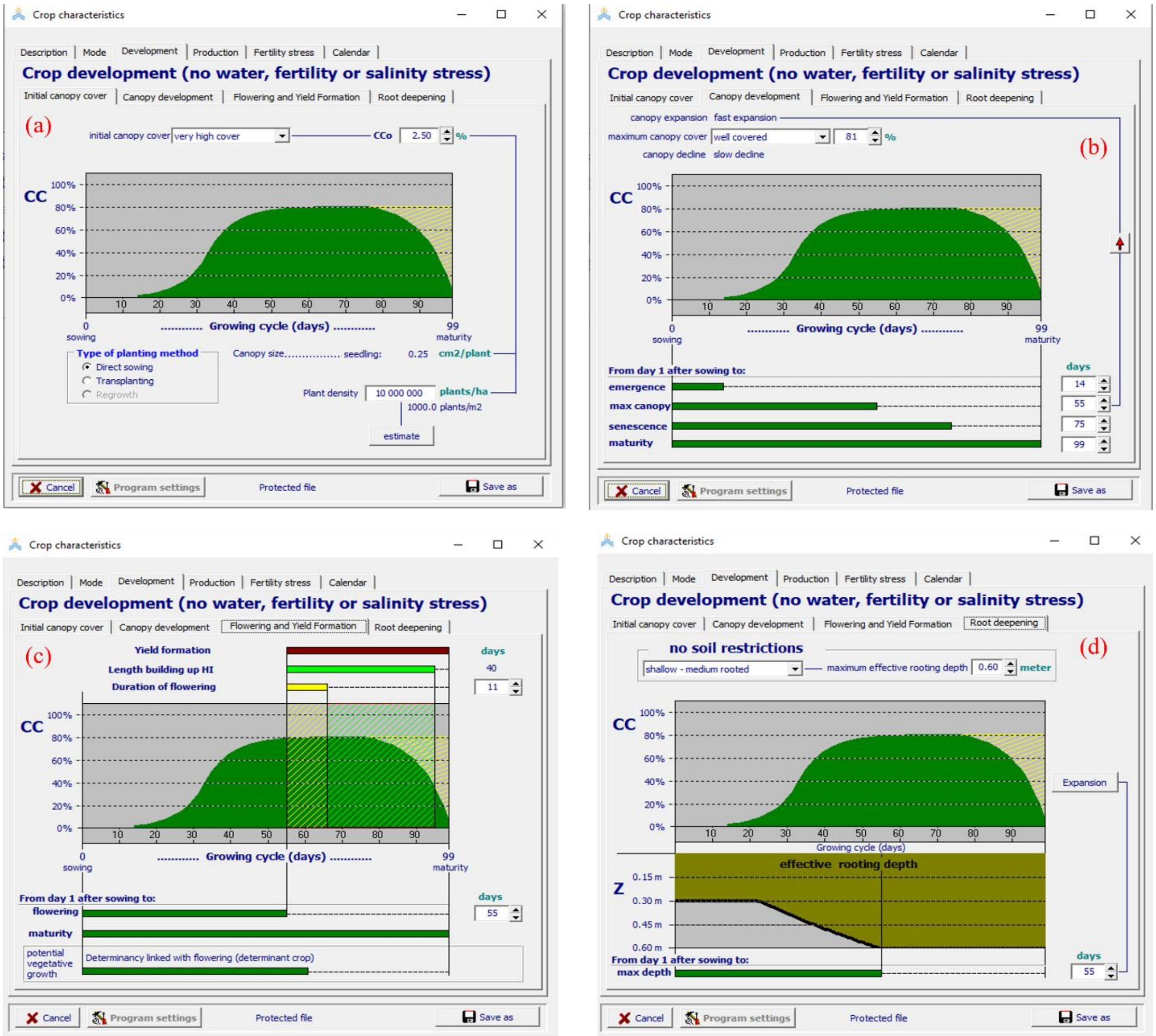
(1) **Description:** to adjust the description of the crop file.
(2) **Mode:** to switch from Calendar days to Growing degree-days at the end of the tuning process
(3) **Development:** to adjust cultivar specific parameters and parameters affected by planting, management, and conditions in the soil profile.
(4) **Production:** to adjust the Harvest Index.
(5) **Fertility-stress:** to calibrate the crop biomass response to soil fertility and/or soil salinity stress.
(6) **Calendar:** to get an overview and/or adjust the calendar of the growing cycle.

Figure 13:
Different crop parameters in tabular sheets.



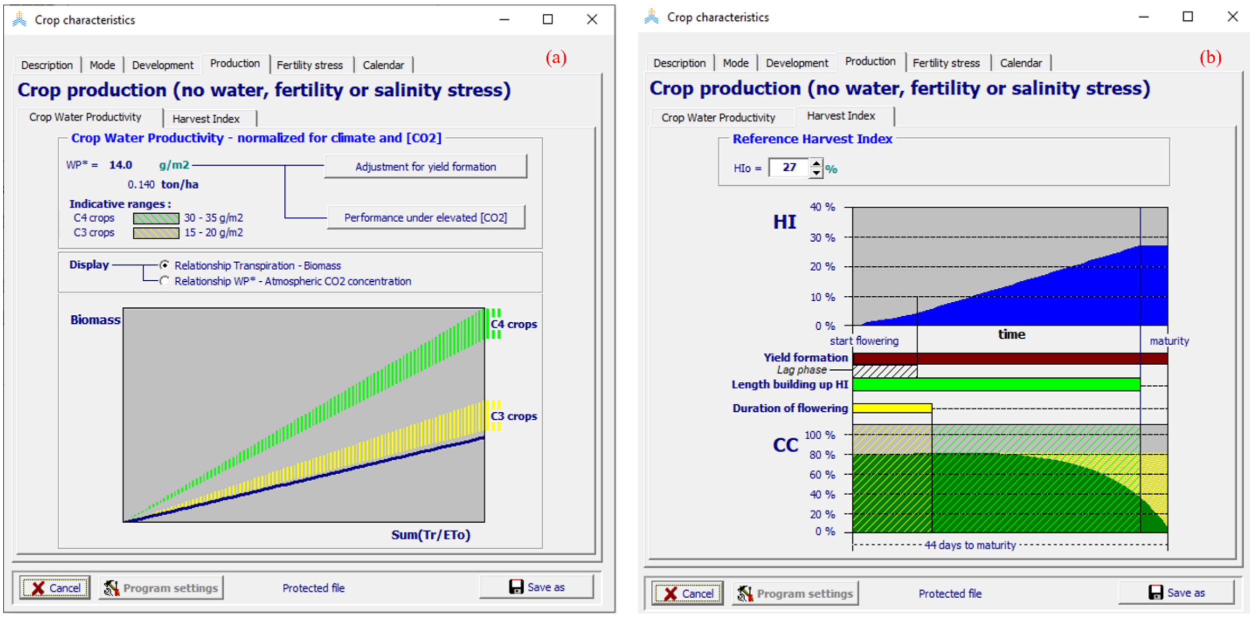
In Description, we select the either limited set or full set crop parameters. After that we proceed to mode. The mode defines whether we want to grow our crop according to calendar days or growing degree days. Mostly, we select calendar days for the simulation of the model. After that we move forward to the development sheet, which describes the crop development with development of canopy cover, flowering and yield formation, root deepening. a) Describes the Initial canopy cover (CCo), planting method and plant density which varies depending upon the crop type. b) Maximum canopy cover (CCx) is defined with duration of emergence, max canopy to maturity days c). Duration of flowering and yield formation and d) Define maximum effective root depth (Zx) (Figure 14).

Figure 14:
(a) Canopy development, (b) Flowering and yield formation, (c) Flowering and Yield formation and (d) Root Deepening tabular sheet of the Development tabular sheet of the Crop characteristics menu.



The crop water productivity and reference harvest index are defined in the Crop Development tabular sheet. The crop water productivity is estimated using the climate and CO2 data, whereas Harvest Index (HI) can be identified from literature review (Figure 15).

Figure 15:
Crop production a) Crop water productivity and b) Reference Harvest Index.



