

## AGRICULTURE GLOBAL PRACTICE TECHNICAL ASSISTANCE PAPER

# MANAGING VULNERABILITY AND BOOSTING PRODUCTIVITY IN AGRICULTURE THROUGH WEATHER RISK MAPPING

## A GUIDE FOR DEVELOPMENT PRACTITIONERS

Carlos Arce and Edgar Uribe

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Drought-stressed corn. Photo: © CraneStation 2012.

Map: Based on 1971 to 2000 data from Environment Canada, Alberta Environment and the U.S. National Climate Data Center. Harvesting corn in Kampong Cham, Cambodia. Photo: © Chhor Sokunthea/World Bank.

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# LIST OF ACRONYMS

Acronym	Definition	Acronym	Definition
AEC	Agro Ecological Cell	JRC	Joint Research Centre
AEZ	Agro Ecological Zone	LGP	Length of Growing Period
AHPS	Advanced Hydrologic Prediction Service	LST	Land Surface Temperature
ARMT	Agricultural Risk Management Team	LUT	Land Use Types
AVHRR	Advanced Very High Resolution Radiometer	MAM	March–April–May
CCD	Cloud Cover Duration	MAP	Modeling Analysis and Prediction
CFS	Canadian Forest Service	MERRA	Modern Era Retrospective-Analysis for Research and Applications
CPC	Climate Prediction Center	MODIS	Moderate Resolution Imaging Spectroradiometer
CRU	Climatic Research Unit	MSPEC	Model Simulation of the Ecological Potential of Crops
CSI	Crop Suitability Index	NARR	North American Regional Reanalysis
CSSWB	Crop Specific Soil Water Balance	NASA	National Aeronautics and Space Administration
CVI	Crop Vulnerability Index	NOAA	National Oceanic and Atmospheric
DEM	Digital Elevation Model	NWPM	Numerical Weather Prediction Models
DJF	December–January–February	NWS	National Weather Service
DNDC	Denitrification-Decomposition	OK	Ordinary Kriging
DSMW	Digital Soil Map of the World	PAR	Photosynthetically Active Radiation
ECMWF	European Centre for Medium-Range Weather Forecasts	PCA	Principal Components Analysis
ENSO	El Niño-Southern Oscillation	RMSE	Root Mean Squared Error
EU	European Union	SBR	Soybean Rust
FAO	Food and Agriculture Organization	SOI	Southern Oscillation Index
GHG	Green House Gas	SON	September–October–November
GIS	Geographical Information Systems	SRTM	Shuttle Radar Topography Mission
GPI	Goes Precipitation Algorithm	TAMSAT	Tropical Applications of Meteorology using SATellite data and ground-based observations
GRDC	Global Runoff Data Centre	TMI	TRMM Microwave Imager
GTS	Global Telecommunications System	TRMM	Tropical Rainfall Measuring Mission
HADS	Hydrometeorological Automated Data System	UK	Universal Kriging
HWSD	Harmonized World Soil Database	U.S.	United States
IAMS	Integrated Aerobiological Modeling System	USDA	United States Department of Agriculture
IPM PIPE	Pest Management Pest Information Platform for Extension and Education	UTC	Universal Coordinated Time
IRI	International Research Institute		
JJA	June–July–August		



# EXECUTIVE SUMMARY



## WEATHER RISK IN AGRICULTURE: OCCURRENCE, IMPACTS, AND VULNERABILITY

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Productivity in the agricultural sector is inherently dependent on weather, such as variations in rainfall and temperature. As a result, weather risk events can cause losses in yield and production that translate into economic losses for producers, as well as other sector stakeholders that depend on income from agricultural trade, transport, processing, or export. Extreme temperatures, floods, droughts, hailstorm, and windstorms are just a few examples of weather risk events that cause major economic losses. In developing countries, weather risk is especially significant due to the importance of the agricultural sector in the overall economy and its contribution to household food security. Up to 90 percent of the population in many developing countries relies on agriculture for a living, since the sector is the primary source of income, employment, and food. Absent effective risk management strategies, weather shocks to agriculture in these countries have far-reaching effects on wellbeing, development, and poverty reduction.

Developing countries also tend to be more vulnerable to weather risks owing to factors that constrain stakeholders' abilities to manage risk. Since households and companies involved in agriculture typically operate with a low level of assets and lack access to well-developed insurance and credit markets, their risk management strategies are limited compared with stakeholders in developed countries. An additional constraint is that weather risk occurrence tends to affect households and businesses in the same community, minimizing the effectiveness of traditional coping mechanisms, such as loans or gifts from family members, on which rural communities rely.

At the same time, the predicted impacts of climate change have only increased the importance of effectively managing weather risk. As a result of global warming, extreme weather events are expected to become more frequent and more intense.

In many countries, weather variability has already increased, making it more difficult for producers to predict and respond to weather patterns.

## WEATHER RISK MAPPING: A RISK MANAGEMENT TOOL

Weather risk mapping for agriculture, or agro-meteorology risk mapping, is one way to manage weather risk. Agro-meteorology involves the application of meteorological information and data to agriculture. Most farm operations are weather sensitive (for example, fertilization, planting, movement of agricultural machinery, and harvesting) and offer better results when executed under the right weather conditions. Medium- and long-range forecasts are expected to allow farmers to identify in advance either optimum or adverse weather conditions. When used in combination with geographical information systems (GIS), agro-meteorology is also able to provide spatially related information in map format, which can be very useful for farmers.

Weather risk mapping can provide historical (past), diagnostic (present) and prognostic (future) analyses of weather patterns in a given zone, allowing agricultural sector stakeholders to better understand weather conditions. When applied as part of a systemic approach to weather risk management, this tool can be used strategically to manage risk and optimize farm productivity. Weather risk mapping techniques are expected to enable more risk-informed planning of production, to facilitate improved information for supply chain stakeholders on potential production risks to crops in given production zones, and to help inform investment.

This document strategically presents a variety of mapping techniques for agricultural risk management and illustrates the application of these techniques for informing public and private sector development strategies. The authors do not intend to present a comprehensive list of techniques. Instead, this is a synthesis document that provides an overview of existing techniques and insight on the suitability of techniques for designing agricultural risk management strategies. Many of the examples cited are designed to be cost effective, automatable, scalable, and

flexible to support a variety of assessments and decision-making frameworks.

This document is a guide for development practitioners as to *why* they should undertake risk mapping in agriculture and *how* to do it step-by-step, including available resources with pros and cons, uses of the findings, and descriptions of the practical applications for various users. The introduction places weather risk mapping within the broader context of agricultural risk, explaining how mapping can enable risk identification, assessment and management activities, and each chapter elaborates on one or more of the technical components. A basic definition of agro-meteorology is provided, along with a discussion of different mapping techniques. The guide presents the available remote (satellite) databases of agro-meteorological variables that can be used for the purpose of weather risk mapping, assessing the advantages and drawbacks of each database and their suitability for different purposes. The authors review current risk mapping analyses based on historical weather observations, which are typically used for risk identification and assessment, including climatologies, hazard and risk maps, climate regionalizations and agro-ecological zones (AEZ).

The document also reviews forward-looking mapping techniques, known as diagnostic and forecasting analyses. Diagnostic analyses are designed to provide a technical description of the current risk situation and its causes. Forecasts, on the other hand, predict potential risk events based on the study and analysis of pertinent observations and simulations. The specific examples of mapping techniques for diagnostic and forecast purposes cited here are drawn from the United States, the European Union, and Australia, and are meant to illustrate the potential use of similar applications in global agriculture. Finally, the guide provides instruction on how and why to conduct agro-ecological zoning, a technique that can be used to assess land-use types, land resources, land suitability, and climatic and agro-climatic regionalizations, as well as to inform land use recommendations. The concluding chapter demonstrates a step-by-step application of agro-ecological zoning in a case study of Mozambique.

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The set of weather risk mapping techniques presented in this guide is illustrative of an increasingly useful set of tools for informing risk management strategies and investment decisions. The growing number and complexity of approaches and models to design risk mapping in agriculture are together making it more and

more difficult for development practitioners to catch up with current developments. The authors hope that this document will help practitioners interested in the subject to familiarize themselves with the technical aspects involved in the design of these products and their potential practical uses.



# CHAPTER ONE

## INTRODUCTION

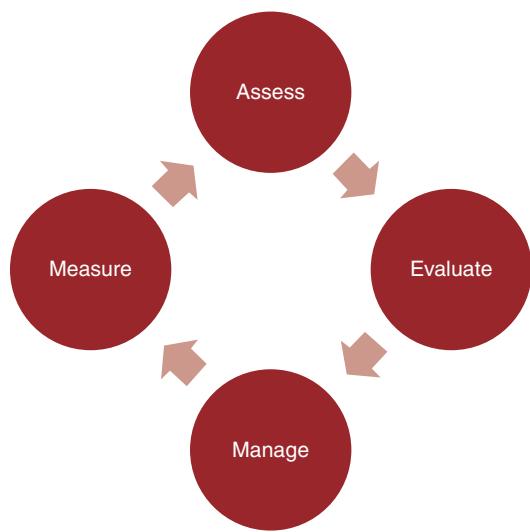


The increasing variety of publications related to practical geospatial applications to analyze weather risks to the agricultural sector is currently overwhelming development practitioners as to their nature and suitability for the purpose of informing agricultural risk management decisions. This document strategically presents a variety of mapping techniques for agricultural risk management and illustrates the application of these techniques for informing public and private sector development strategies. The target group is development practitioners that need to start incorporating these techniques into their analytical framework to assess weather risks to investment projects. As with all guides, this document is not comprehensive and does not intend to be, but it illustrates in a simplified way a number of current applications that are generally accepted for providing geo-referenced risk information in the agricultural sector. Many of the example techniques are designed to be cost effective, automatable, scalable, and flexible to support a variety of assessments and decision-making frameworks. It is hoped that this introduction to risk mapping in agriculture will illustrate a representative array of applications used today in various countries.

Making agricultural risk maps would be relatively simpler if reliable historical databases of yields (spatially distributed) were available, as well as the causes of losses, and applied management practices. Unfortunately, these databases are usually not available, reliable, or sufficiently comprehensive in developing countries. In addition, adaptation, mitigation, and management practices vary widely by geography and in response to stress. Therefore, in order to estimate yields, the usual approach is yield simulation through crop models, which try to emulate the response of the crop to climatological, management, and edaphological conditions (in short, how soils influence land use). Crop models can reproduce the vulnerabilities of crops to hazards of interest, which usually requires additional information like vulnerability functions. One additional challenge is that for crops, unlike infrastructure (for example, buildings, homes, bridges), the vulnerability is a function of the crop stage. Therefore, robust agricultural risk mapping requires an extensive range of simulations of different crops, stages, and hazards, as well as management responses, which at times can become very complex and laborious.

Risk management analyses can be classified by their target time horizon so it seems also natural to classify agricultural mapping techniques by this criterion as well. Risk

**FIGURE 1.1. BASIC RISK MANAGEMENT CYCLE**



analysis usually starts with identification and assessment, which are based on past events (historical analysis). Historical mapping techniques include: climatologies, risk maps, hazard maps, climatological regionalizations, and agro-ecological zonings. These analyses present an idea of what has happened in the past in order to offer an expectation of possible events that can occur in the future.

Weather risk management strategies are defined once the risk assessment is complete (figure 1.1). Strategies are usually grouped in risk mitigation, risk transfer, and/or risk retention (or absorption). Risk mitigation implies the development of exante activities that will reduce the impact of risks once an adverse event happens. Risk mitigation seeks to find a balance between the negative impacts of risk and the positive benefits of the activity. Examples of risk mitigation are the typical good agricultural practices as they relate to risks (that is, drought tolerant seeds, supplemental irrigation, fertilizations and/or mulching, soil drainage, pesticides, water harvesting, and so on). Risk transfer involves sharing with another party the burden of loss and the benefit of gain (for example, insurance, risk pools). Finally, there is risk retention. Risks that are not avoided or transferred are retained, and stakeholders need to absorb or cope (expost). The literature also classifies risk strategies in formal and informal risk coping mechanisms that households, communities, and governments use in order to cope with risks as

adverse events produce shocks to stakeholders (savings, government handouts, sale of assets, migration, reduction of consumption, and so on). Weather risk mapping techniques aim at producing information that is useful for designing risk management strategies either for risk mitigation, risk transfer products, or for risk coping.

This document outlines agricultural risk management mapping techniques developed around the world and classifies them in the three time horizons. The next chapters present examples of historical (past), diagnostic (present), and prognostic (future) analyses for illustrative purposes. It offers particular attention to the work developed by the Agricultural Risk Management Team (ARMT) at the World Bank and colleagues, who have used modeling, remote sensing data, and geospatial analysis to derive diverse mapping techniques for assessing weather risks for the agricultural sector in developing countries, where data are usually very limited. The last chapter presents several agro-ecological zoning cases, including an account by the World Bank in Mozambique.

Weather risk mapping techniques are expected to enable more risk-informed planning of production and facilitate improved information for supply chain stakeholders on potential production risks to crops in given production zones and also to help inform investment. This document is a guide for development practitioners on why they should undertake risk mapping in agriculture, a step-by-step approach to this exercise, the available resources with pros and cons, uses of the findings, and descriptions of the practical applications for various users. After this introduction, the second chapter explains the basic concepts of agro-meteorology and mapping techniques. The third chapter introduces the available remote (satellite) databases of agro-meteorological variables that can be used for the purpose of weather risk mapping, assessing the advantages and disadvantages of each database for different purposes. The fourth chapter presents a review of current risk mapping analyses based on historical weather observations, illustrating the various products and uses, while chapter 5 reviews numerous mapping techniques for diagnostic and forecasting purposes. The concept and explanation of agro-ecological zoning is addressed in chapter 6, and its step-by-step application for Mozambique is illustrated in chapter 7.