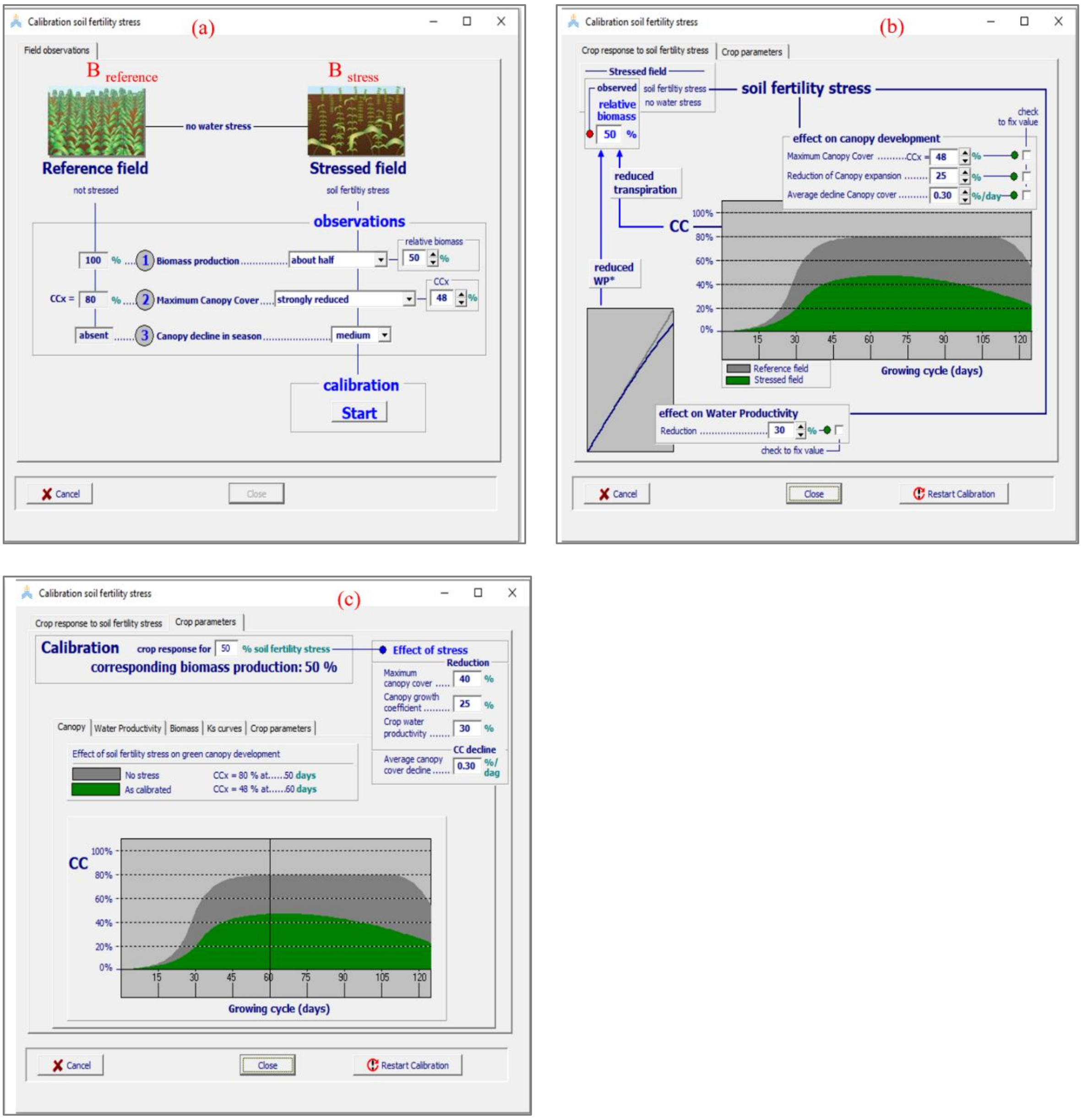
The consideration of fertility stress depends on the types of crops. If the aboveground biomass (B) in the stressed field is limited, which is mostly due to decreased canopy cover (CC) and biomass water productivity (WP*), soil fertility stress calibration must be performed. The effect of soil fertility stress is affected by the type of limiting nutrients, and environmental conditions such as climate and soil type, a calibration of the crop response to soil fertility stress is required and most likely will have to be repeated for each type of environment. The crop response to soil fertility stress is calibrated in the Crop characteristics menu (Figure 16). In the ‘Field observation’ tabular sheet of the Calibration soil fertility stress menu.

The main parameters for soil fertility stress are:

(1) Total biomass produced in a stressed field, expressed as a relative value, B_{rel} (= 100 x $B_{stress}/B_{reference}$). B_{rel} is the maximum relatively dry aboveground biomass (Brel) that can be expected in that field with limited soil fertility as compared to stress-free conditions;
(2) Maximum canopy cover that can be reached in a stressed field (CCxstress); and
(3) The degree (small, medium, or strong) of the canopy cover decline in the season.

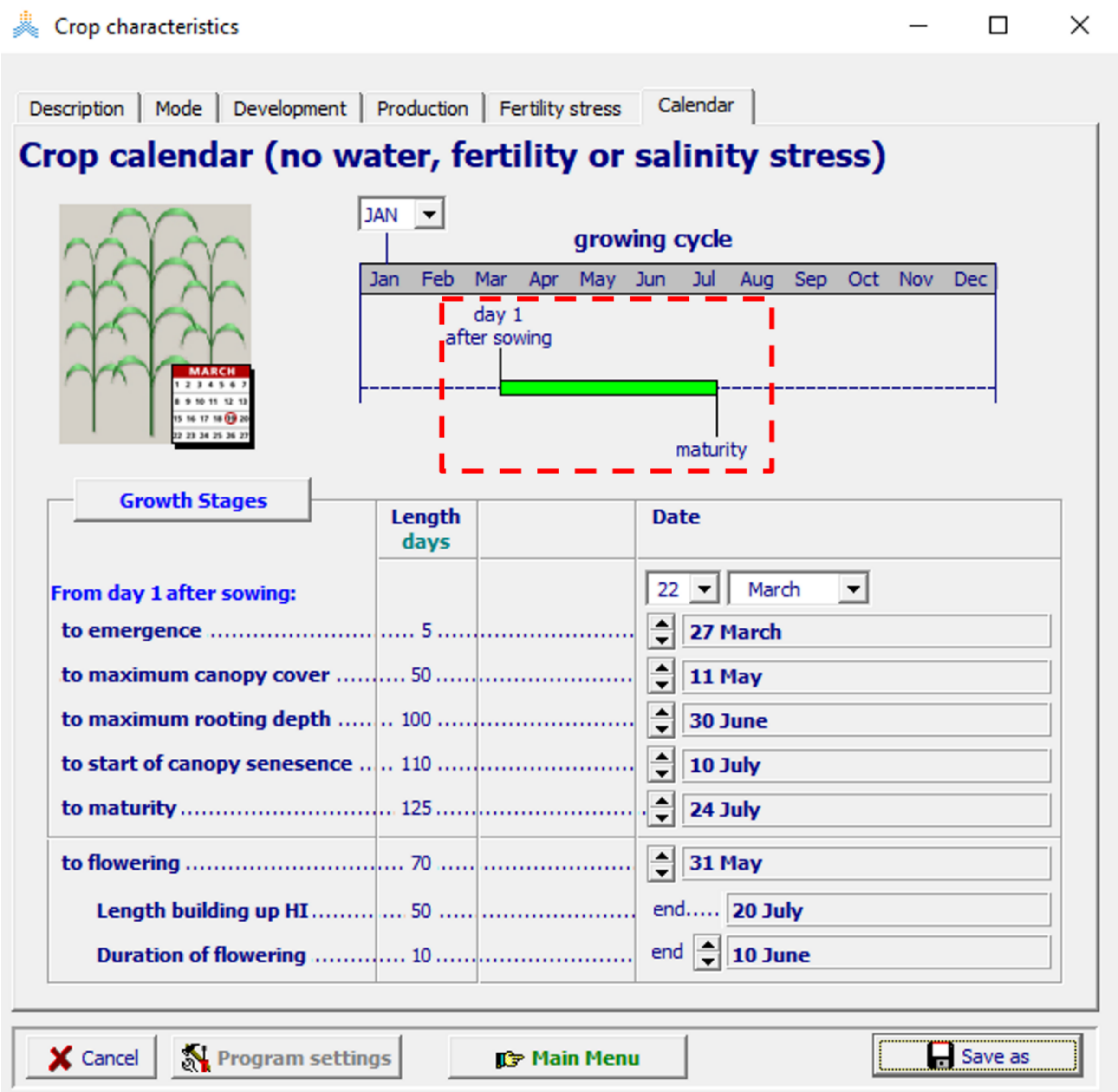
After launching calibration process, After launching the calibration process, AquaCrop searches for a setting of the 4 stress coefficients, for which the reduced WP* and smaller CC results in a Brel equal to the Brel for which the crop response is being calibrated.

Figure 16:
Start of calibration soil fertility stress b) Crop response to soil fertility stress’ c) Calibration of crop parameters.



The crop files end with the calendar of the growing cycle displayed in calendar tabular sheet of the crop characteristics. We can adjust the planting date and the length date of the different growth stages of the different crops. We can use the spin button to change the months of the cropping cycle (Figure 17). After all the adjustment in crop characteristics, we can click Save As command to save the changes.

Figure 17:
Calendar tabular sheet to inspect or adjust the calendar of the growing period



11.12.4 Management

The management consist of two files a) Irrigation management files and b) field management files.

Irrigation Management Files

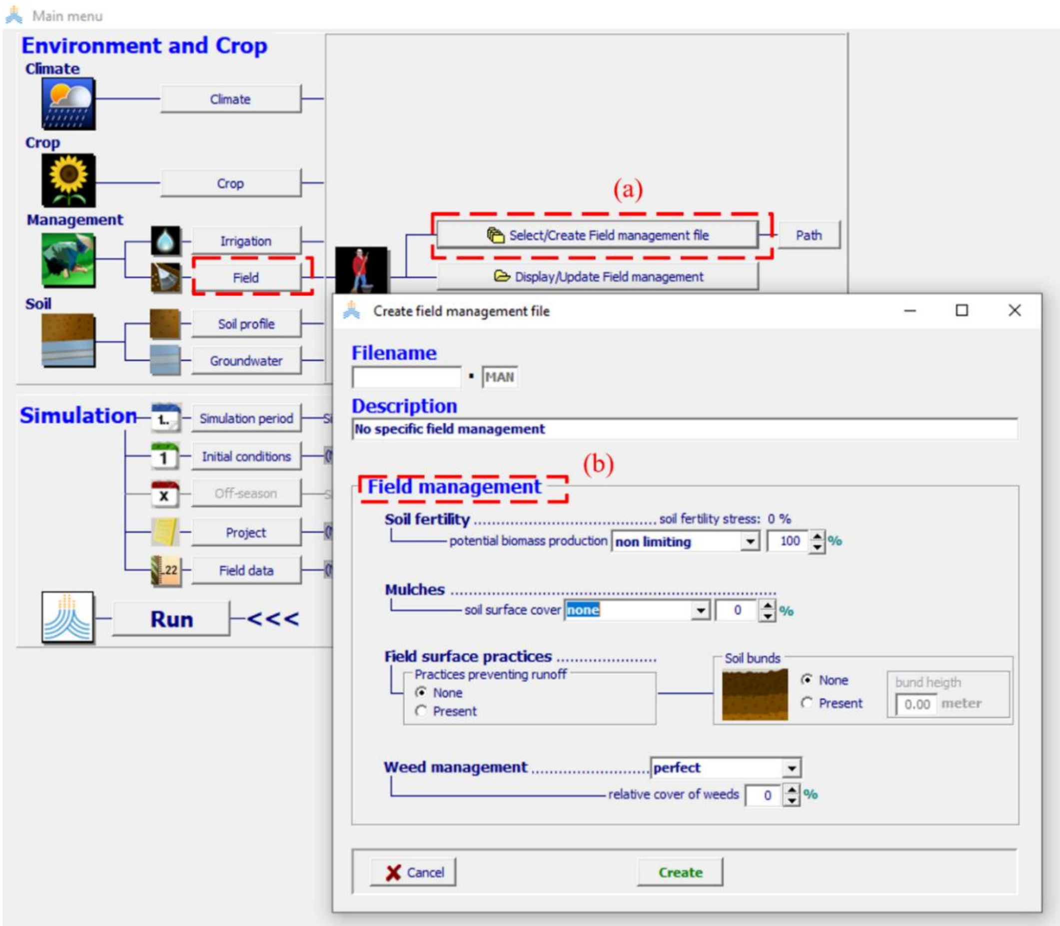
This file is considered when irrigation is performed for the growth and management of crops. If the crop is rainfed, we do not adjust this file.

Field Management Files

The field management files is the user specified file where we can update different field management practices according to the crop type and farmer management practices. The data are usually based on baseline survey data from the field. The field management characteristics are as follows:

(1) **Description**: to adjust the description of the soil profile file.
(2) **Soil fertility**: to specify the maximum relatively dry aboveground biomass that can be expected when soil fertility is limited;
(3) **Mulches**: to specify the soil cover by mulches and the type of mulches.
(4) **Field surface practices**: to specify if surface runoff is affected or inhibited by the practices, or if soil bunds are available between which water can be stored on top of the field surface.
(5) **Weed management**: to specify the degree of weed management and the corresponding relative cover of weeds.

Figure 18:
Select/Create field management file command to create field management files b) Different field management practices to create field management file.



In the management panel, we can find Field command, after we click the command, a new dialog box will appear to select/create the field management files and Display/Update the field management. We need to click select/create the field management, where we can adjust the field management practices according to our baseline survey data. Previously, under Crop Characteristics, if soil fertility calibration was considered, only the option appears whether to change soil fertility management or not. After that, we can adjust the mulches and types of surface mulches.

Depending on the baseline survey data, we can know if the field surface practices preventing runoff are practiced or not. If they are practiced, we need to choose present command and provide the height of soil bund also. And at last, we need to scale the weed management of the field from poor to perfect with help of the spin button (Figure 18)

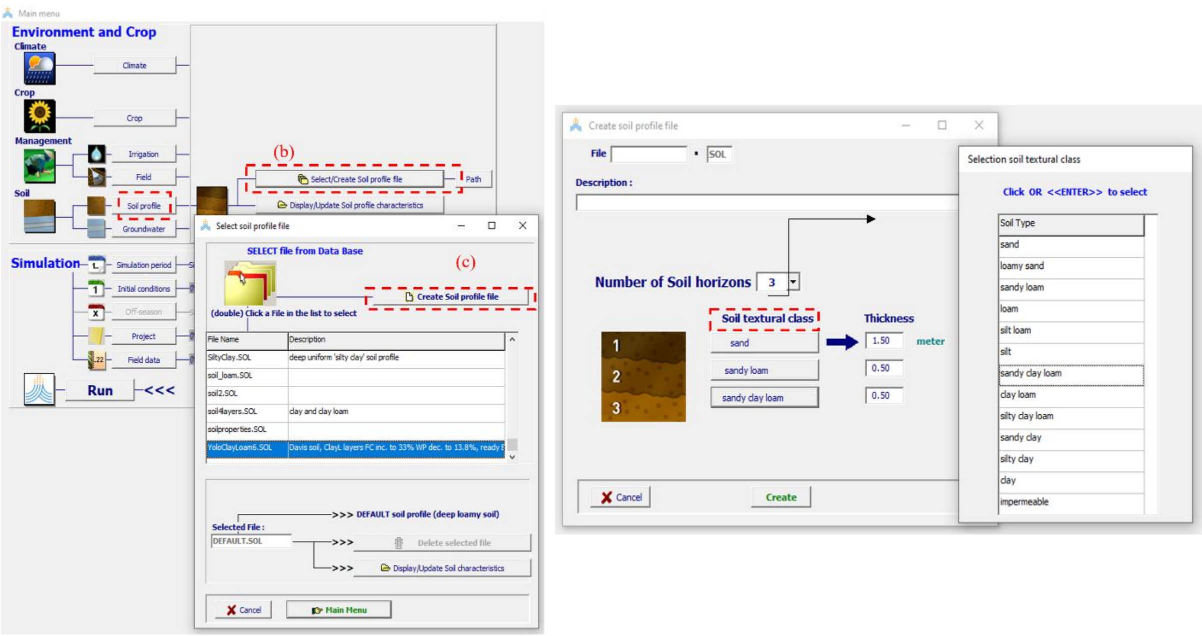
11.12.5 Soil

The soil file consists of two inputs: a) Soil and b) Groundwater.

Soil

The soil data are mainly archived from the respective region land development department. For the soil file, we need to define the number of soil horizons, soil textural class and thickness of each horizon. The classes are selected from a list, which contain data for a set of soil textural classes. From the data, default values for the required soil physical characteristics of each layer and the soil surface are derived (Figure 19).

Figure 19:
a) Select the Soil profile command b) Select/Create soil profile file command in the file management panel of the Main menu c) Select Create soil profile file command to create soil management file.

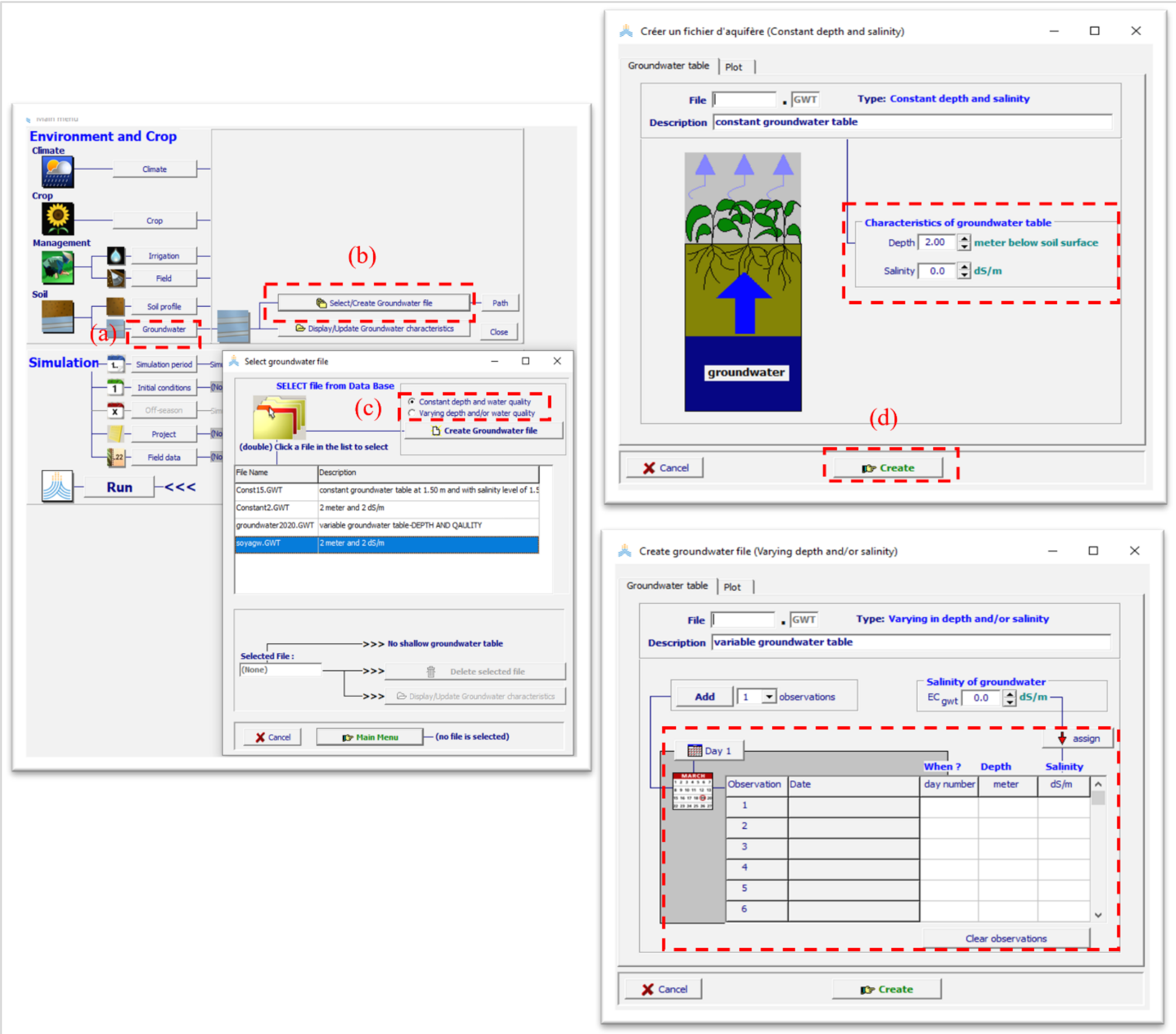


Groundwater table files

To create Groundwater table files, we need to choose select/create groundwater file from the file management panel (Figure 20). The groundwater data are also collected from the groundwater department of the region. We need groundwater depth and quality data to make groundwater file. While making groundwater table files, we need to specify whether we want (a) Constant depth and water quality; or (b) Varying depth and/or water quality.

If the groundwater table is not shallow (more than 4 meters below the root zone), there is no need to specify a groundwater table since capillary rise can be disregarded.

Figure 20:
Ground water table files a) Select the Groundwater command b) Select the select/create command file c) Choose between Constant depth and water quality; or Varying depth and/or water quality d) Click create command to create groundwater table file.