# CHAPTER TWO

## AGROMETEOROLOGY AND MAPPING

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### AGROMETEOROLOGY

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It is important to differentiate between the two central concepts of weather and climate. Weather refers to the atmospheric short-term conditions (hours, days, or weeks) in a given place. Climate, on the other hand, refers to the expected conditions of the weather. Climate is usually estimated as the average value of a given meteorological variable (for example, precipitation, temperature). The weather is studied by the meteorology, while the climate, by the climatology.

The factors that condition the climate in a given place include:

1. Latitude
2. Altitude
3. Continentality
4. Topography
5. Vegetation
6. Land and water distribution
7. Soil type
8. Sea currents

The climate and weather largely influence crop systems and their yields. Climate plays a critical role in the determination of the more appropriate zones for agricultural development. The three most important elements from the point of view of crop development are: light, temperature, and precipitation. Additional variables such as wind, hurricanes, and hail can be crucial in specific areas. Such elements, along with carbon dioxide and oxygen, integrate the climatic and weather factors that drive agricultural yield, and that are practically outside human control (excluding irrigation accessibility). Additional factors that influence crop yields but that can be managed by humans include: crop selection, farming practices, soil fertility, irrigation systems, and control of plagues and diseases.

Agrometeorology is defined as the science that investigates the relevant meteorological, bioclimatologic and hydrological conditions for the processes and elements

related to the agricultural production. Agrometeorology assists farmers in the efficient use of the physical environment so the agricultural production improves in terms of quantity and quality while maintaining the sustainability of natural resources. In order to achieve its goals, agrometeorology follows a four-stage procedure. Firstly, it formulates a description of the environment and its biological responses. Secondly, it interprets the biological responses in terms of the physical environment. In a third stage, it generates agrometeorological forecasts. Finally, it develops services, strategies, and support systems for tactical and strategic decisions in the field.

Agrometeorology involves the application of meteorological information and data to agriculture. Most farm operations are weather sensitive (for example, fertilization, planting, movement of agricultural machinery, and harvesting). These operations offer better results when they are executed under the right weather conditions. Medium- and long-range forecasts are expected to allow farmers to identify in advance either optimum or adverse weather conditions. When used in combination with geographical information systems (GIS), agrometeorology is also able to provide spatially related information in map format, which can be very useful for farmers. However, in order to generate maps, it is required to have information that describes the agrometeorological system. The system includes climate, soil, terrain, and land use, for example (these components are described in following chapters). Since in many developing countries the information relative to these components is quite limited, some databases and crop models (proxies for yield data) are provided in the following chapter.

## CLIMATE

Crop development depends on water availability (soil moisture), nutrients, management, and solar radiation, among other factors. Soil moisture is not usually measured systematically so it is indirectly estimated from climatic variables that help quantify components of the water cycle. Precipitation, for example, is the most critical source of water for rain-fed crops. Evapotranspiration (the loss of humidity) is not usually measured either so it is usually estimated from other variables like temperature, solar radiation, and wind.

Crops also require certain temperature conditions. Frost or extreme heat waves, for example, can be lethal for crops. Therefore, thermal regimes can be defined for a given region in order to identify suitable conditions for crop development. On the other hand, crops also require certain amounts of heat. This requirement is usually expressed in terms of reference temperatures, which are calculated by accumulating daily average temperature in excess of temperature thresholds to derive growing degree day metrics. (Growing degree days are metrics of agricultural output, also as a function of mean temperature. The computation of degree days involves certain threshold temperatures, for example, 65°F for heating and cooling degree days. These thresholds are referred to as base temperatures.)

The length of growing period (LGP) combines the climatological factors necessary for crop development in a single concept. The LGP identifies the climatic season where both moisture and temperature conditions are suitable for crop production. The resulting period provides a framework during which climate elements, such as temperature, precipitation, and climatic hazards become more relevant for crop production. The estimation of the beginning of the growing period is associated with the onset of the rainy season. A general rule defines this as occurring when precipitation exceeds half of evapotranspiration. Growing period zones can be plotted on a map at fixed intervals of mean LGP or at a given level of probability. In addition to these important climatological factors, there are also other factors to consider including frost-free periods, multi-cropping suitability, and aridity indices (precipitation divided by ET).

## SOIL

The soil works as a reservoir of water and nutrients for plant growth. In that sense, soil properties relevant for production are related to the capacity of the soil to hold and provide water, which in turn depend upon soil parameters, such as water retention capacity, rooting depth, field capacity, permanent wilting point, and soil water depletion factor. In addition to soil properties related to moisture, there are additional soil qualities that affect crop production such as: nutrient availability, nutrient retention capacity, rooting conditions, oxygen availability to roots, excess salts, toxicity, and workability. These qualities are measured through soil attributes like: texture, organic carbon, pH, exchangeable bases, base saturation, exchange

capacity of soil and of clay fraction, coarse fragments, vertic properties, phases, depth, volume, salinity, sodicity, content of calcium carbonate and gypsum, and drainage capabilities. Crop models usually take into account soil conditions, so simulated yields also seek to take these factors into account.

## TERRAIN

Slope is strongly associated with sustainability. Strong slopes favor erosion, which renders cropping unsustainable in the long term. The application of some practices also depends on terrain, such as whether mechanized equipment can be used on sloping land. Strong slopes also favor fertilizer loss. Since erosion also depends on precipitation, crop suitability associated with terrain also depends on precipitation distribution. Usually, slope values are used to divide a region into suitable and unsuitable zones.

## MAPPING

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Maps are a visual representation of an area with symbolic depictions highlighting relationships between elements of that space such as objects, regions, and themes (for example, crops, climatologies, soil classification, and so on). In maps, the aspects of the image are analogies of values related to the information presented. Maps can be very useful in agriculture because they can be related to assets (crops) for decision making and assessment. This document shows examples of maps that are considered useful for risk management in agriculture. However, in order to be able to create maps, information is required that often is not available in developing countries. Therefore, it is important to identify suitable databases for poorly documented regions. The next chapter provides examples of databases and models that can be used in developing countries.



# CHAPTER THREE

## DATABASES AND CROP MODELS



If spatial databases of climate, yield, and the causes of losses were readily available, perhaps map-making for risk management would be a more straightforward task. However, most developing countries lack reliable, consistent, or sufficiently extensive databases suitable for risk analysis. Therefore, risk analysis in these regions relies partially in databases proxies and surveys. Yields, for example, have to be estimated using crop models. In those cases, the issue of finding yield data is traded for an issue of simulation, calibration, and finding models and input data appropriate for the simulation of yield and the impact of hazards. Solving these issues is not an easy task. Most developing countries, for example, do not have reliable, shareable, and appropriate soil and climate databases suitable for crop models. However, there is growing experience in the use of climate data proxies (for example, satellites and reanalysis). Additionally, there are also national and global efforts underway to map agro-ecological resources. This information can be used along with crop models to estimate yields for agricultural risk analysis. In this section, we describe public and globally available climate, topography, and soil databases, as well as crop models. Although the discussion is focused on proxies, it is important to understand that developing countries may have useful databases. For example, most countries have a network of weather stations. These observations are usually more reliable than proxies, and they should be used whenever possible. However, the local databases usually have low coverage, a good portion of missing data, or poor quality, so their application can be very limited unless they are combined with other sources of information, like proxies.

### WEATHER AND CLIMATE

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There are several types of weather proxies. In this section, we provide examples derived from the following types: satellite, reanalysis, interpolation, and objective analysis. Satellite proxies rely on observations from space, while reanalysis is based on Numerical Weather Prediction Models (NWPM). Interpolation relies on observation, while objective analysis combines a proxy (for example, satellites) with observation. There is no single best dataset. The user needs to ensure the spatial and temporal

coverage and resolutions are suitable for the specific requirements. On the other hand, most products perform better in some regions than others, so an evaluation of the product should be part of the selection criteria.

The most important issues associated with climate proxies are perhaps accuracy and resolutions. Generally, proxies use readily available observational data as input or for calibration purposes. However, this information is usually very limited, particularly in developing countries. It is therefore recommended to evaluate the accuracy of proxies in the region of interest, and to calibrate or make adjustments whenever necessary. In addition to the description of some climate proxies, this document includes a brief description of a methodology that has been implemented by the Agricultural Risk Management Team (ARMT) to calibrate proxies using weather stations (objective analyses or gridded analysis). This methodology not only allows higher accuracy but also higher resolutions.

The following is by no means an exhaustive list of the plethora of climatological databases but represents a selection of databases based upon four criteria: (1) importance for developing countries, (2) timeliness, (3) representativeness, and (4) availability (most are publically available).

## SATELLITE

The advantage of weather satellite data is that they usually provide complete databases for the period and domain of interest (some missing data are infrequent but possible due to instrumental errors or inappropriate environmental conditions). The disadvantages include inaccuracy (this needs to be addressed locally), short-term records (usually starting in the 1980s), a small portion of missing data, and changes in methodologies, which results in inconsistent databases. Perhaps the most important selection criteria for these products are temporal coverage (again, most of them start in the 1980s) and accuracy, which has to be addressed locally (for example, comparing ground observational data with satellite data).

**Tropical Rainfall Measuring Mission (TRMM):** TRMM precipitation estimates are based on both active and passive microwave instruments. TRMM employs the Visible and Infrared Scanner and TRMM Microwave

Imager (TMI) instrumentation to provide quantitative rainfall information. TMI quantifies water vapor, cloud water, and rainfall intensity in the atmosphere by assessing microwave energy emitted in the lower boundary layer. The TRMM Ground Validation program operates from the Goddard Space Flight Center of the U.S. National Aeronautics and Space Administration (NASA). This team uses gauge, station, field, and modeled data to calibrate and validate precipitation. These ground data are used to improve the rain rate interpretation algorithm. Wolff et al. (2005) reported monthly rainfall accumulation scheme of TRMM matches ground precipitation measurements within  $\pm 5$  percent. This dataset is publically available and starts in 1998. TRMM data are available only between latitudes 50°N and 50°S. Several products are derived from TRMM with different time and space resolutions. The highest spatial resolution is 0.25 (~27 km), and the highest temporal resolution is three hours.

**Moderate Resolution Imaging Spectroradiometer (MODIS)—Land Surface Temperature (LST):** Land surface thermal data can be obtained from the MODIS instrument onboard the Terra (descending) and Aqua (ascending) satellite platforms. The MODIS sensor collects measurements in 36 spectral bands every 1–2 days at native spatial resolutions of 1 km for LST products. MODIS products are available from the Warehouse Inventory Search Tool at the Land Processes Distributed Active Archive Center. MODIS has different products and resolutions. The MODIS MYD11C3 LST, for example, has a spatial resolution (pixel size) of 0.05 degree, which is equivalent to approximately 5 km. The MODIS LST products have been extensively refined and validated to provide precise and accurate information. LST accuracy is reported to be within 1K under clear-sky conditions in a range of ecosystems (Wan 2008; Wan et al. 2002). Validation across multiple sites incorporating wide ranging ecosystems and atmospheric conditions has consistently shown that MODIS LST products are within  $\pm 1$  km in the range 263–322 lm. Further, comparisons between V5 LSTs and in-situ values in 47 clear-sky cases (in the LST range from  $-10^{\circ}\text{C}$  to  $58^{\circ}\text{C}$  and atmospheric column water vapor range from 0.4 to 3.5 cm) indicate that the accuracy of the MODIS LST product is better than 1 km in most cases (39 out of 47),

and the root of mean squares of differences is less than 0.7 km for all 47 cases or 0.5 km for all but the eight cases apparently with heavy aerosol loadings. Thus, the precision, accuracy, and reliability of MODIS LST makes it well-suited for assessing land surface temperature zones in data poor regions. Finer scale remote sensing imagery, such as from Landsat, can provide field level thermal information that when fused with MODIS provides a more thorough assessment of spatiotemporal trends in indices useful for mapping agricultural conditions and crop status at key stages.

**TAMSAT TARCAT v1.0:** The TAMSAT group produces the TARCAT v1.0 data sets. It includes a 10-daily (dekadal), monthly, and seasonal rainfall estimates for Africa. The Cloud Cover Duration (CCD) method is applied using Meteosat thermal infrared channels. It is based on the recognition of convective storm clouds, and is calibrated against ground-based rain gauge data. Data covers the period 1983–2010. For some annual/dekadal combinations, no data are available due to corrupt satellite images. Over the past 15 years, a number of calibration workshops at regional centers have been carried out by TAMSAT, resulting in good calibrations for the main rainy seasons for East Africa (except Somalia and Djibouti); for all Southern Africa (except Tanzania, Mauritius, Madagascar and Angola); and for all of West Africa south of 25°N. Because of the involvement of national weather services, these calibrations have been performed with much more data than are generally internationally available. Recent validation experiments (Dinku et al. 2007) have shown that careful local calibration of CCD in this manner produces more reliable rainfall estimates than more sophisticated systems which rely on global calibrations or other parameterizations. The same studies also showed that these local calibrations are stable in time, lending weight to the idea of pre-calibrating with historic data. This methodology is used by the AGRHYMET regional center and by a number of African meteorological services to provide vital, up-to-the-minute information on the state of the rainy season. In a separate operational service, TAMSAT provides dekadal, monthly, and seasonal rainfall totals and anomalies to the European Commission Joint Research Centre FOODSEC Action. Since May 2010, TAMSAT rainfall estimates have been available via GEONETCast.