11.12.6 Simulation

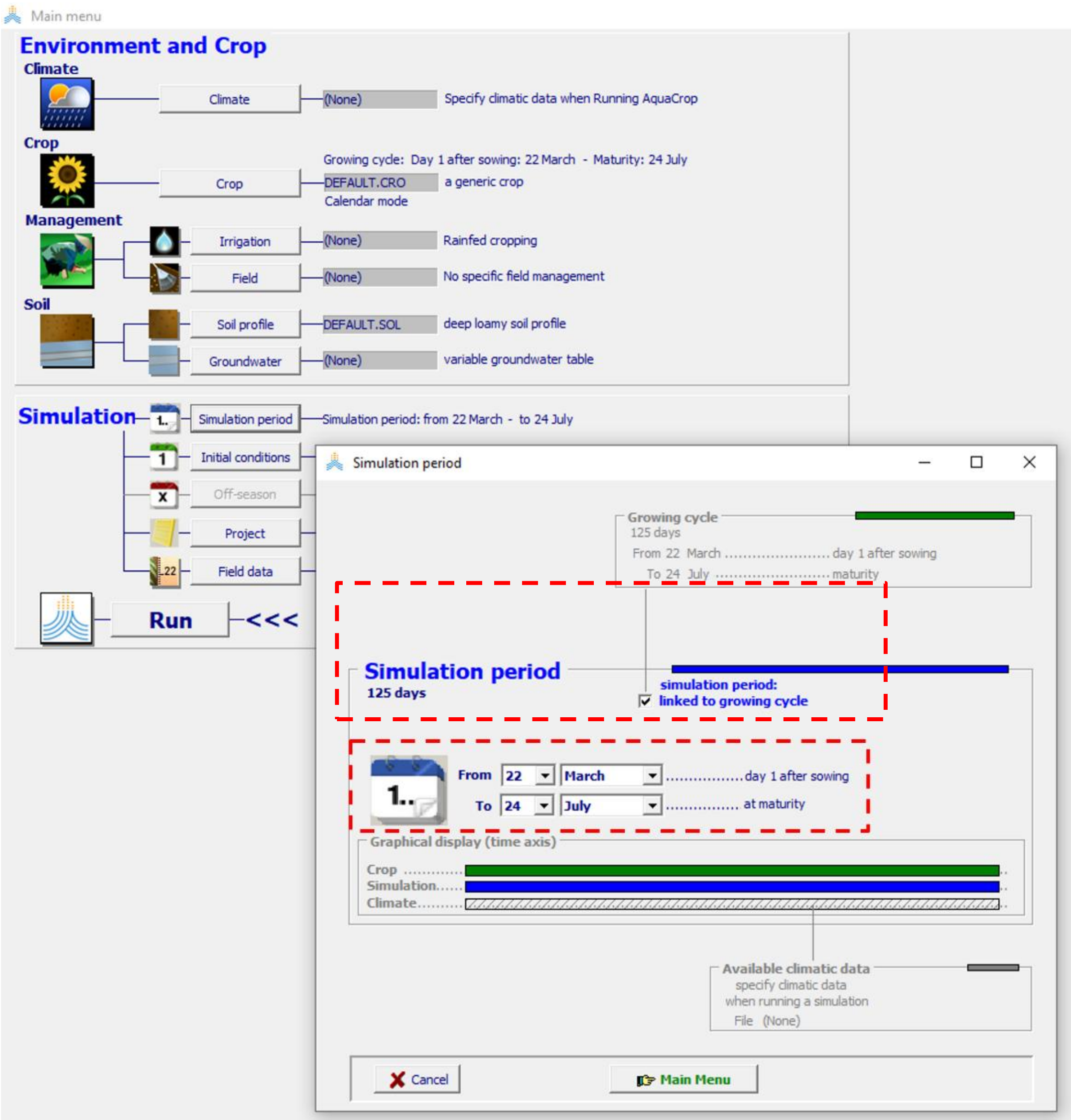
The second panel of AquaCrop model is simulation panel. In this panel we check the simulation period, initial conditions, define the project and import the field data for the simulation.

Simulation Period

The simulation period can be adjusted in the simulation period menu. Sometime the simulation period may or may not coincide with the growing cycle of the crop but can be shorter or longer as long as the period does not exceed the range of climatic data.

Select the Simulation period, then a dialog box will appear where we can adjust simulation period from 1 set after sowing to maturity (Figure 21).

Figure 21:
Adjustment of Simulation period according to crop growing cycle.

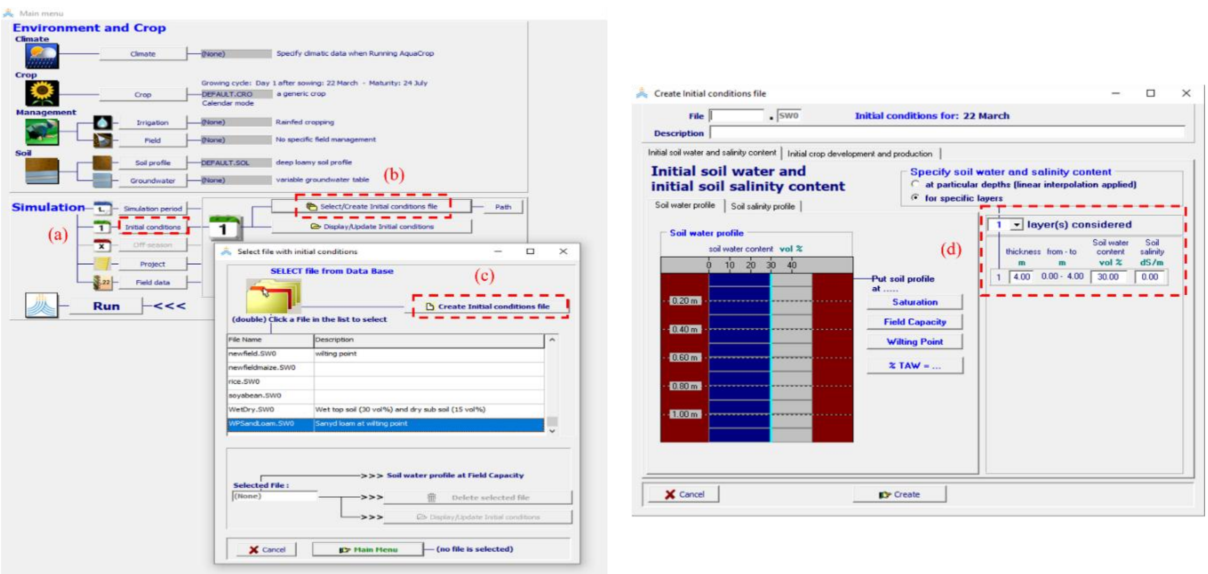


Initial conditions

The initial conditions refer to the status of the soil water and salt content in the soil profile, and the crop development and production, at the start of the first day of the simulation period. To create an initial conditions file, we can click the initial conditions command in Simulation panel. Then we need to select the create initial condition files where initial conditions are displayed and we can update the conditions according to our requirements (Figure 22). The initial conditions are:

(1) **Description**: to adjust the description of the file containing the initial conditions.
(2) **Initial soil water and salinity content**: to adjust the soil water and salinity contents.
(3) **Initial crop development and production**: to adjust the degree of crop development and production when the simulation period starts after germination.

Figure 22:
a) Select the Initial conditions command b) Select/create initial conditions file c) Create initial conditions file d) Adjust the thickness, soil water content, and soil salinity depending on the soil profile.

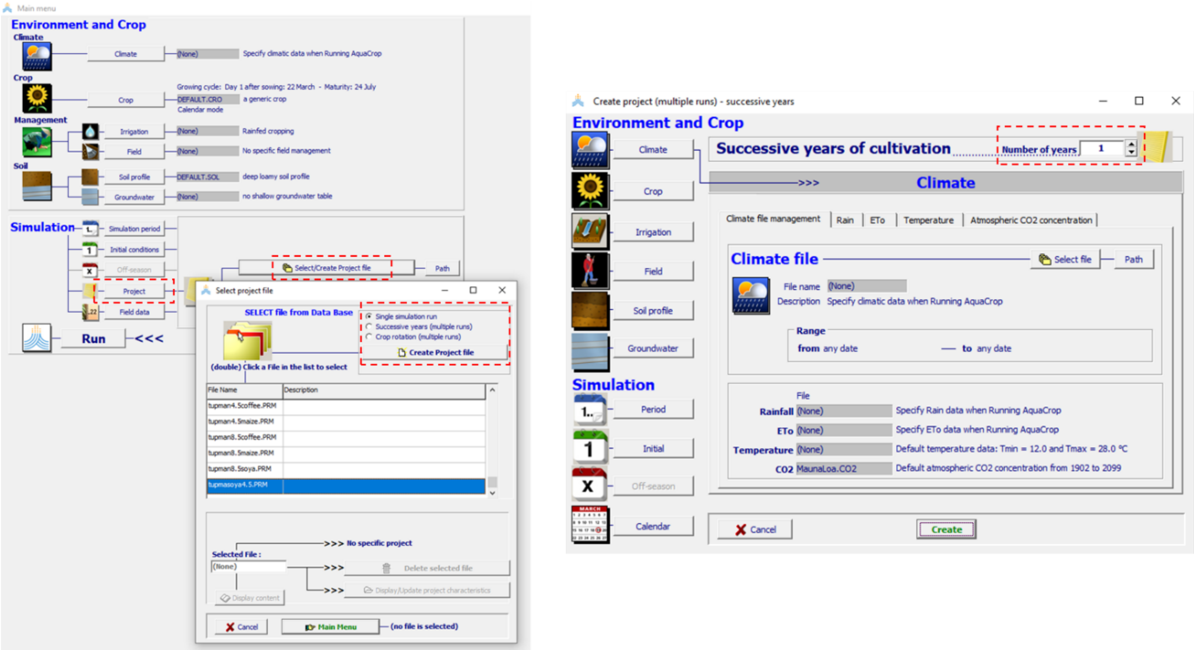


Project

After providing all the input files and adjusting simulation period and initial conditions, we need to prepare a project file before running the model, where every input file (climate, crop, soil, groundwater, and field management) can be overviewed, and we can select whether we want to run the model for single simulation run or successive runs for years.

The project is selected from simulation panel. Then the project is created by selecting the <Create project file> command in the Select project file menu. After selecting the <Create project file> command, the Create project menu is displayed where we can select the single run or multiple runs. In the case of a multiple run project, which consists in repeating a simulation over a number of successive years, the number of years (according to the data available in the selected Climate file) are displayed at the top of the menu. By means of a spin button, the number of years (series of simulation runs) can be altered (Figure 23). After that we click create button, which create project file with extension ".PRO".

Figure 23:
a) Select the Project from Simulation panel b) Select/create project file c) Choose between single or multiple run d) In case of multiple run we can adjust number of years depending on climate data.



Running AquaCrop in Project Mode

Once the project file is loaded, we can give field data such as observed biomass, green canopy cover data, crop yield data. If we don't have field data, we can simulate the model (Figure 24). To run the model, we can click the run command which is situated below the model interface. When we click the run button a simulation run dialog box will appear (Figure 24). This dialog box shows the climate input values, and we can adjust the time to end the simulation run. After checking the time, we can click the start command and wait for simulation to end.

Figure 24:
a) Select field data b) Select/create field data file c) Create field data file d) Field data can be filled according to the date and year.

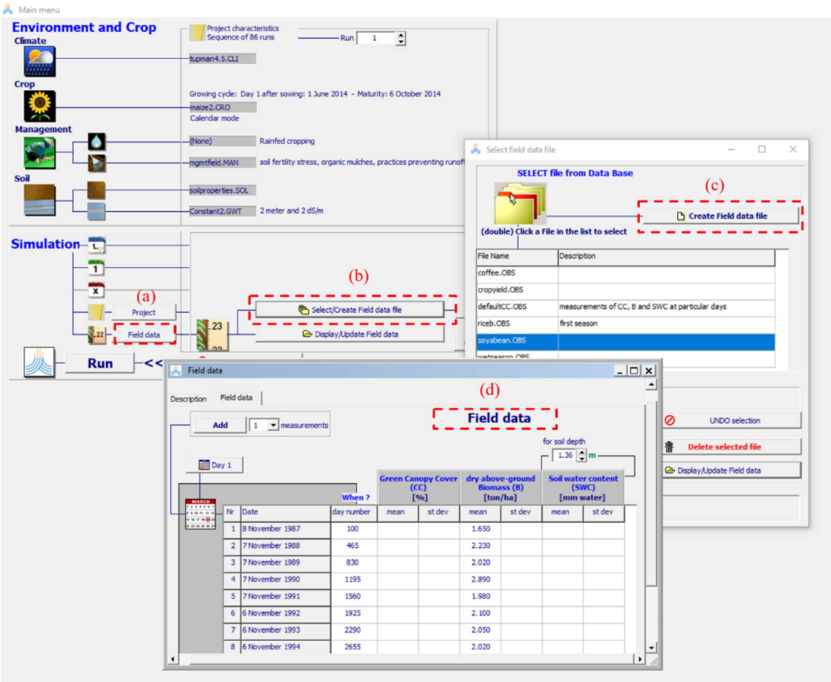
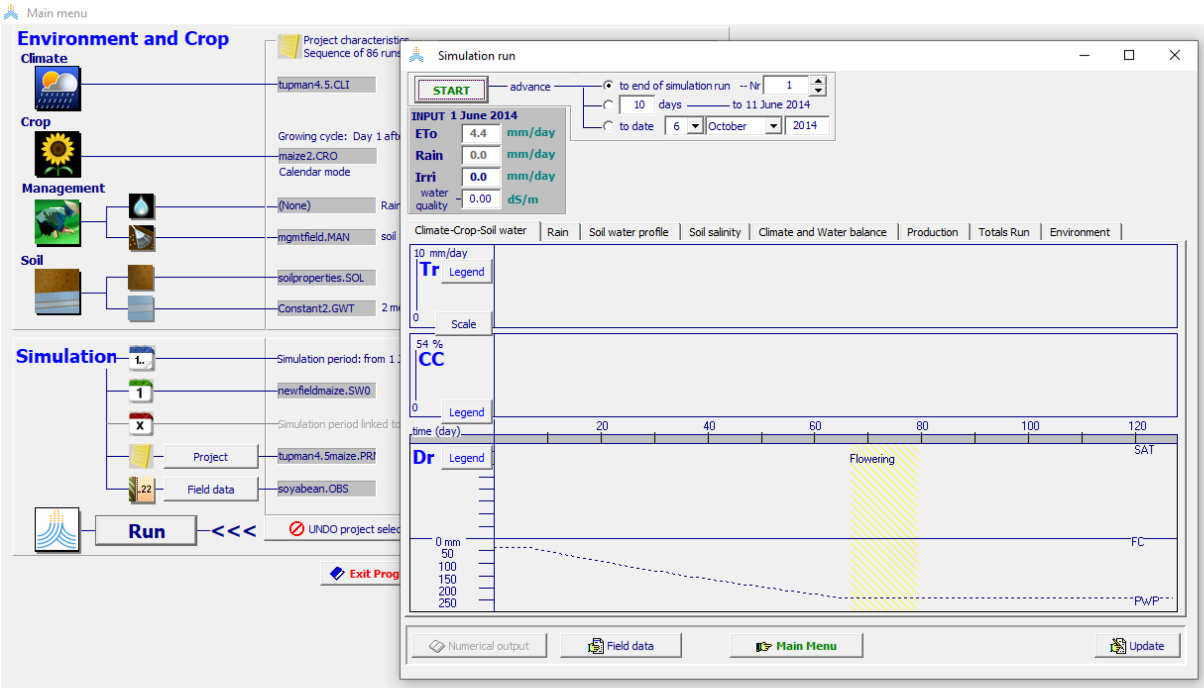


Figure 25:
Click Run command b) Adjust end simulation time c) Click Start command for simulation run of the model.



11.12.7 Model calibration

The AquaCrop model is calibrated on a trial-and-error basis. The climate, soil, crop and management inputs are specified during the calibration along with actual observed values such as crop yield, soil water content and leaf area index. The parameters of the crop growth model are manually adjusted until the best match between simulated and observed values of crop yield, soil water content, and leaf area index are obtained. The typical parameters of AquaCrop model to be trained during calibration are given in Table 11.

11.12.8 Model validation

AquaCrop model validation is testing and validating manually calibrated crop model with optimized parameters. Independent observed crop yield, leaf area index and soil water content are used to validate the model through comparing simulated and observed values. After model validation, the calibrated/validated model is used for future prediction of crop yield under climate change, water availability and other management scenarios.

Table 11:
AquaCrop model parameters.

Symbol	Parameter description	Unit	Type
T_{base}	Base Temperature	°C	Conservative
T_{upper}	Upper Temperature	°C	Conservative
CC_0	Soil surface covered by an individual seedling at 90% emergence	cm^2/plant	Conservative
	Number of plants per hectare	-	Management
	Time from sowing to emergence (growing degree day)	days	Management
CGC	Canopy growth coefficient (fraction per growing degree day)	-	Conservative
CC_x	Maximum canopy cover	%	Management
	time from sowing to start senescence	days	Cultivar
CDC	Canopy decline coefficient (fraction per growing degree)	days	Conservative
	Time from sowing to maturity/length of growing cycle (growing degree day)	days	Cultivar
	Time from sowing to flowering (growing degree days)	days	Cultivar
	Length of the flowering stage (growing degree days)	days	Cultivar
Z_n	Minimum effective rooting depth	m	Management
Z_x	Maximum effective rooting depth	m	Management
	Shape factor describing root zone expansion	-	Conservative
$KC_{Tr,x}$	Crop coefficient when canopy is complete but prior to senescence	-	Conservative
	Decline of crop coefficient as a result of ageing nitrogen deficiency, etc.	% per day	Conservative
	Effective canopy cover on reducing soil evaporation in late season stage	-	Conservative
WP*	Water productivity normalized for ET_0 and CO_2	g/m^2	Conservative
	Water productivity normalized for ET_0 and CO_2 during yield formation (as % WP* before yield formation)	%	Conservative
HI_0	Reference harvest index	%	Cultivar
	Possible increase of HI due to water stress before flowering	%	Conservative

Symbol	Parameter description	Unit	Type
	Excess of potential fruits	%	Conservative
	Coefficient describing positive impact of restricted vegetative growth during yield formation on HI		Conservative
	Coefficient describing negative impact of stomatal closure during yield formation on HI		Conservative
	Allowable maximum increase of specified HI	%	Conservative

12. Adaptive Capacity

Adaptive capacity (A) is the capacity of a system to recover from disasters and hazards. In the context of climate change's impact on highland agriculture, adaptive capacity is about how well the farmers are able to cope with the adverse conditions due to climate change and climate hazards in highlands. Several factors can be considered as adaptive capacity which include land holding size, employment rate, availability of credit, literacy rate are few of them. The list of indicators described here are listed in Table 12.

Table 12:
Indicators derived from the reviewed indices of adaptive capacity and their functional relationship to agricultural vulnerability.

Index	Indicators (unit)	Calculation	Relation	Reference
AC1	Land holding size (rai/HH)^	Total landholding area/No. of HH	Negative	Gbetibouo et al. (2010); Wiréhn et al. (2015)
AC2	Employment rate (% of respondents employed)	No. of respondents employed/Total no. of respondents*100	Negative	Gbetibouo et al. (2010)
AC3	Availability of credit (% of respondents believing credit is easy)	No. of respondents believing in that credit is easy/Total no. of respondents*100	Negative	Gbetibouo et al. (2010)
AC4	Proportion of off-farm median income to total income (%)	Off-farm median income of HH/Average HH income*100	Negative	Gbetibouo et al. (2010)
AC5	Education level (% of respondents with education higher than primary level)	No. of respondents with education higher than primary level/Total no. of respondents*100	Negative	KC et al. (2015)
AC6	Livestock density (Animal Unit: AU/HH)^	Total no. of livestock in terms of Animal Unit (AU)/No. of HH raring livestock	Negative	
AC7	Transportation cost from home to selling place (Baht/rai)*	Transportation cost from home to selling place/ Total area of cultivation	Positive	

^ : Min and max bounds are evaluated from baseline survey
* : Min and max bounds are evaluated based on indicator values across unit of analysis (villages) during baseline and future periods

12.1 Land holding size

The land holding size is directly linked with the adaptive capacity of the farmer. As the size of the farm increases, the adaptive capacity of the farmer also increases. The large land holding farmers have the capacity to adapt to adverse conditions.