**CPC (Climate Prediction Center)—RFE (Rainfall Estimate):** A combined gauge-satellite precipitation dataset has been developed as part of the Famine Early Warning System Network (FEWS-NET) for Africa and was upgraded from version 1.0 to version 2.0 in 2001. Version 1.0 (Herman et al. 1997) covers the period 1995–2000 while version 2.0 from 2000 to the present. The rainfall algorithm (RFE version 1.0) uses infrared temperature satellite data (METEOSAT), rain gauge data, and modeled wind and relative humidity data to compute 10-day rainfall estimates. METEOSAT infrared temperature data are first used to compute estimated rainfall via the Goes Precipitation Algorithm (GPI). Modeled relative humidity and wind data are then compared to topographical data to estimate cross-terrain flow as orographic precipitation. These two estimates are then compared to Global Telecommunications System (GTS) rain gauge measurements. Calibration is performed to remove bias and create the final rainfall estimate. The merging process allows the final rainfall estimates to have the magnitude of the station data, with the shape of the precipitation field determined by the satellites. The RFE 2.0 is generated from the Advanced Microwave Sounding Unit, the Special Sensor Microwave/Imager and GPI (infrared) precipitation estimates using a maximum likelihood method. They are then merged with daily rain gauge data from up to 1,000 GTS stations in Africa (although typically, the number of stations is closer to 500 owing to erroneous station data and/or poor station maintenance). There are significant differences between RFE version 2.0 and 1.0 (RFE version 2.0 uses passive microwave estimates while RFE version 1.0 includes a procedure to estimate warm orographic rain), leading to possible biases in the combined operational series.

## INTERPOLATION<sup>1</sup>

These datasets are created through the interpolation of data from meteorological stations. This analysis can be made at different temporal scales (for example, daily and monthly). Advantages include accuracy associated with observational data and completeness. Disadvantages include the requirement of observational data, low resolution, and the fact that most traditional methods

<sup>1</sup> Method of constructing new data points within the range of a discrete set of known data points.

arbitrarily assign zeros when no nearby station is available. This methodology, however, is quite appropriate for climatological products.

### Global Climatologies from the Climate Research

**Unit (CRU):** CRU has developed climatologies at pixel sizes of  $0.5^{\circ}$  ( $\sim 55$  km) and  $10^{\circ}$  ( $\sim 18$  km). The dataset contains eight mean (1961–90) monthly and annual values of precipitation, wet-day frequency, temperature, diurnal temperature range, relative humidity, sunshine duration, ground frost frequency, and wind speed. The dataset is created through the interpolation of station means. The data are available through the International Water Management Institute World Water and Climate Atlas (<http://www.iwmi.org>) and the Climatic Research Unit (<http://www.cru.uea.ac.uk>).

## REANALYSIS

Reanalysis methods rely on historical databases of simulations with hundreds of variables in four dimensions (4D; space plus time). Latest generation reanalysis, such as Modern Era Retrospective-analysis for Research and Applications (MERRA; see the next section), already includes satellite data as input in simulations. Reanalyses are based on highly sophisticated NWPMs. Their development requires large multi-disciplinary teams as well as powerful computational resources, particularly necessary for processing and storage. These models can be used for forecasting and historical purposes.

### Modern Era Retrospective-analysis for Research and Applications (MERRA):

MERRA is the highest quality, latest generation reanalysis available worldwide. It covers the modern era of remotely sensed data, from 1979 to near real-time, and the special focus of the atmospheric assimilation is the hydrological cycle. MERRA develops products with several frequencies and resolutions. Table 3.1 summarizes the characteristics of the finest resolution MERRA products.

### North American Regional Reanalysis (NARR):

This is a long-term, dynamically consistent, atmospheric and hydrologic database, with high spatial and temporal resolutions, generated with the numerical weather model eta (eta stands for the Greek letter, which represents an alternative height variable in atmospheric

**TABLE 3.1. CHARACTERISTICS OF MERRA**

Element	Characteristics
<b>Pixel size</b>	$dx = 0.6666^{\circ}$ ( $\sim 72$ km); $dy = 0.5000^{\circ}$ ( $\sim 55$ km)
<b>Time reference</b>	Universal Coordinated Time (UTC)
<b>Temporal resolution</b>	1hr
<b>Initial Date</b>	January 1st, 1979
<b>Final Date</b>	Semi-Current
<b>Geographical Reference System</b>	Geographic
<b>Coordinates of the lower left corner (center of pixel)</b>	Latitude: $90^{\circ}$ S; Longitude: $180^{\circ}$ W
<b>Coordinates of the upper right corner (center of pixel)</b>	Latitude: $90^{\circ}$ N; Longitude: $180^{\circ}$ E

**TABLE 3.2. CHARACTERISTICS OF NARR**

Element	Characteristics
<b>Pixel size</b>	$dx = dy = 0.1875^{\circ}$ ( $\sim 20$ km)
<b>Time reference</b>	Universal Coordinated Time (UTC)
<b>Temporal resolution</b>	3hr (0–3, 3–6, 6–9, 9–12, 12–15, 15–18, 18–21 and 21:00–0:00 UTC every day)
<b>Initial Date</b>	January 1st, 1979
<b>Final Date</b>	Semi-Current (five days lag)
<b>Geographical Reference System</b>	Geographic
<b>Coordinates of the lower left corner (center of pixel)</b>	Latitude: $0.000^{\circ}$ N; Longitude: $-220.000^{\circ}$ E
<b>Coordinates of the upper right corner (center of pixel)</b>	Latitude: $89.625^{\circ}$ N; Longitude: $-0.625^{\circ}$ E

models; Mesinger et al. 1988). NARR is only available for the northern hemispheric portion of the American continent (including Mexico and most of Central America). NARR was developed by the National Center for Environmental Prediction of the National Oceanic and Atmospheric Administration (NOAA). The characteristics of NARR are indicated in table 3.2. The NARR dataset is freely available from: <http://www.emc.ncep.noaa.gov/mmb/rreanal/>. Table 3.2 shows the characteristics of NARR.

## OBJECTIVE ANALYSIS (GRIDDED DATASETS)

All the previous climate datasets are proxies estimated from satellites, atmospheric models, the combination of both satellites and models, or interpolation. These proxies are usually calibrated with observational data available in semi-real-time. However, only a small portion of the databases are shareable in real-time by the local national weather services so this information is usually very limited. However, it is possible to develop regional weather data grids through the combination of reanalysis and the most updated and complete version of the local meteorological database, directly obtained from the local weather services. The gridded datasets can be created following a methodology extensively used in the atmospheric sciences, which is known as objective analysis; more specifically, a successive correction method called Cressman (Cressman 1959). The procedure allows the calibration of a proxy based on the observational data. In addition to the reduction of errors associated with the calibration, the advantage of developing regional gridded analysis is that, unlike the global datasets presented earlier, the characteristics of the grid are defined based on the coverage analysis of the meteorological network. The analyses for some applications have resulted in grids with resolutions as high as  $0.06^\circ$  ( $\sim 7$  km) while the resolutions of the proxies are usually lower. Grids of precipitation, maximum and minimum temperatures, evapotranspiration, solar radiation and relative humidity, have been developed by the World Bank for Guatemala, Honduras, Nicaragua, Mozambique, Haiti, and the Dominican Republic (Uribe Alcántara, 2010).

Additionally, Cressman has been applied extensively by different national weather services and scientists around the world, including the CPC from the National Oceanic and Atmospheric Administration and the European Centre for Medium-Range Weather Forecasts. Also, gridded analyses based on Cressman (or other successive correction methods) have been developed for different countries and regions, that is, for the United States, Mexico (Uribe Alcántara and Arroyo Quiroz 2010), Brazil (Silva et al. 2007), India (Sinha et al. 2006), and Europe (Drusch et al. 2004). The advantages of using Cressman are its high reliability, the incorporation of a second predictor from indirect sources, and worldwide recognition.

## SOIL

### **Harmonized World Soil Database (HWSD; FAO 2009):**

The HWSD is the next iteration of the Digital Soil Map of the World (DSMW) from the Food and Agriculture Organization (FAO). It is the most updated and highest resolution product available worldwide. It is a 30 arc-second raster database with over 16,000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5,000,000 scale FAO-UNESCO DSMW. It contains the composition in terms of soil units and the characterization of selected soil parameters (organic carbon, pH, water storage capacity, soil depth, cation exchange capacity of the soil and the clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class and granulometry).

## TOPOGRAPHY (DIGITAL ELEVATION MODELS)

Countries usually have topographical maps in which relief is represented using contour lines. However, these charts are usually not practical for risk analysis. The most useful format for topography and risk analysis is perhaps Digital Elevation Models (DEM) that can be implemented in geographical information systems (GIS) for spatial analysis (integration with additional information like political divisions, land use, and so on). Furthermore, DEM are also highly appropriate for hydrological analysis (for example, flood risk).

### **NASA Shuttle Radar Topography Mission (SRTM):**

The SRTM is an international research effort that obtained DEM on a near-global scale from  $56^\circ\text{S}$  to  $60^\circ\text{N}$ , to generate one of the most complete high-resolution digital topographic databases. SRTM consisted of a specially modified radar system that flew on board the Space Shuttle Endeavour in February 2000. The elevation models are arranged into tiles, each covering one degree of latitude and one degree of longitude. The resolution of the raw data is one arc-second (30m), but this has only been released over U.S. territory. For the rest of the world, only three arc-second (90m) data are available.

The elevation models can be downloaded freely over the Internet. The Shuttle Radar Topography Mission is an international project spearheaded by NASA and the U.S. National Geospatial-Intelligence Agency.

The elevation datasets have void data in areas of very high relief. This amounts to no more than 0.2 percent of the total area surveyed. Accordingly, groups of scientists have worked on algorithms to fill the voids of the original SRTM data. Two datasets offer global coverage void-filled SRTM data at full resolution: the CGIAR-CSI versions and the U.S. Geological Survey's HydroSHEDS dataset. The CGIAR-CSI version 4 provides the best global coverage full resolution SRTM dataset. The HydroSHEDS dataset was generated for hydrological applications and is suitable for consistent drainage and water flow information.

## CROP MODELS

By the late 1960s and early 1970s, there was sufficient literature documenting plant growth in relation with environmental conditions (Decker 1994; Mavi and Tupper 2004) to allow for the development of crop models in the 1980s and 1990s. By the end of the twentieth century, there were thousands of crop models. Crop models are generally divided into empirical and mechanistic models. Empirical models try to relate a behavior with attributes of the same level, without regard to any theory. The procedure is just adjusting a set of equations to a dataset. For example, a model that relates crop yield directly to a level of fertilizer through an equation is an empirical mathematical model.

Mechanistic models, on the other hand, are usually dynamic<sup>2</sup> and deterministic.<sup>3</sup> The mechanistic models try to represent a behavior, which has some understanding of the process at lower levels. Unlike empirical models that try to connect variables in whatever way that fits the data, the mechanistic models break the system down into components. This process introduces processes and properties

from lower level behaviors that are expressed in equations. Finally, the integration of these equations, representing the responses of the plant at all levels, defines the system. Dynamic models have output that varies with time. Processes are characterized using state variables (variables that define the state of the system at some point in time). Dynamic crop models predict changes in crop status as a function of biogenetic parameters (Hume and Callander 1990). These models simulate the evolution of a real crop, growing of leaves, stems and roots. These models simulate the evolution of a real crop, growing of leaves, stems and roots.

The development of dynamic models requires multidisciplinary collaboration. In order to establish the general specifications required in the model and the relationships between plant growth and the environment, plant physiologists, agronomists and soil scientists are usually involved. Entomologists and plant pathologists define insect and pathogen subsystems that are an important part of the crop ecosystem. Agrometeorologists contribute databases of weather and energy fluxes (in and around the canopy). Computer programmers select the programming language and develop the model's algorithms model's algorithms (Ritche et al. 1986). The model then passes to verification and validation processes. The verification tests the model's exactitude by comparing the output with observational data. The model may need to be functionally adjusted or the coefficients may need to be calibrated to improve the exactitude. Finally, the validation compares model predictions with results from independent observational databases or experiments. A model is considered valid if its output is within projected confidence bands.

The applications of crop models include:

1. **Crop Breeding:** Produce high-yielding and more resistant cultivars based on sensitivity analysis of genetic characteristics.
2. **Physiological Probes:** Processes that are not experimentally accessible can be explored using comprehensive models for scientific purposes.
3. **Sequence Analysis:** Optimal crop rotations can be identified based on sets of simulations that are able to capture long-term water, nitrogen and carbon, as continuums.

<sup>2</sup> Dynamic models account for time-dependent changes in the state of the system. Dynamic models are typically represented by differential equations.

<sup>3</sup> In deterministic models, every set of variable states is determined by parameters and sets of previous states of these variables. Therefore, the results in deterministic models are the same for a given set of initial conditions.

4. Strategic and Tactical Applications: Models are run to compare different management scenarios.
5. Forecast Applications: Similar to strategic and tactical applications, but the main interest is in the final yield and other final variables.
6. Spatial Analysis: The result of linking crop models with geographical information systems to cross-reference with other spatial information.
7. Seasonal Analysis: A model is used to support decisions related to crop, plant density, planting date, irrigation, and fertilizer strategies, for example.
8. Scenarios: Models can be used to assess performance under different stressors such as heat waves and drought or changes in management practices.
9. Forecasting: Models can be used in conjunction with weather forecasts to supply estimates of yield with given weather conditions.