12.2 Employment rate

The more the people in a household are employed the more they are likely to adapt to adverse conditions because would be less needed to support other members of the household.

12.3 Availability of credit

Availability of credit open several opportunities such as new business ventures, enterprises, agribusiness and off-farm activities. Hence, credit is an important aspect of adaptive capacity.

12.4 Proportion of off-farm median income to total income

Off-farm income are those alternative sources of income derived from non-farming activities. It plays a vital role in sustaining the livelihoods of the households when farm income is insufficient to thrive during adverse conditions.

12.5 Education level

Education level of a farmer and the farming community elevates the level of understanding on the climate cycle, forecasted rainfall, selection of the crops according to the anticipated climatic conditions which help them to overcome and adapt to the adverse conditions. Technology use and adopting advanced technologies help to adapt to the anticipated extreme climatic conditions such as drought hazard.

12.6 Livestock density

Livestock are part of agricultural system. Farmers having livestock can utilize byproducts such as manure in their field while byproducts from farms such as straw can be used as fodder. This creates a cycle called integrated farming practice where two systems are integrated into one to take most of them. Thus, beside the alternative income source livestock help in reducing vulnerability of agricultural system towards climate hazards.

12.7 Transportation cost

Besides production cost, transportation cost of agricultural goods to the market is another major source of expenditure. Hence, it is essential not to leave transportation costs out of the equation.

13. Using Vulnerability Assessments for Decision Making

13.1 Use in project and policy contexts

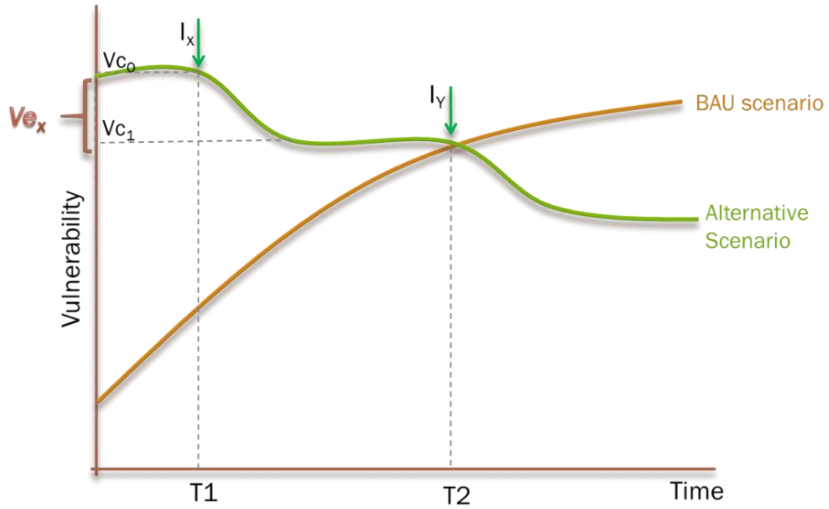
Vulnerability assessments (VAs) have a wide range of applications. These applications vary depending on the nature of the problem and context. VA outputs can be used for decision-making both in climate change adaptation projects and policies. Most of the climate change adaptation and developmental interventions are carried out in a project mode. Projects usually have a specific start date and end date and often cover a narrow field of influence and narrow geographical area. Projects have well-defined activities and stakeholders chalked out with their precise roles and responsibilities. In the case of policies, though they may have a certain prescribed duration, policies are often not as well defined as projects as they tend to cover a longer duration and cover a broader scope of influence compared to projects. Often, policies determine the nature and scope of projects implemented. The VAs helps projects in the following manner:

(1) Help prioritize projects that provide better vulnerability reduction outcomes over other projects.
(2) Help better design projects to better target the most vulnerable sections of society.
(3) Help better implement projects in terms of monitoring and evaluation of project progress, outputs and outcomes.
(4) Help project administration by acting as an adaptation metric so that the project implementation agencies can track the progress in adaptation.

Since there has been much attention on the need for adaptation metrics, it is imperative here to understand how VAs can act as a metric to assess the effectiveness of adaptation actions.

Figure 26 shows a simplified scheme of how vulnerability assessments can be used for assessing adaptation interventions. According to this approach, the VAs conducted at regular intervals during and after the project implementation would provide a metric to assess if adaptation interventions are leading to an overall increase or decrease in vulnerabilities assessed in the project area.

Figure 26:
Using vulnerability as a metric to assess adaptation interventions (Source: Authors).



Vulnerability reduction effectiveness (Vex) can be derived as:

$$Ve_x = Vc_1 - Vc_0 \tag{26}$$

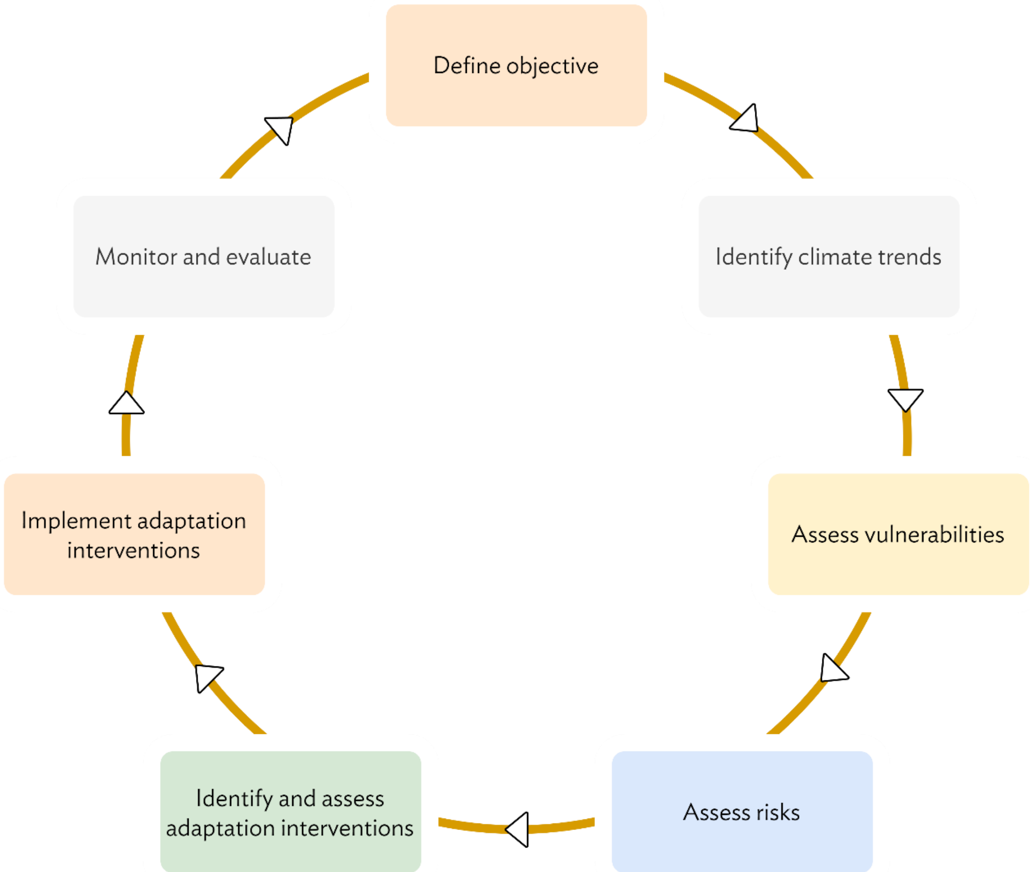
Where Ve_X is the effectiveness of adaptation action x; Vc_0 and Vc_1 are vulnerabilities assessed at times T_1 and T_2. I_X, I_Y represent interventions x and y implemented at the time of T_1 and T_2.

13.2 Use in agricultural adaptation planning

In addition to the application in different project and policy contexts, adaptation planning is another important area where VAs can be used. For illustration purposes, the application of VAs in community-based adaptation planning has been described here. The place of vulnerability assessments in the community-based adaptation planning cycle is shown in Figure 27.

Community-based adaptation plans can be understood as climate change adaptation plans that are designed by the involvement of communities and implemented at the community level by the community and for the benefit of the community. Community-based adaptation plans are at the center of the community-based adaptation (CBA) approaches. CBA approaches have received growing interest for several reasons. The foremost reason has been that communities are the ones who undergo climate impacts first. This approach is derived from the field of disaster risk reduction where community-based disaster risk management (CBDRM) plans have evolved much before CBA planning has produced very useful results in reducing disaster risks at the community level.

Figure 27:
A typical Community-based adaptation planning cycle (Source: Authors).



CBA plans derive their strength from the fact that communities understand their vulnerabilities and capacities more than external actors. In most natural resource-based societies, communities are also the stewards of local resources including natural resources. It has been widely proved that access to local natural resources is an important element of community resilience and long-term risk reduction as climate change impacts will have a debilitating effect on the local natural resources as well upon which communities are dependent for their livelihoods and well-being.

A major part of CBA plans also dwell on the response component aftermath of climatic hazards. Since communities are the primary responders by being there and having felt the impacts of the climatic events, it makes sense that the capacities of communities are enhanced so that the losses and damages can be mitigated well before external support arrives. As a result, CBA plans enable local governments to focus more on long-term risk reduction efforts than to focus on immediate relief measures. This reduces the burden on the governments and helps focus efforts on risk mitigation.

The CBA planning cycle is a rich participatory process that engages several participatory techniques (Table 13). Focused group discussions, hazard impact matrix, hazard mapping, problem ranking, simple ranking, seasonal calendars, and vulnerability and capacity matrix are prominent among these Participatory Rural Appraisal (PRA) tools.

Table 13:
Participatory rural appraisal tools used in the CBA process.

(1) Communication maps	(2) Problem/Preference ranking
(3) Cross impacts analysis	(4) Rain calendars
(5) Focus group discussions	(6) Ranking
(7) Gender audit (institutions)	(8) Resource maps
(9) Gender analysis	(10) Seasonal calendar
(11) Hazard impact on livelihood matrix	(12) Social maps
(13) Hazard mapping	(14) Transect walks
(15) Hazard trend analysis	(16) Venn diagrams
(17) Mental models	(18) Vulnerability and capacity matrix
(19) Participatory scenario development	(20) Wealth ranking
(21) Power mapping	

A typical CBA planning process can be visualized as a five-step process that starts with the identification of a community based on a variety of factors shown in Figure 28.

Some of these factors include historical climate and hazard characteristics, population characteristics including that age, indigenous groups, and gender groups, and vulnerability characteristics such as poverty and the nature of infrastructure present. Most CBA planning processes are hindered by the physical access factors of the location and hence access plays an important role as well. Once the community where CBA is to be carried out is known, the subsequent process involves knowing the community in a detailed manner. Close community engagement is necessary to understand the community in detail, and this can be achieved through a series of informal meetings. Some of the important characteristics of a community that needs details include livelihoods of communities, seasonality of livelihoods, how the responsibilities are divided among the community members, spatial aspects of the village such as low-lying areas, and socio-economic profiling of vulnerable sections of the community such as indigenous groups, women, children, and elderly.

Figure 28:
Sequence of steps involved in the CBA planning process.

While the steps presented in sections hazard, sensitivity, capacity and vulnerability assessment provide technical details to conduct VAs, the CBA process engages some additional processes to use the VA outputs obtained previously. These processes help assimilate the previously obtained VA outputs and may even help in refining the VA outputs through a participatory review. For this, the CBA process engages steps such as ranking hazards, mapping hazards within the community, identifying specific vulnerabilities and capacities using a matrix etc. Once the vulnerabilities are identified, the community members can compare these results with the VA outputs presented from the technical analysis. Most practitioners suggest that VA outputs be reviewed in a participatory manner well before they are presented for CBA planning purposes. One of the important aspects of CBA planning at this stage is to facilitate discussion among community members on what vulnerabilities need to be prioritized among several vulnerabilities assessed and identified.

Community members may also want to identify certain risks to be addressed on a priority basis. Since risk mitigation involves the utilization of community resources, at this stage community members may also discuss what resources available within the community can be readily utilized to effectively implement risk reduction initiatives.

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15. Annex

15.1 Important Glossary of Terms

Term	Description
Adaptation	Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploit beneficial opportunities.
Adaptive capacity	Is the property of a system to adjust its characteristics or behavior, to expand its coping range under existing climate variability, or future climate conditions.
Capacity	A combination of all the strengths and resources available within a community, society or organization can reduce the level of risk or the effects of a disaster. (Capacity may include physical, institutional, social or economic means as well as skilled personal or collective attributes such as leadership and management. Capacity may also be described as capability.)
Climate change	Climate change is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable periods.
Coping capacity	How people or organizations use available resources and abilities to face adverse consequences that could lead to a disaster. (In general, this involves managing resources, both in normal times as well as during crises or adverse conditions. The strengthening of coping capacities usually builds resilience to withstand the effects of natural and human-induced hazards.)
Disaster	serious disruption of the functioning of a community or a society causing widespread human, material, economic or environmental losses which exceed the ability of the affected community or society to cope using its resources
Exposure	Degree of climate stress upon a particular unit analysis; may be represented as either long-term changes in climate conditions, or changes in climate variability, including the magnitude and frequency of extreme events.
Mainstreaming	Mainstreaming refers to the integration of adaptation objectives, strategies, policies, measures or operations such that they become part of the national and regional development policies, processes and budgets at all levels and stages
Maladaptation	Any changes in natural or human systems that inadvertently increase vulnerability to climatic stimuli; an adaptation that does not succeed in reducing vulnerability but increases it instead.
Resilience	The capacity of a system to tolerate disturbance without changing state or ability to bounce back after a disturbance or ability to tolerate the disturbance.
Risk	is the result of the interaction of physically defined hazards with the properties of the exposed systems – i.e., their sensitivity or (social) vulnerability. Risk can also be considered as the combination of an event, its likelihood, and its consequences – i.e., risk equals the

Term	Description
	probability of climate hazard multiplied by a given system's vulnerability.
Sensitivity	The degree to which a system will be affected by, or responsive to climate stimuli. Sensitivity is the biophysical effect of climate change, but sensitivity can be altered by socio-economic changes. For example, new crop varieties could be either more or less sensitive to climate change.
Vulnerability	The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

15.2 R script for empirical quantile mapping

```
# THIS SCRIPT PERFORMS EMPIRICAL QUANTILE MAPPING---------------------------
----------------
# Since this script uses grided data from era5, 9km resolution it downscales
the GCM data to same 9km
# REQUIREMENTS:
# The computer should have R program and RStudio installed
# All the libraries mentioned below should be pre-installed unless RStudio
will show a prompt

# All the files for each GCM should be in ".csv" format
      # All files should be at working directory; i.e. "D:\\data\\" refer
Change point 1
      # All files should include following in filename:
# Variable name =pr, tasmax, tasmin etc.
# GCM name = "EC-Earth3", "NorESM2-MM" etc.
      # There should be a folder named "cor" within directory to save bias
corrected files

# COMPILED BY: SUWAS GHIMIRE, SENIOR RESEARCH ASSOCIATE, ASIAN INSTITUTE OF
TECHNOLOGY
# DATE: 5 JUNE 2023

####  START OF THE SCRIPT      ####
# List of libraries
library(hydroTSM)
library(qmap)
library(xts)
library(hydroGOF)
library(tidyverse)

# Removes any data in the environment
rm(list = ls())

# Change Point 1: Define working directory
wd <- "D:\\data\\"
setwd(wd)
var<-c("pr")

# Generate dates
date_h<-seq.Date(as.Date("1985-01-01"),as.Date("2014-12-31"),by=1)
date_f<-seq.Date(as.Date("2015-01-01"),as.Date("2100-12-31"),by=1)

# Change Point 2: Enter the name of GCMs/RCMs as provided in the filename of
data
gcm_list <- c("EC-Earth3","NorESM2-MM")
files <- list.files(path = wd,recursive = F, pattern = paste0(var,".*.csv"))


# Change Point 3: Provide pattern to detect obs data from the rest
fn_obs <- str_subset(files,"era5")

obs<-read_csv(fn_obs)
maxi <- 11*length(gcm_list)
pb=txtProgressBar(min=0, max=maxi, style = 3)   # Progress bar
```

```
# This for loop selects each GCM file for QM
for (a in 1:length(gcm_list)) {
  fn_fut1 <- files[grep(paste0(var,".*.",gcm_list[a],"_ssp245"),files)]
  fn_fut2 <- files[grep(paste0(var,".*.",gcm_list[a],"_ssp585"),files)]
  fn_his <- files[grep(paste0(var,".*.",gcm_list[a],"_historical"),files)]

  his <- read_csv(fn_his)
  fut1 <- read_csv(fn_fut1)
  fut2 <- read_csv(fn_fut2)

  # Define simulated and future data in xts format
  hisx <-xts(his[,names(his)!="Date"],order.by = his[['Date']])
  fut1x<-xts(fut1[,names(fut1)!="Date"],order.by = fut1[['Date']])
  fut2x<-xts(fut2[,names(fut2)!="Date"],order.by = fut2[['Date']])
  obsx <-xts(obs[,names(obs)!="Date"],order.by = obs[['Date']])

  allcorrected_b = NULL
  allcorrected_f1 = NULL
  allcorrected_f2 = NULL

  # This for loop conducts quantile mapping for all 12 months from 0 to 11
  for(m in 0:11){
    month_obs<-obsx[.indexmon(obsx) %in% c(m)]
    month_his<-hisx[.indexmon(hisx) %in% c(m)]
    month_future1<-fut1x[.indexmon(fut1x) %in% c(m)]
    month_future2<-fut2x[.indexmon(fut2x) %in% c(m)]

    dmonth_obs<-data.frame(month_obs,row.names=NULL)
    dmonth_his<-data.frame(month_his,row.names=NULL)
    dmonth_future1<-data.frame(month_future1,row.names=NULL)
    dmonth_future2<-data.frame(month_future2,row.names=NULL)

  # Change point 7:  Change the qmap functions/ settings here if you've got
the know-how on qmap
    fitQ<-fitQmapRQUANT(dmonth_obs,dmonth_his,qstep=0.01,nboot=1,wet.day=T)
    doQ_b<-doQmapRQUANT(dmonth_his,fitQ,"tricub")
    doQ_f1<-doQmapRQUANT(dmonth_future1,fitQ,"tricub")
    doQ_f2<-doQmapRQUANT(dmonth_future2,fitQ,"tricub")

    xdata_b<-xts(doQ_b,order.by = index(month_his))
    xdata_f1<-xts(doQ_f1,order.by = index(month_future1))
    xdata_f2<-xts(doQ_f2,order.by = index(month_future2))

    allcorrected_b <- rbind(allcorrected_b,xdata_b)
    allcorrected_f1 <- rbind(allcorrected_f1,xdata_f1)
    allcorrected_f2 <- rbind(allcorrected_f2,xdata_f2)

    xcount <- m*a
    setTxtProgressBar(pb,xcount)
  }

# End of quantile mapping
  his_c <-  NULL
  fut1_c <- NULL
```

```
  fut2_c <- NULL

# Compilation of historical and future corrected data
his_c <-  round(allcorrected_b,1) %>%
    as.data.frame %>%
    mutate(Date=index(allcorrected_b)) %>%
    select(Date,everything())

  fut1_c <- round(allcorrected_f1,1) %>%
    as.data.frame %>%
    mutate(Date=index(allcorrected_f1)) %>%
    select(Date,everything())

  fut2_c <- round(allcorrected_f2,1) %>%
    as.data.frame %>%
    mutate(Date=index(allcorrected_f2)) %>%
    select(Date,everything())

  # Writing output data and saving in folder "cor" within the selected
directory

write.csv(his_c,paste0(wd,"cor\\",str_replace(fn_his,".csv","_cor.csv")),ro
w.names=F)

write.csv(fut1_c,paste0(wd,"cor\\",str_replace(fn_fut1,".csv","_cor.csv")),
row.names=F)

write.csv(fut2_c,paste0(wd,"cor\\",str_replace(fn_fut2,".csv","_cor.csv")),
row.names=F)
 }
# End of for loop for one GCM
# Next loop will conduct quantile mapping for another GCM

####  END OF EMPIRICAL QUANTILE MAPPING SCRIPT  ####
```