Mechanistic models are usually more desirable to use due to their comprehensive reproduction of crops. Unfortunately, they usually have higher data requirements and they are more complex to use. As such, the selection of the model is also restricted by the data available and the hazards of interest. It is important to make sure that the model is able to reproduce negative effects of regional hazards on yield. In case, for example, frost has been documented as one of the regional hazards, the users need to make sure crop's vulnerability as a function of temperature is taken into account by the model. Examples of empirical and mechanistic models are provided in the next sections.

## EXAMPLE OF AN EMPIRICAL MODEL: WATER USE EFFICIENCY MODEL

**The model is based on the FAO Crop Specific Soil Water Balance** (CSSWB; Frere and Popov 1986). It is a simple soil water balance model used to assess the impact of weather conditions on crops. The soil profile functions as a water reservoir. When the climatic water balance ( $P_d - ET_{MD}$ ) exceeds the storage capacity of the soil, excess rainfall is accounted for as water surplus or deep percolation. Crops may suffer from drought stress when the combined total of dekadal effective rainfall ( $P_d$ )

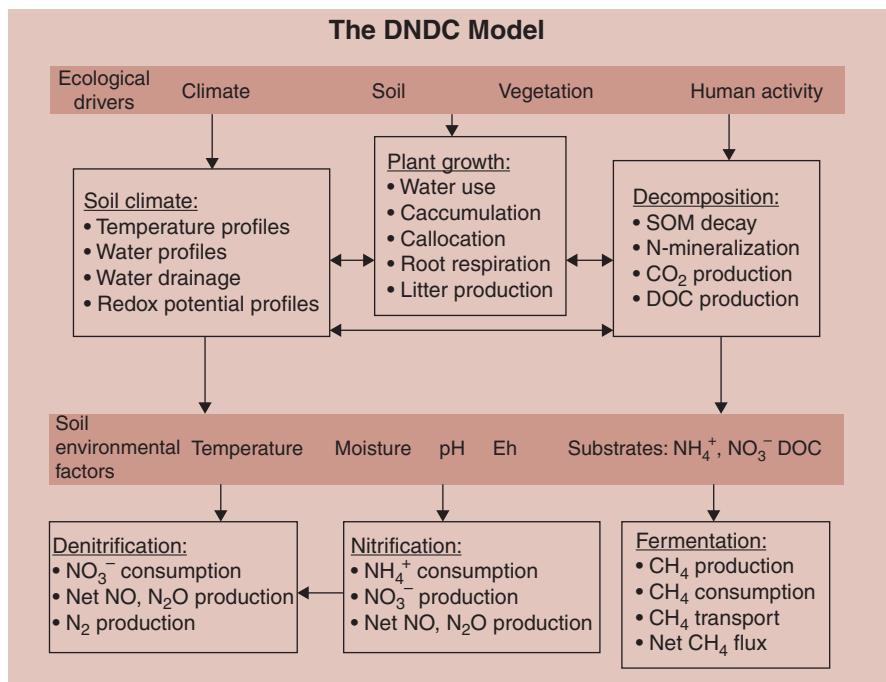
and available soil water of the previous dekad ( $W_{d-1}$ ), is lower than the crop demand ( $ET_{MD}$ ). It is assumed that not all rainfall is effective, and, on average, 20 percent of the rainfall is lost by run-off. The main output of CSSWB is the Water Satisfaction Index, which describes the cumulated water shortage over the crop season. This index has become the most widely used crop yield indicator for the yield reduction assessment due to drought, worldwide. The Water Use Efficiency model calculates the end-of-season grain yield under rain-fed conditions based on potential evapotranspiration and a reduction of the yield, taking into account crop physiology and water deficit.

## EXAMPLES OF MECHANISTIC (DYNAMIC AND DETERMINISTIC) MODELS

**Denitrification-Decomposition Agro-ecological Model (DNDC):** The DNDC model (Li et al. 2006; Li et al. 1992a; Li et al. 1992b) is a process-based computer simulation model focusing on the exchanges of water, carbon (C), and nitrogen (N) between terrestrial ecosystems and the atmosphere. DNDC can be downloaded for free at <http://www.dndc.sr.unh.edu/>. DNDC works at the molecular or microorganism level driven by thermodynamic and reaction kinetic principles. DNDC has been widely tested at multiple scales with accurate results. Accordingly, DNDC is a good tool for high-resolution and/or regional studies such as the district or zonal level, and scaled to national levels for inventory or risk programs. DNDC requires a suite of input parameters and predicts yield, water, C, and N exchanges between the atmosphere and the plant-soil systems at a daily time step (see figure 3.1).

The DNDC model was originally developed to simulate the effects of major farming practices (for example, crop rotation, tillage, fertilization, manure amendment, irrigation, flooding, weeding, grass cutting, and grazing) and climate change (temperature and precipitation) on yield and C and N cycles in various ecosystems. By tracking vegetation biomass production and decomposition rates, DNDC also simulates long-term soil organic carbon dynamics, predicts methane ( $CH_4$ ), nitrous oxide ( $N_2O$ ), and greenhouse gas (GHG) emissions by tracking the reaction kinetics of nitrification, denitrification, and

**FIGURE 3.1. ENGINEERING FRAMEWORK AND INPUT CATEGORIES FOR DNDC TO GENERATE YIELD**



fermentation across climatic zones, soil types, and management regimes. The simulated vegetation growth can be used to generate yield distributions, suitability indices, and assess climate scenarios. The application of this model is illustrated in chapter 7.

**Model Simulation of the Ecological Potential of Crops (known by its Spanish abbreviation, MSPEC):** Since 1990, the National Institute for Forestry, Agriculture, and Livestock in Mexico has promoted the application of dynamic simulation models in the identification and solution of problems in agriculture. As a result of this process, a simulation model of the ecological potential of crops was developed (MSPEC; Quijano et al. 1998) that allows the estimation of growth and production of crops (corn, wheat, sorghum, barley, potatoes, and beans) to determine the effects of light, temperature, moisture availability, genotype, and planting date. The MSPEC model calculates the daily dry matter production of these crops under conditions of potential output, as moisture limitation. The model components are:

**Physiological Age of the Crop:** calculated from the accumulation of heat units (UC) or degree days above a certain base temperature. The method used for the

accumulation of UC is called Residual Method. For purposes of standardization of the rate of development of cereals, a scale ranging from 0 to 1 is considered for the periods of emergency and start of grain filling, and from 1 to 2 for the period between grain filling and physiological maturity.

**Gross CO<sub>2</sub> Assimilation:** The Photosynthetically Active Radiation (PAR) is estimated from the total global radiation, which can be fed directly into the model or estimated with the Angstrom equation if no observational records are available. Gross CO<sub>2</sub> assimilation is estimated using the index of Radiation Use Efficiency, which multiplies the PAR and is corrected for incomplete interception of light through the Leaf Area Index. Leaf area is estimated based on specific leaf area and leaf dry weight.

**Distribution of dry matter, from the stage of crop development, determines the priority of growth.** In this stage, the model calculates the leaf area and growth of different plant organs from the physiological age. Fraction partition dry matter is obtained from experimental data of the level of growth analysis of genotypes. The respiration rate, organ senescence, and the effects of water stress on grain yield, are also related to the physiological

age and used to calculate daily gain and dry weight accumulation in each organ of the plant.

Since 2003, the MSPEC was supplemented with models of population dynamics of harmful organisms like the *corn's rootworm* (*Diabrotica virgifera zae* K. and S.). The applications of the model serve different levels of users (producers, agronomy students, field technicians, professors, researchers, and government officers) so a platform that serves as an interface between models, databases (climate, soil, genotypes, harmful organisms) and stakeholders was created. This platform, called Information System

for Monitoring Ecological Potential Crop, has been used in the state of Guanajuato since 2001 for:

1. Yield forecasts of corn, sorghum, wheat, and barley.
2. Development studies and risk warning bulletins for various phytosanitary problems in collaboration with the Phytosanitary Alert System of the State of Guanajuato, which has been operating since 2003.
3. The estimation of yields and other agricultural parameters required for the design of the Weather Index Insurance program from AGROASEMEX.



# CHAPTER FOUR

## HISTORICAL ANALYSES

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This section reviews risk-mapping analyses based on historical weather observations. These mapping techniques usually target risk identification and, ultimately, assessment. Within this category, we include: climatologies, hazard and risk maps, climate regionalizations and agro-ecological zoning. Climatologies are defined as the expected value of the weather for a given period and region. They are usually estimated as the average value in the last 30 years. An annual climatology of precipitation, for example, is the average annual cumulative precipitation for the last 30 years. There are also climatologies associated with temperatures and other meteorological variables. Climatologies are useful to have for a general idea of the climate in a given region, as they offer a snapshot of what has usually happened in the past 30 years or so.

Hazard and risk maps are similar to climatologies because they are also based on historical information. However, in the case of hazard and risk maps, they usually try to quantify intensity, probability of occurrence, or expected losses, while climatologies are only an expression of the expected value of a given meteorological variable.

### CLIMATOLOGIES

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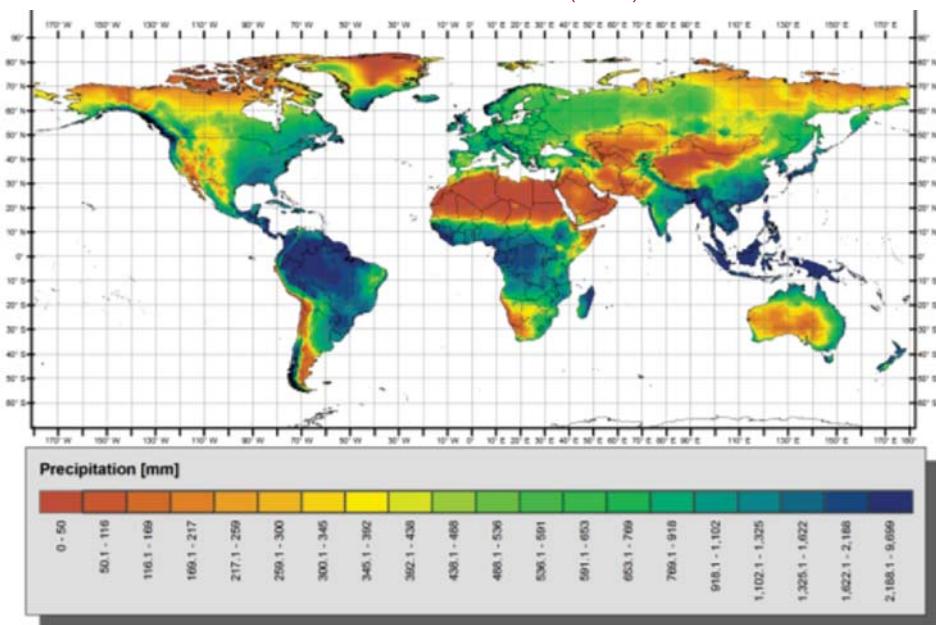
#### GLOBAL CLIMATOLOGIES FROM THE CLIMATE RESEARCH UNIT

The Climate Research Unit (CRU) has developed climatologies at pixel sizes of  $0.5^{\circ}$  ( $\sim 55$  km) and  $10'$  ( $\sim 18$  km). The dataset contains eight mean monthly and annual values of precipitation (1961–1990), wet-day frequency, temperature, diurnal temperature range, relative humidity, sunshine duration, ground frost frequency and wind speed. The dataset is created through the interpolation of station means. The data are available through the International Water Management Institute World Water and Climate Atlas (<http://www.iwmi.org>) and the Climatic Research Unit (<http://www.cru.uea.ac.uk>). Figure 4.1 shows the world's climatology of annual precipitation at the highest resolution.

#### NATIONAL CLIMATOLOGIES BASED ON GRIDDED DATASETS

Based on the gridded datasets developed using objective analysis techniques and applied by the World Bank (see page 11), climatologies can be obtained averaging

**FIGURE 4.1. WORLD'S CLIMATOLOGY (1960–90) OF ANNUAL PRECIPITATION (MM) FROM CRU**



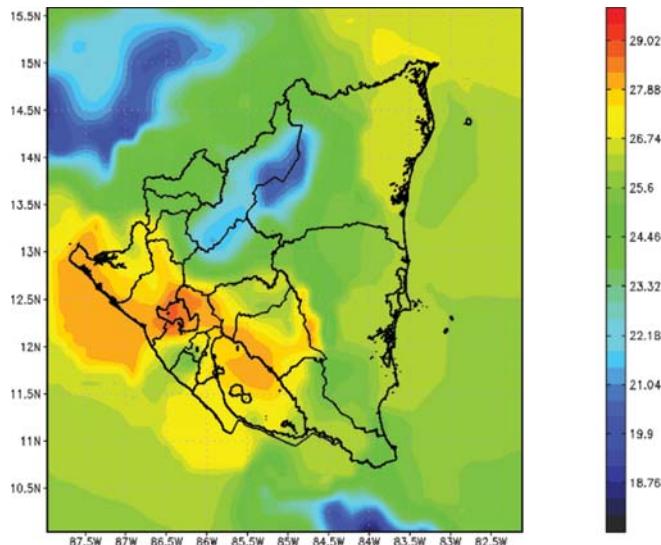
Source: CRU.

the daily records for the last 30 years from the grid. For example, figure 4.2 shows the climatology of average temperature for Nicaragua. The resolution achieved in this country was 16 km for temperature and 8 km for precipitation. The difference with global analysis like the one from CRU is that these gridded products are developed with databases collected locally so the analysis is developed with the most updated and complete information available. Besides, the World Bank has used a secondary predictor from atmospheric models. These methodologies are compared with independent sources. An additional advantage over CRU, for example, is that these climatologies usually correspond to the average of the last 30 years (for example, 1979–2009) while the latest climatologies from CRU run from 1961–1990 so there is a significant delay in the update of these climatologies.

## REGIONAL CLIMATOLOGIES— ALBERTA, CANADA

Climatologies in general can address many different aspects of the climate's variability, and it is important to develop climatologies that will be useful for end users. The communication between the developer and end users helps in the definition of what is needed and what is feasible. Figure 4.3, for example, shows a climatology of the annual number of days with rainfall of more than 0.2 mm, which can provide an idea of the distribution of

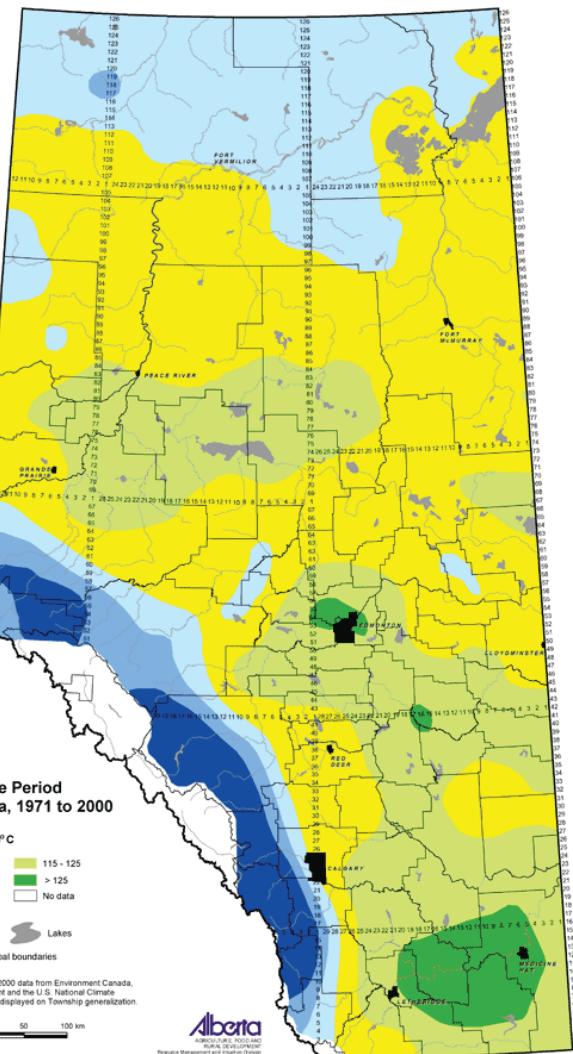
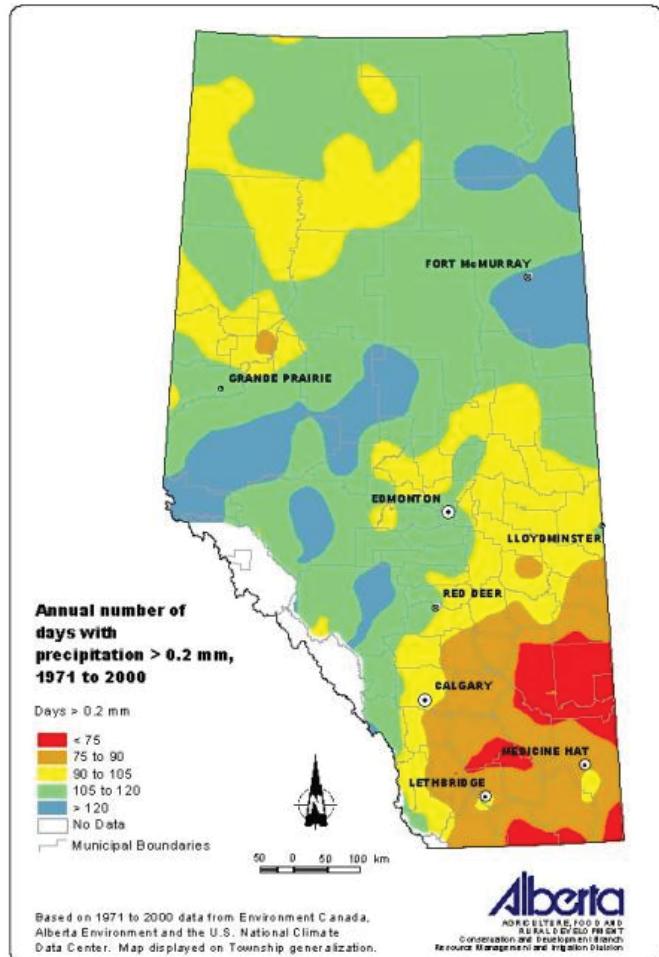
**FIGURE 4.2. CLIMATOLOGY (1979–2008) OF AVERAGE TEMPERATURE (°C) OF NICARAGUA BASED ON AN OBJECTIVE ANALYSIS FROM THE WORLD BANK**



Source: World Bank.

precipitation throughout the year. There are climatologies that can be critical for the user, and if they are addressing characteristics of climate that can result in yield losses, they can be called hazard maps (described in the next section). More information can be obtained from: <http://www.agric.gov.ab.ca/acis/climate-maps.jsp>.

**FIGURE 4.3. CLIMATOLOGIES (1971–2000)**



Left panel: Annual number of days with precipitation greater than 0.2 mm. Right panel: Frost-free period of Alberta, Canada.  
Sources: Crown copyright. Government of Alberta Agriculture and Rural Development, AgroClimatic Information Service.

## HAZARD AND RISK MAPS

Risk is usually defined as a function of the hazard,<sup>4</sup> vulnerability,<sup>5</sup> and exposure.<sup>6</sup> Making a risk map requires the selection of the magnitude (intensity to produce losses) and of the return probability (frequency of occurrence)

<sup>4</sup> A situation that poses a level of threat to life, property, or environment. In the case of agriculture, natural hazards include hurricanes, droughts, frosts, and so on.

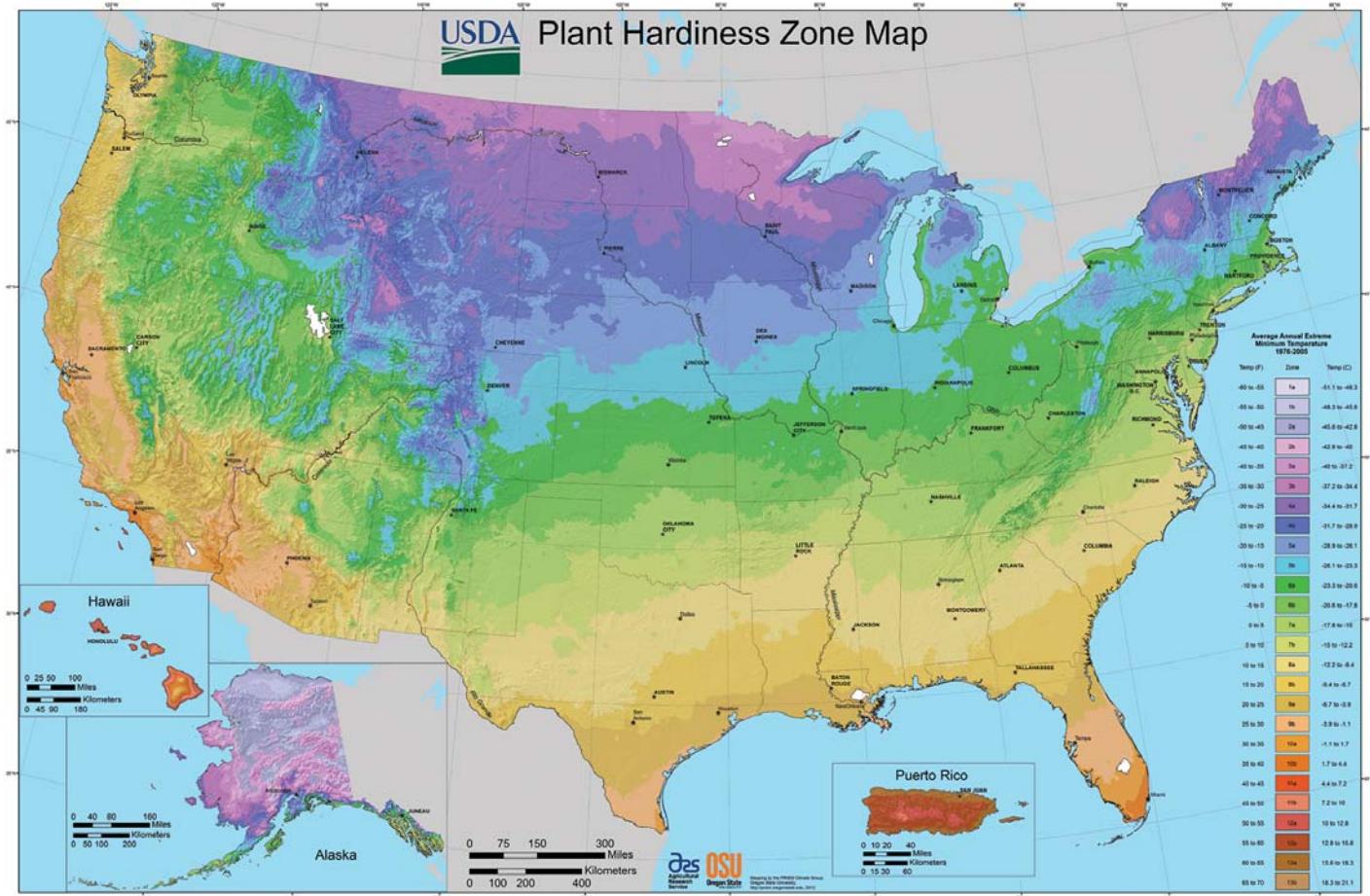
<sup>5</sup> Grade of ability to withstand the effects of a hazard. In the case of agriculture, some conditions can decrease or increase vulnerability. For example, if the farmer is prepared to withstand losses associated to pests (for example, by using pesticides), his vulnerability decreases.

<sup>6</sup> Condition of being subject to loss because of some hazard. In the case of agriculture, exposed goods are crops. Their exposure is indicated by their location and value.

of the hazard. For example, a risk map can display frost in the early stage of maize growth. The map, in this case, can indicate either the annual probability of this hazard, average annual losses (in yield or cash), or the product of the loss times the probability, which is the generally accepted numerical expression of risk. However, these maps can be built only if yield data are available and loss causes are identified.

In cases where yield data are not available, the community usually develops hazard maps (which sometimes are erroneously presented as risk maps). Hazard maps usually have an intensity or probability scale associated to the magnitude or probability of a given hazard. Hazard

**FIGURE 4.4. U.S. PLANT HARDINESS ZONE MAP (CLIMATOLOGIES OF AVERAGE ANNUAL EXTREME MINIMUM TEMPERATURE CLASSIFIED AT 5°F INTERVALS)**



Source: U.S. Department of Agriculture.

maps, however, don't take into account vulnerability and exposure so the scales and classifications are not necessarily related to losses (that is, risk). Since these maps require the least amount of information, they are much more common than risk maps. This document contains examples of representative hazard and risk maps in this section. Unfortunately, most hazard maps commonly available are only for developed countries. It is to be hoped these maps will illustrate and encourage their generation in developing countries as well.

## PLANT HARDINESS ZONES

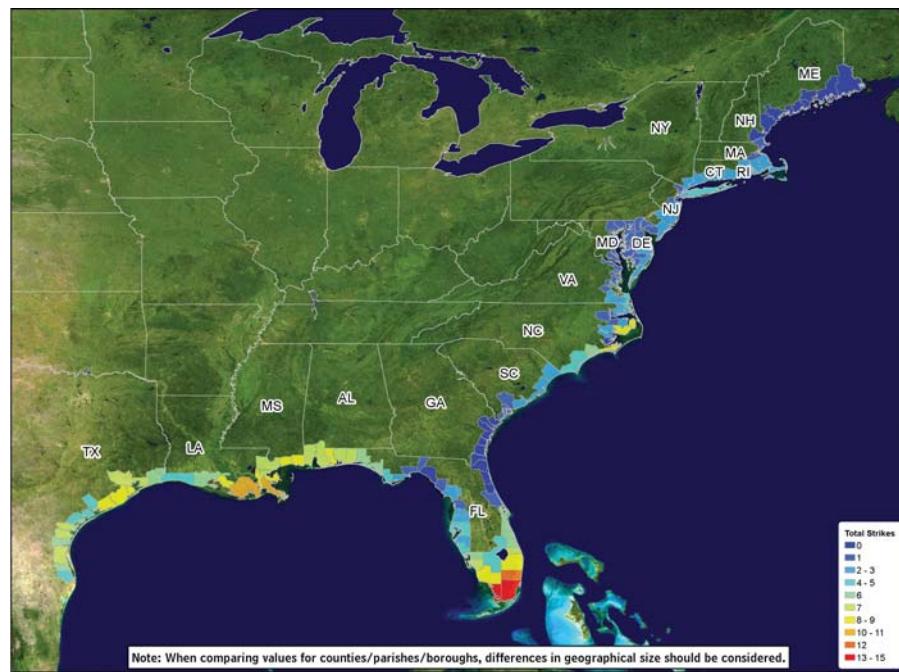
A hardiness zone is a geographical area within defined ranges of average minimum temperatures during the winter (divided into 5°F zones) where specific categories of

plants are expected to grow. Figure 4.4 shows the hardiness zone map for the United States.