15.3 R script for SPEI, Temperature and Rainfall slopes and Crop water demand calculation

```
# THIS SCRIPT CALCULATES THE FOLLOWING:
# SIX MONTHS SPEI AND DEFINES DROUGHT AND FLOOD As PER DEFINED THRESHOLD
"thres"
# MEAN ANNUAL TEMPERATURE AND RAINFALL SLOPE
# CROP WATER DEMAND

# NOTE: ALL VARIABLES ARE CALCULATED FOR BASELINE AND FUTURE PERIODS

# REQUIREMENTS:
# The computer should have R program and RStudio installed
# All the libraries mentioned below should be pre-installed unless Rstudio
will show a prompt

# Input data (Change point 2)
    # Rainfall, minimum temperature and maximum temperature in ".csv" format
    # Unit of analysis shape file (here villages) in wgs projection ".shp"
format
    # All files should be at working directory; i.e. "D:\\data\\" refer
Change point 1
    # All input data can be at daily or monthly time step

# COMPILED BY: SUWAS GHIMIRE, SENIOR RESEARCH ASSOCIATE, ASIAN INSTITUTE OF
TECHNOLOGY
# DATE: 5 JUNE 2023

####  START OF THE SCRIPT           ####

# Import libraries  -------------------------------------------------------
-----
library(tidyverse)
library(xts)
library(lubridate)
library(sf)
library(sp)
library(SPEI)
rm(list=ls())


# Change point 1: Define working directory --------------------------------
-----
wd <- "I:/suwas/nan/Station_analysis/"
setwd(wd)
thres <- 1.5

# Change point 2: Import input data ---------------------------------------
-----
rain = read.csv("gcms_villages_fut_new/pr_Ensemble_ssp245.csv")
tmin = read.csv("gcms_villages_fut_new/tmin_ensemble_ssp245.csv")
tmax = read.csv("gcms_villages_fut_new/tmax_ensemble_ssp245.csv")
centroid <- read_sf("shapefiles/centroid_villages_new_2018_wgs.shp")
basin <- read_sf("shapefiles/Villages_wgs.shp")
```

```
# Define centroid of unit of analysis -----------------------------------
-----
centroid <- centroid %>% subset(subset=LUL1_CODE=="A")
centroid_df <- data.frame(centroid, sf::st_coordinates(centroid)[,1:2])
names(centroid_df) <- str_to_lower(names(centroid_df))
centroid_df <- centroid_df[order(centroid_df$village_no,decreasing = F),]

str(centroid_df)
plot(basin$geometry)
plot(centroid$geometry,add=T)


# Convert daily data to monthly--------------------------------------------
-----
names(rain) <- str_to_lower(names(rain))
names(tmin) <- str_to_lower(names(tmin))
names(tmax) <- str_to_lower(names(tmax))

date <- mdy(rain$date)
month <- format(x = date,format="%Y-%m")

rain_m  <-  rain  %>%  mutate(date=month)  %>%  group_by(date,period)  %>%
summarize_all(sum)
tmin_m  <-  tmin  %>%  mutate(date=month)  %>%  group_by(date,period)  %>%
summarize_all(mean)
tmax_m  <-  tmax  %>%  mutate(date=month)  %>%  group_by(date,period)  %>%
summarize_all(mean)

tmean_m <- (tmin_m[str_c("v",1:8)]+tmax_m[str_c("v",1:8)])/2
tmean_m <- cbind(date=tmin_m$date,period=tmin_m$period,tmean_m)


# Calculate PET & SPEI ---------------------------------------------------
-----
pet1    <-    hargreaves(Tmin    =    tmin_m[str_c("v",1:8)],Tmax    =
tmax_m[str_c("v",1:8)],lat=centroid_df$y)
pet1 <- pet1 %>% round(1)
rain1 <- rain_m[str_c("v",1:8)]
rain1 <- rain1 %>% round(1)
def_all= (rain1-pet1) %>% as.matrix
periods <- unique(rain_m$period)%>% na.omit() %>% as.vector()

# Loop to calculate spei over different time periods and seasons-----------
-----
  spei_list <- list()
  for (a in 1:length(periods)) {
  id <- which(rain_m$period==periods[a])
  def <- def_all[id,] %>% as.matrix
  spei_fit <- spei(data = def,scale = 6)$fitted
  #        plot(spei(ts(def,freq=12,start=c(1985,1)),3,ref.start=c(1985,1),
ref.end=c(2100,1)))


  # Define season and baseline and future periods -------------------------
-----
```

```
  month_id <- as.numeric(str_sub(rain_m$date,6,-1))[id]
  season <- ifelse(month_id==c(1,2,3,10,11,12),"dry","wet")

  spei_df <- spei_fit %>%
    data.frame() %>%
    mutate(period=periods[a]) %>%
    mutate(season=season)
  spei_list[[a]] <- spei_df
  }
# End of loop ----------------------------------------------------------
spei_df <- do.call(rbind,spei_list)

drt_sev <- spei_df %>%
  group_by(period,season) %>%
  na.omit() %>%
  summarise_all(.funs = function(x) sum(x[which(x<=-thres)]))

drt_dur <- spei_df %>%
  group_by(period,season) %>%
  na.omit() %>%
  summarise_all(.funs = function(x) length(x[which(x<=-thres)]))

drt_int <- drt_sev %>% data.frame() %>% dplyr::select(!c(period,season))/
  drt_dur %>% data.frame() %>% dplyr::select(!c(period,season))
drt_int <- cbind(period = drt_sev$period,season=drt_sev$season,drt_int)


drt <- rbind(drt_sev %>% mutate(variable="sev"),
             drt_dur %>% mutate(variable="dur"),
             drt_int %>% mutate(variable="int"))


flood_sev <- spei_df %>%
  group_by(period,season) %>%
  na.omit() %>%
  summarise_all(.funs = function(x) sum(x[which(x>=thres)]))

flood_dur <- spei_df %>%
  group_by(period,season) %>%
  na.omit() %>%
  summarise_all(.funs = function(x) length(x[which(x>=thres)]))

flood_int       <-       flood_sev       %>%       data.frame()       %>%
dplyr::select(!c(period,season))/
  flood_dur %>% data.frame() %>% dplyr::select(!c(period,season))
flood_int                <-                cbind(period                =
flood_sev$period,season=flood_sev$season,flood_int)


flood <- rbind(flood_sev %>% mutate(variable="sev"),
               flood_dur %>% mutate(variable="dur"),
               flood_int %>% mutate(variable="int"))

# End of SPEI calculation ------------------------------------------------
```

```
# Calculate crop water demand ------------------------------------------------
-----
# Initial abstraction is assumed to be 20%
demand    <-    (pet1-rain1*0.8)[id,]    %>%    data.frame()    %>%
mutate(period=periods[a]) %>% mutate(season=season)
demand_season  <-  demand  %>%  group_by(period,season)  %>%  na.omit()  %>%
summarise_all(function(x)  sum(x)/length(x)*6)  #  multiply  by  six  because
length(x) = (no. of months is season i.e. 6) * (no. of years in period)

# Calculate change in mean temperature and rainfall change ----------------
-----

# Calculate annual values of temperature and rainfall
yr <- year(as.Date(tmean_m$date,format="%Y"))
tmean_yr  <-  tmean_m  %>%  mutate(date=yr)  %>%  group_by(date,period)  %>%
summarize_all(mean) %>% na.omit()
rain_yr   <-   rain_m   %>%   data.frame()   %>%   mutate(date=yr)   %>%
group_by(date,period) %>% summarize_all("sum") %>% na.omit()

plot(x=tmean_yr$date,y = tmean_yr$v1)
abline(lm(tmean_yr$v1~tmean_yr$date))

plot(x=rain_yr$date,y=rain_yr$v1)
abline(lm(rain_yr$v1~rain_yr$date))


# Loop to calculate temperature and rainfall slope ------------------------
-----

tmean_slp <- list()
rain_slp <- list()

  for (i in 1:length(periods)) {
    df <- tmean_yr %>% data.frame() %>% subset(subset=period==periods[i])
    time <- 1:nrow(df)
    t_slope <- apply(df[str_c("v",1:8)],MARGIN = 2,FUN = function(y) lm(y ~
time)$coefficients[2])
    tmean_slp[[i]] <- t_slope

    df <- rain_yr %>% subset(subset=period==periods[i])
    time <- 1:nrow(df)
    r_slope <- apply(df[str_c("v",1:8)],MARGIN = 2,FUN = function(y) lm(y ~
time)$coefficients[2])
    rain_slp[[i]] <- r_slope
  }

rain_slope <- do.call(rbind,rain_slp) %>% data.frame() %>% round(2)
rain_slope <- cbind(period=periods,rain_slope)

tmean_slope <- do.call(rbind,tmean_slp) %>% data.frame() %>% round(4)
tmean_slope <- cbind(period=periods,tmean_slope)

# Write results ---------------------------------------------------
write.csv(drt,"drt_ssp245.csv",row.names=F)
write.csv(flood,"flood_ssp245.csv",row.names=F)
```

```
write.csv(spei_df,"spei_df_ssp245.csv",row.names=F)

write.csv(tmean_slope,"tmean_slope_ssp245.csv",row.names=F)
write.csv(rain_slope,"rain_slope_ssp245.csv",row.names=F)

write.csv(demand_season,"demand_ssp245.csv",row.names=F)

#### END OF SCRIPT ####
```