Hardiness zones have to be used in combination with plant vulnerabilities to be practical. The zones have drawbacks because the following factors are not taken into account: summer temperatures, impacts of snow cover, soil moisture, humidity, number of days with frost, and duration of low temperatures. Arguably, instead of average minimum temperatures, perhaps the probabilities of specific lethal minimum temperatures would be more useful. More information is available at: <http://planthardiness.ars.usda.gov/PHZMWeb/>.

Although the zones were first developed for the United States by the Department of Agriculture (USDA), the

**FIGURE 4.5. TOTAL NUMBER OF HURRICANE STRIKES BY U.S. COUNTIES/PARISHES/BOROUGHS, 1900–2010**



Source: National Weather Service (NWS).

use of the zones has been adopted by other nations. The Canadian Forest Service (CFS) from the Natural Resources Canada, for example, develops hardiness zone maps, but it is also aiming to develop potential range maps for individual species of trees, shrubs, and perennial flowers (<http://planthardiness.gc.ca/>). The CFS has requested support from Canadian experts and the public to identify plants that survive at their location. Once enough data are collected to develop a climatic profile, the range maps will be generated.

### CONUS HURRICANE STRIKE DENSITY

The National Hurricane Center within NOAA has developed several tropical cyclone climatologies, which provide a general idea of the typical timing, magnitude, and location of tropical cyclones based on the analysis of historical records of cyclone tracks (<http://www.nhc.noaa.gov/climo/#uss>). Figure 4.5 displays the total number of hurricane strikes by counties between 1900 and 2010 in the Atlantic basin (Atlantic Ocean, Caribbean Sea, and Gulf of Mexico). The Atlantic hurricane season runs from June 1 to November 30, and the Eastern Pacific hurricane season runs from May 15 to November 30. Farmers usually

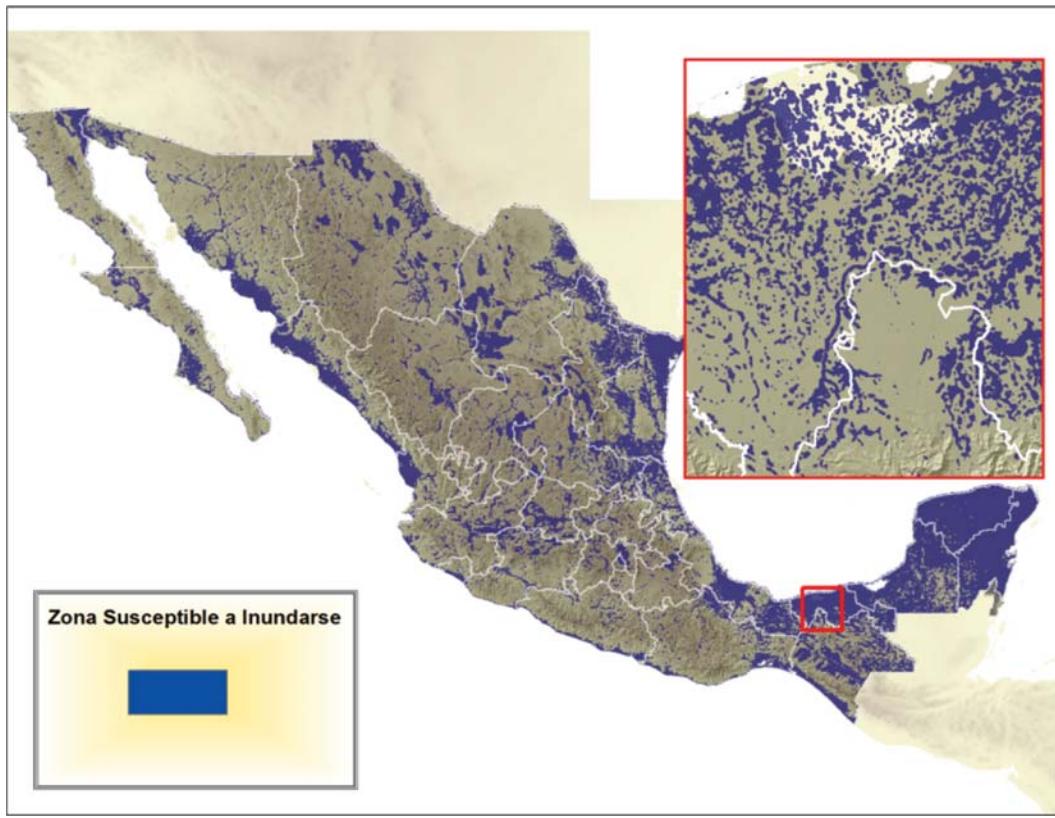
have a general idea of their exposure to hurricanes; however, these maps provide an objective point of comparison and reference.

### FLOOD INDEX—MEXICO

Floods are classified into: (1) flash-floods (intense precipitation events that exceed the soil's infiltration capacity); (2) riverine floods (runoff exceeds the capacity of rivers and channels so the water overflows the stream banks); (3) coastal floods (for example, high tides associated with tropical cyclones, that is, storm surges); and (4) urban floods (due to lack of proper drainage in an urban area). Unfortunately, consistent national databases of floods are practically nonexistent; therefore, risk assessments are generally based on indirect methods such as physical mathematical modeling. In this context, the application of models generally attempts to document the magnitude and probability of flood damages based on simulations that depend on historical records of precipitation and stream flow.

The definition of a flood index that allows the identification of regions prone to floods based on limited

**FIGURE 4.6. FLOOD-PRONE REGIONS OF MEXICO (URIBE ALCÁNTARA ET AL. 2010)**



Source: Uribe Alcántara et al. 2010.

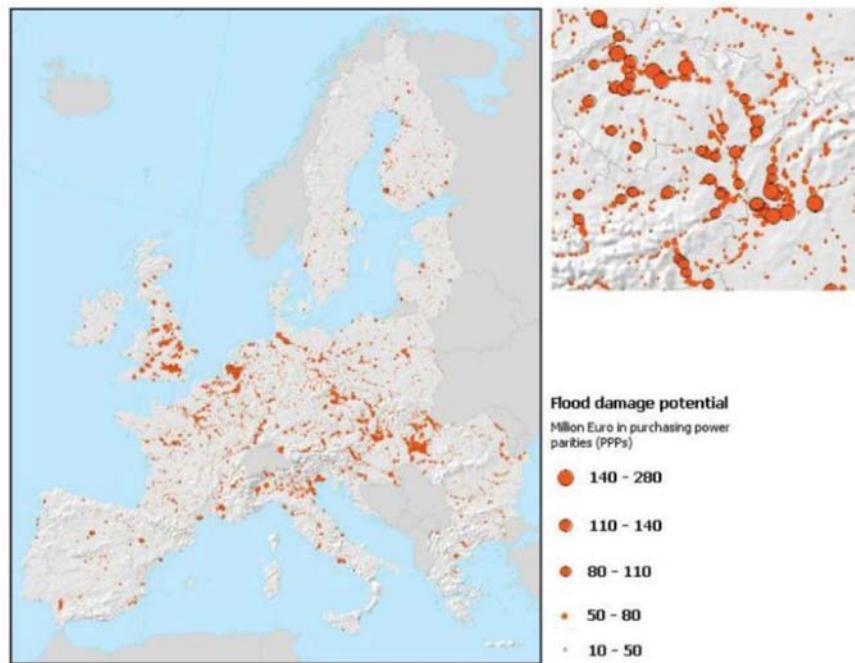
information was proposed in Mexico (Uribe Alcántara et al. 2010). The index is based on the topographic index developed by Beven (1979), but additionally it considers soil, hydrologic, and climatologic factors. Additionally, the results are compared, with corresponding simulations of a routing model, to the floodplain of the state of Tabasco. The results indicate that the index is able to capture reasonably well the perennial and ephemeral flooded regions. The methodology is applied to all the basins in Mexico for the generation of a national map of flood-prone regions (figure 4.6).

#### FLOOD DAMAGE POTENTIAL MAP FOR THE EUROPEAN UNION

In these maps, flood risk areas are defined on the basis of associated risk factors, that is, exposure and hazard (figure 4.7). Geo-referenced data on land use is processed for setting up the exposure component. The hazard factor is implemented by hydrological methods at different scales and for many return periods. Among the causal

factors of flood disasters, one is the triggering natural event in the form of extreme precipitation and consequently extreme river discharge. The threatening natural event represents the hazard component in the assessment. In addition, exposure is among the anthropogenic factors that contribute to increasing flood risk at a given location. Advanced GIS-based techniques and datasets were fundamental elements within the approach. The issue of flood risk mapping is studied at continental scale. The aim was to identify and map the regions prone to flood disasters and to quantify the potential losses with the support of stage-damage functions. This map provides support to several European Commission initiatives including the European Flood Action Programme, the Directive on the Assessment and Management of Flood Risks, the Solidarity Fund, and EU regional policies. More information can be obtained from: <http://floods.jrc.ec.europa.eu/>. Incidentally, this is perhaps the only actual risk map shown in this document because it actually shows potential economical annual losses due to flood.

**FIGURE 4.7. MAP OF FLOOD DAMAGE POTENTIAL  
(MILLIONS OF EUROS IN PURCHASING  
POWER PARITIES) OF THE EUROPEAN UNION**



Source: European Commission Joint Research Centre Floods Portal (<http://floods.jrc.ec.europa.eu/flood-risk.html>).

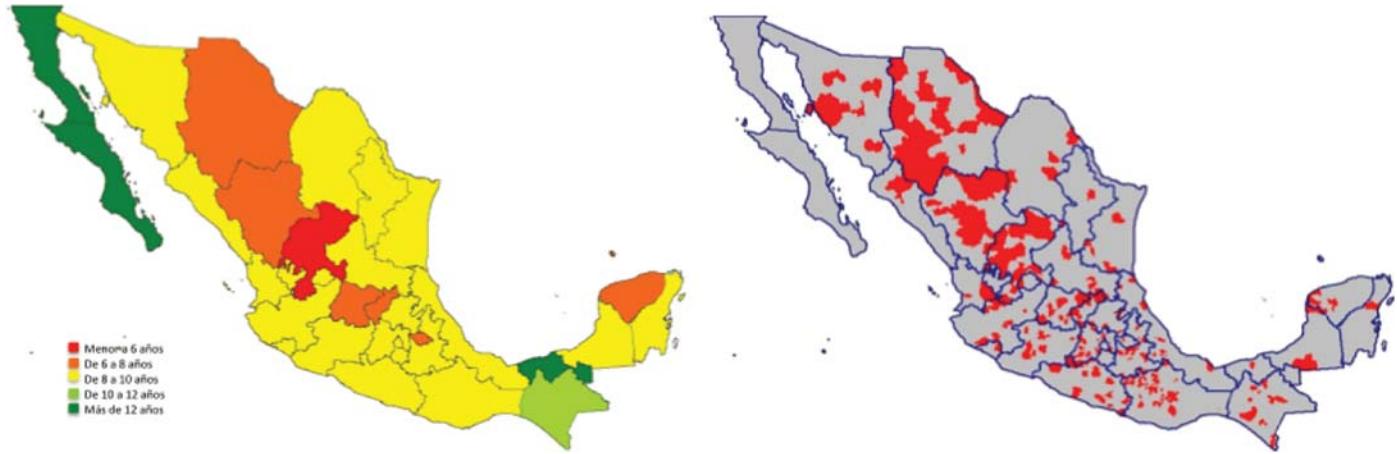
## MAPS OF THE RETURN PERIOD<sup>7</sup> OF AGROMETEOROLOGICAL CATASTROPHIC EVENTS IN MEXICO

Mexico is highly vulnerable to the occurrence of catastrophic natural hazards, mainly catastrophic and geologic, which involve 60 percent of the population and increase the probability of having high economical damages. The amount of losses has been increasing in recent decades. During 2001–03, the losses involved annual average contributions from the government around US\$207.8 million. In 2007 and 2009, the contributions increased to US\$884.2 million. While in 2010, the amount increased to US\$1,963 million. Ninety percent of this amount is related to hydrometeorological events, mainly hurricanes and extreme precipitation events.

Maps of the return periods of agrometeorological catastrophic events in Mexico have been developed (Escamilla Juárez 2012). The definition of a catastrophic event was based on the Operation Rules from the programs of the Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food, except for flood and precipitation excess, where the definition from the National Disasters Fund was applied. Maps for drought, frost, precipitation excess, and flood were developed at state and county levels. Figure 4.8 shows maps of return periods for catastrophic droughts at state and county levels. Based on the maps, it was concluded that drought is the most important risk for the agricultural sector. In average, the country presents catastrophic drought every 9.5 years, that is, 13.7 percent average annual probability. Five states present annual probabilities above 15 percent (six to seven years). However, at county level the probabilities can reach between 18 and 30 percent (three to five years). More importantly, 77.1 percent of these counties are located in only nine out of the 32 Mexican states.

<sup>7</sup> Average time, in years, between events.

## FIGURE 4.8. MAPS OF RETURN PERIOD OF CATASTROPHIC DROUGHT



State (left panel) and counties (right panel) with return period between three and five years.

Source: Jesus Escamilla.

### BOX 4.1. PRINCIPAL COMPONENTS ANALYSIS AND CLUSTERING

**Principal component analysis (PCA):** PCA is a mathematical procedure that transforms a set of observations of possibly correlated variables into a set of uncorrelated variables. The first principal component has the largest possible variance (that is, accounts for the largest portion of the variability in the data), and each succeeding component, in turn, has the highest variance possible under the constraint that it be orthogonal (uncorrelated) to the preceding components. PCA reveals the internal structure of the data. If a multivariate dataset is visualized as a set of coordinates in a high-dimensional data space, PCA can afford a lower-dimensional picture when viewed from its most informative viewpoint. This results from using only the first few principal components, so that the dimensionality of the transformed data is reduced.

PCA can be used to make climate regionalizations. There are two possibilities: The PCA can be applied to either the correlation matrix or the covariance matrix. The first option will

result in regions whose variability is different; the second, in regions whose range of values is different.

**Cluster analysis or clustering:** Cluster analysis can be achieved by utilizing one of several algorithms. Popular notions of clusters include groups with small distances among the cluster members, dense areas of the data space, intervals or particular statistical distributions. Clustering can therefore be formulated as a multi-objective optimization problem. The appropriate clustering algorithm and parameter settings (for example, distance function, density threshold, or number of expected clusters) depend on the individual data set and intended use of the results.

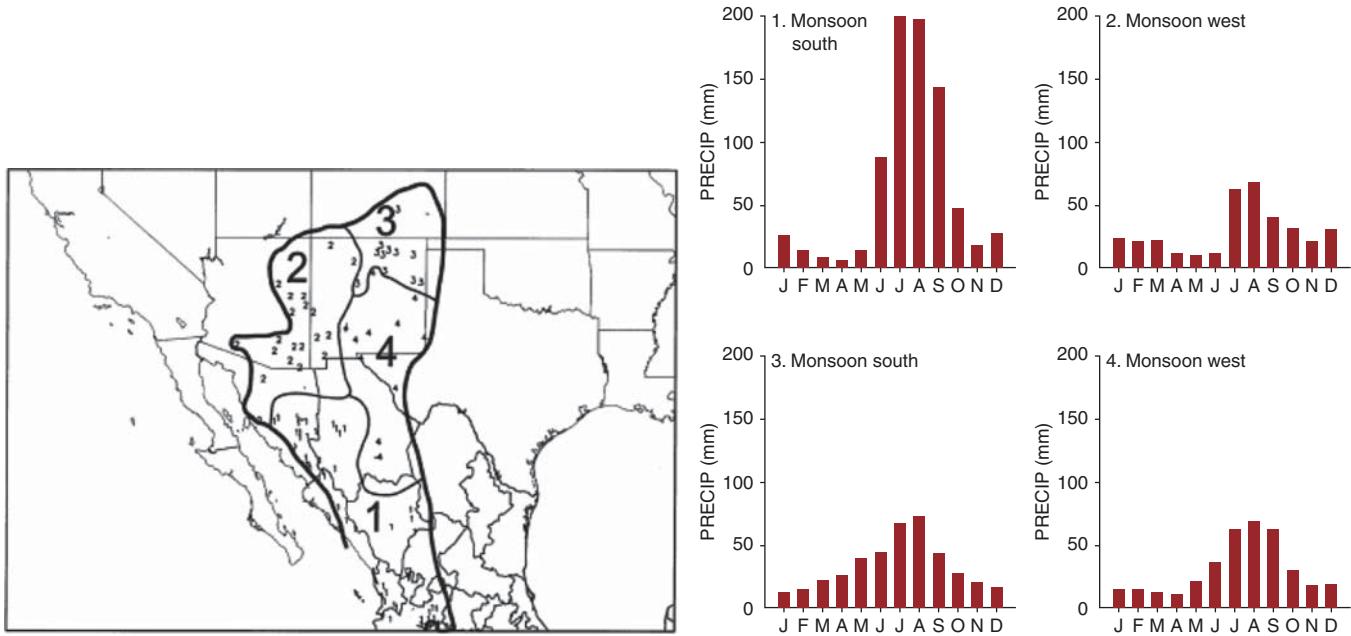
Clustering can be used to make climate regionalizations. In this case, the options are related to the number the variables involved to determine similarity (small distance). Variables can include, for example, precipitation, temperature, altitude, and so on.

## CLIMATE REGIONALIZATIONS

The most widely used climate regionalization is the Koppen Climate Classification, which relies on the principle that vegetation is the best expression of climate; as such, the boundaries between zones are selected with vegetation distribution in mind. The classification is based on the combination of annual and monthly temperatures

and precipitation, and the seasonality of precipitation. There are additional classifications based on cluster analysis that attempt to group unit cells with similar climatological values (for example, annual precipitation, length of the rainy season, and so on) within regions. On the other hand, there are also regionalizations that attempt to group unit cells in regions with similar behavior (for example, variability; see box 4.1). Figure 4.9 (left panel)

## FIGURE 4.9. NORTH AMERICAN MONSOON REGIONALIZATION



Precipitation (left panel) and corresponding annual cycles (right panel).

Source: Comrie & Glenn 1998.

shows a regionalization for the North American monsoon region, which defines four regions with distinctive annual cycles of precipitation (figure 4.9, right panel). These analyses are usually based on the rotation of the most important principal components of the correlation (or covariance) matrix. In terms of applications for risk analysis, for example, AGROASEMEX developed a cluster-based regionalization for the definition of regions sharing the same Weather Index Insurance scheme in Mexico (AGROASEMEX 2006). These regions can also be useful for the identification and characterization of

relatively independent regions. When the extension of the region of analysis is large and the spatial variability of climate is strong, very different annual cycles are present. The regionalization can help identify relatively independent regions that need to be characterized. In this way, the characterization simplifies from hundreds of stations/pixels to a few regions. With the advent of gridded databases, point analysis is becoming more common than regionalizations; however, regions can still be useful to simplify the definition and application of policies and analysis.



# CHAPTER FIVE

## DIAGNOSTIC AND FORECASTING ANALYSES



There are numerous mapping techniques for diagnostic and forecasting purposes. Diagnostic techniques are designed to provide a technical description of the current risk situation and its causes. Forecasts, on the other hand, predict potential risk events based on the study and analysis of pertinent observations and simulations. They have been included together in this chapter given that (1) many diagnostic techniques are used to make decisions in the near future, (2) applied agrometeorological forecasting techniques are still scarce, and (3) as the products become more sophisticated, the line between diagnostic and forecast products becomes thinner. The mapping techniques include, for example: monitors, outlooks, watches, warnings, and forecasts, which are formally issued in bulletins. Monitors are based on continuous or periodic measurements of existing, changing, agrometeorological conditions. Outlooks, watches and warnings are issued to indicate the probability of a hazardous event. Their difference is the likeliness that the event will occur. Outlooks have low certainty; watches, higher certainty; and warnings, the highest. These techniques aim to provide information in advance so stakeholders can prepare for hazardous events.

On the other hand, there are forecasts, which are the most likely prediction. In atmospheric sciences, forecasts are classified in short- (up to 48 hours ahead), medium- (up to 7 days), and long-term (more than seven days). Forecasts are classified in this way partially because of the technical challenges associated with each lead time. Furthermore, as the lead time increases, the uncertainty increases. Short- and medium-range forecasts can be particularly valuable for frosts and pests, for example, because risk mitigation activities can be implemented to reduce losses. Seasonal (long-term) forecasts of precipitation, with lead times of a few months, can be particularly useful for events such as drought. These forecasts usually indicate the probabilities of climate anomalies of variables like precipitation and temperature (that is, probabilities of having higher than usual precipitation). Finally, with Anthropogenic Climate Change, additional analyses (scenarios), which have lead times of decades, have been broadly developed. Such scenarios are a description of a possible future state for a given baseline condition (for example, rate of emissions of greenhouse gases). Usually, a set of scenarios is developed to reflect the range of uncertainty in projections.

This chapter contains examples of diagnostic and forecast mapping techniques that illustrate their potential use in the agricultural sector. The selections it contains seek to provide a representative mapping technique for each diagnostic and forecasting classification and hazards. Regarding climate change scenarios, an example of the application of projections to assess crop vulnerability on a regional basis for Mozambique is shown on page 47.

## U.S. DROUGHT MONITOR

Drought is an insidious hazard, often referred to as a “creeping phenomenon.” Its definition is not straightforward because what might be considered a drought in, say, Bali (six days without rain) would certainly not be considered a drought in Libya (annual rainfall less than 180 mm). In the most general terms, droughts originate from a precipitation deficit over an extended period of time (a season or more), which interplays with the demand of water supply for crop production, for example. Depending on the effect of the precipitation deficit, droughts are classified as: meteorological (precipitation deficit), economical (precipitation deficit with economic consequences), and agricultural (precipitation deficit that affects the sector).

There are conceptual and operational definitions of drought. Conceptual definitions of drought may be important in establishing drought policy. For example, in Australia, financial assistance is provided to farmers only under “exceptional drought circumstances.” Declarations of exceptional drought are based on science-driven assessments to prevent unjustified or unsustainable claims (for example, frequent claims from farmers in semi-arid areas). Operational definitions also help define the onset, severity, and end of droughts. No single operational definition of drought works in all circumstances. Therefore, most drought planners now rely on mathematical indices to decide when to start implementing drought response measures. To determine the onset of drought, for example, operational definitions specify the degree of departure from the average of precipitation. This is usually achieved by comparing the current situation with the climatological value (30-year average).

The U.S. Drought Monitor map provides a summary of drought conditions across the United States and Puerto

Rico. It began in 1999 as a federal, state, and academic partnership, growing out of a Western Governors’ Association initiative to provide timely and understandable scientific information on water supply and drought for policymakers. The Monitor is produced by a rotating group of authors from the USDA, the NOAA, and the National Drought Mitigation Center. It incorporates reviews from a group of 250 climatologists, extension agents, and others across the nation.

The map is updated weekly by combining a variety of data-based drought indices and indicators, as well as local expert input. The map denotes four levels of drought intensity (ranging from D1–D4) and one level of “abnormal dryness” (D0). Also depicted are areas experiencing agricultural (A) or hydrological (H) drought impacts. These impact indicators help communicate whether short- or long-term precipitation deficits are occurring (figure 5.1).

The U.S. Drought Monitor sets the standard for communicating the location and intensity of drought to a broad audience. The map summarizes and synthesizes information from the local and state levels to the national scale, making it the most widely used gauge of drought conditions in the country. Policymakers rely on it to allocate relief dollars, states use it to trigger drought response measures, and it is a frequent source for the media. The USDA utilizes the map to distribute millions, and sometimes billions, of dollars in drought relief to farmers and ranchers each year, and the Internal Revenue Service also refers to it for ranching-related tax determinations. More information available at: <http://drought.unl.edu/MonitoringTools/USDroughtMonitor.aspx>.

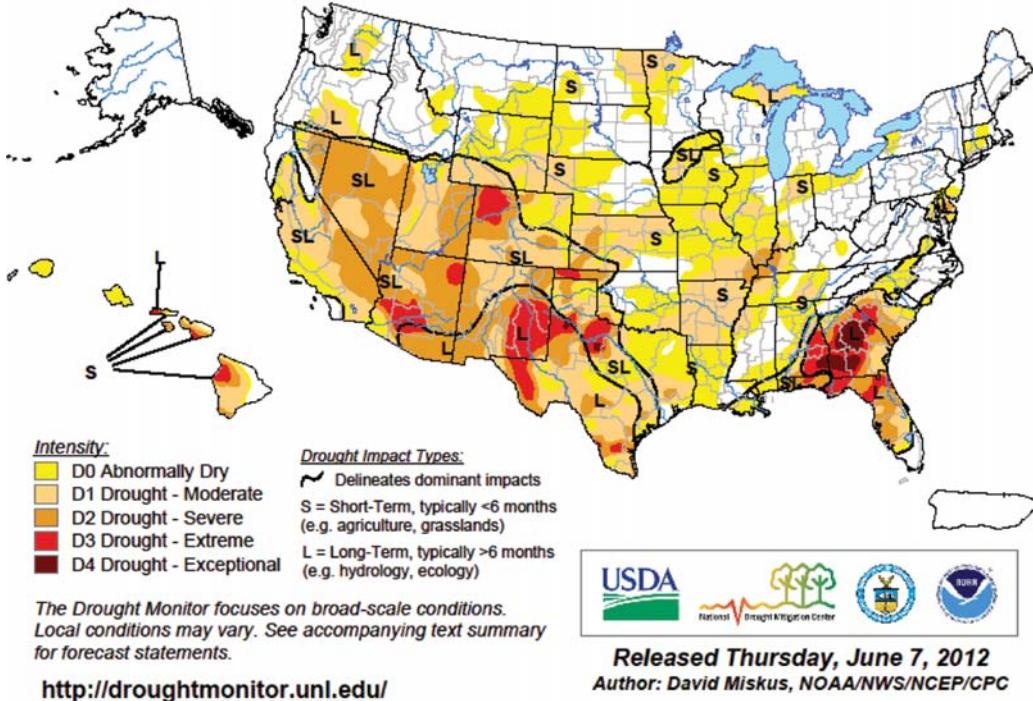
## METEOROLOGICAL MONITOR (AUSTRALIA)

Australia’s Bureau of Meteorology regularly produces a number of important, objective analyses (see page 11) to provide a constant and rapid overview of rainfall and temperature distribution across Australia. The analyses are computer generated using the Barnes successive correction technique. On most maps (both rainfall and temperature), each grid point represents a square area with sides of

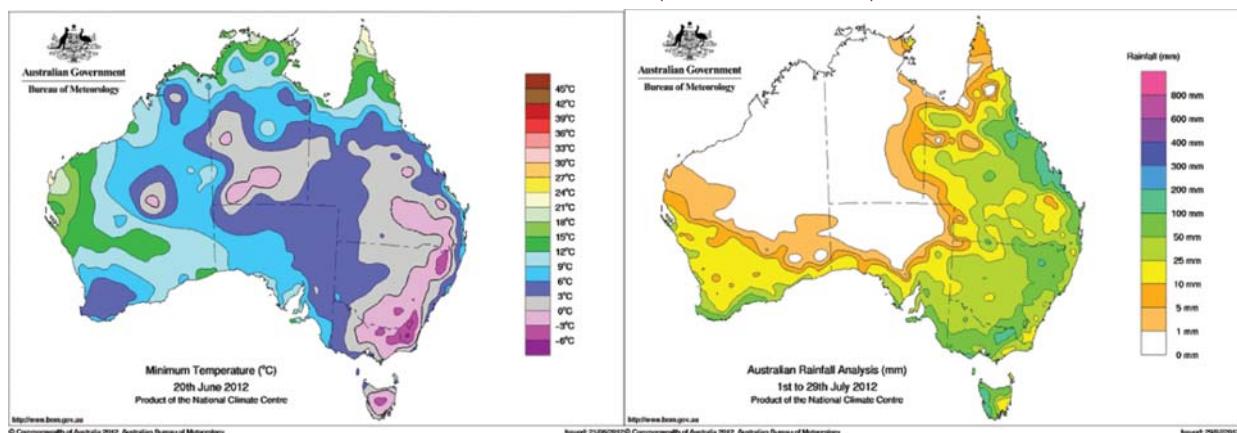
**FIGURE 5.1.** U.S. DROUGHT MONITOR FOR JUNE 5, 2012

## U.S. Drought Monitor

June 5, 2012  
Valid 7 a.m. EDT



**FIGURE 5.2.** EXAMPLES OF MAPS OF DAILY TEMPERATURE (LEFT PANEL) AND CUMULATIVE PRECIPITATION (RIGHT PANEL) FOR AUSTRALIA



approximately 25 km. The size of the grids is limited by the relatively coarse average data separation between stations. Daily rainfall maps are available at around 2:00 p.m. (Eastern Standard Time; EST), which is only a couple of hours after the morning observations from all time zones are received in the central database. Daily temperature maps for the previous day are available at around 12:30 p.m. (EST). The Bureau of Meteorology's rainfall and

temperature analyses use data collected through electronic communication channels. These data have been screened for errors, but are not yet fully quality controlled. Figure 5.2 shows the objective analysis of minimum temperature for a given day. The map suggests subzero temperatures in the eastern portion of the country. More information available at: <http://www.bom.gov.au/climate/austmaps/mapinfo.shtml>.

## SOYBEAN RUST OUTLOOK (U.S.)

A number of maps can be developed to improve management of risks associated with pests and diseases. This section presents an example for soybean rust (SBR) in the United States, but similar efforts can be developed for other pests and diseases in other regions of the world. SBR, caused by two fungi species called *Phakopsora pachyrhizi* and *Phakopsora meibomiae*, is an aggressive pathogen that has spread from Asia to Africa, South America, and North America. Yield losses associated with SBR can be severe (10–80 percent). Soybean rust was first detected in the United States in the fall of 2004, and the national sentinel plot network has subsequently monitored its spread and development.

Weather conditions are critical for the determination of spread of this disease. Soybean rust development is favored by temperatures ranging from 54°–84°F (65°–80°F is optimum), with relative humidity above 90 percent for more than 12 hours. Soybean rust can be active with daytime temperatures as high as 100°F (and possibly higher) as long as night temperatures fall into the optimum range for disease development. In order for spores to germinate and infect the plant, 6 hours of continuous leaf wetness are required. Infection increases with longer leaf wetness periods of up to 12 hours. In South America, significant rust development is associated with rain events.

The Penn State University Ensemble SBR Forecasting Program simulates the local development of soybean rust infections based on weather-driven transport of spores from infected geographic regions to downwind areas with potential host vegetation. The aerobiology ensemble modeling project follows the movement and development of SBR across the country with three models: (1) the Integrated Aerobiological Modeling System (IAMS), (2) the HYSPLIT trajectory model (NOAA ARL), and (3) a climatological based model. Composite Precipitation/Relative Humidity, Solar Radiation/Minimum Temperature, and Wind Speed/Direction maps are created from model output from the National Weather Service (NWS). SBR observations and IAMS model outputs are interpreted to produce SBR transport, deposition, and disease severity

“ensemble maps” as well as an additional product that combines these three maps. A student team integrates the composite weather maps with the “ensemble maps” to create an “SBR activity ensemble” that defines wait, watch, and warning zones for field scouting and soybean rust decision support. Three times a week, the student team issues 1–2 day and 3–5 day forecasts in text format on a restricted-access website. The maps of spore movement and infection development both in the present and the future are invaluable in guiding extension specialists as to the likelihood, location, and timing of soybean rust in their states. Figure 5.3 (left panel) shows the results of a soybean rust scouting for July 25, 2005. Since the spread of soybean rust is strongly associated with weather conditions, scouting efforts can be combined with meteorological conditions to issue spread forecasts (figure 5.3, right panel).

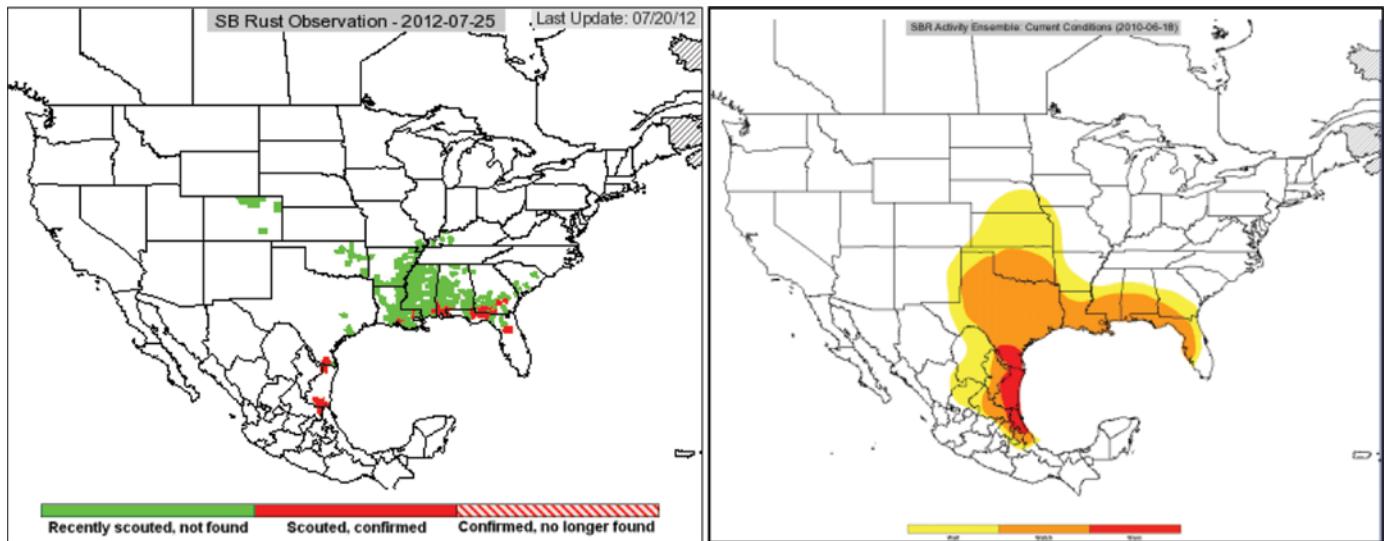
## FLOOD: WARNING SYSTEM (UNITED STATES AND THE EUROPEAN UNION)

The Advanced Hydrologic Prediction Service (AHPS) is a component of the Climate, Water, and Weather Services offered by the NWS from NOAA in the United States. AHPS is a suite of accurate and information-rich forecast products. They display the magnitude and uncertainty of occurrence of floods or droughts, from hours to days and months in advance. These products enable government agencies, private organizations, and individuals to make more informed decisions about risk-based policies and actions to mitigate the dangers posed by floods and droughts.

The vast majority of the observed water level data displayed on the AHPS web pages originates from the Hydrometeorological Automated Data System (HADS) operated by the Office of Hydrologic Development. Following the processing of the raw data, HADS delivers the observational data to the Weather Forecast Offices and River Forecast Centers, which use the data in their hydrologic models and create the informational displays for the AHPS.

Using sophisticated computer models and large amounts of data from a wide variety of sources such as super computers, automated gauges, geostationary satellites,

**FIGURE 5.3. SOYBEAN RUST OBSERVATION FROM THE INTEGRATED PEST MANAGEMENT**



Pest information platform for extension and education (IPM PIPE) in July 25, 2005 (left panel) and simulation of potential deposition areas for soybean rust spores (June 2010) based on weather conditions (right panel).

Source: U.S. Department of Agriculture Pest Information Platform for Extension and Education.

**FIGURE 5.4. FLOOD MONITOR BASED ON GAUGE DATA**

**AHPS Gauge Map**



Last map update: 06/28/2012 at 12:04:49 pm EDT  
06/28/2012 16:04:49 UTC

Source: National Weather Service (NWS).

U.S. gauges are shown as squares, and the colors of the squares change depending on flood status.

Doppler radars, weather observation stations, and the computer and communications system, called the Advanced Weather Interactive Processing System, the NWS provides hydrologic forecasts for almost 4,000 locations across the United States.

The information is presented through user-friendly graphical products. Figure 5.4, for example, shows the presence of floods based on readings from gauge stations. The information, such as the flood forecast level to which a river will rise and when it is likely to reach its peak or

**FIGURE 5.5. FLOOD MONITOR OF THE EU BASED ON GAUGE DATA (MAY 23, 2010)**



Source: European Commission Joint Research Centre Floods Portal.

The symbol of the gauges changes depending on the flood status.

crest, is shown through hydrographs. Additional information includes:

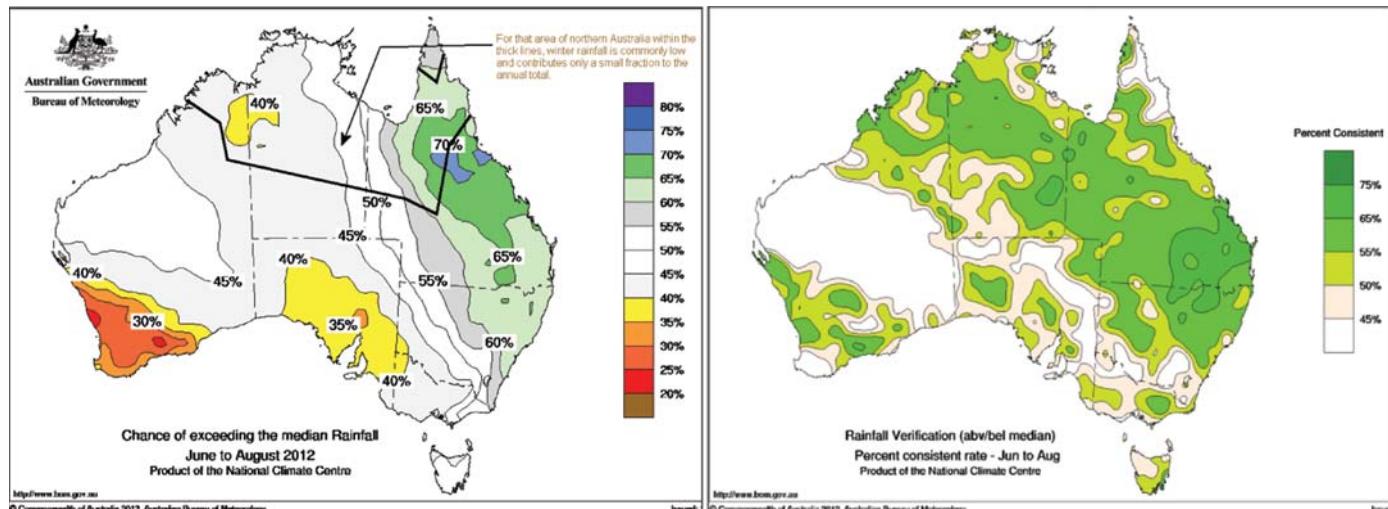
1. The chance or probability of a river exceeding minor, moderate, or major flooding,
2. The chance of a river exceeding certain level, volume, and flow of water at specific points on the river during 90 day periods, and
3. A map of areas surrounding the forecast point that provides information about major roads, railways, landmarks, and so on, likely to be flooded, the levels of past floods, and so on.

AHPS forecast products are a basis for operation and management of flood-control structures. Emergency management officials at local and state levels use these forecasts to fight floods, evacuate residents, and to take other measures to mitigate the impact of flooding. In addition to farmers, these products can be used by a wide

range of people, such as barge operators, power companies, recreational users, households, businesses, and environmentalists. More information can be obtained from <http://water.weather.gov/ahps/index.php#>.

A similar overview of the current floods in Europe is made through the European Terrestrial Network for River Discharge, based on a close collaboration with European Hydrological Services and the Global Runoff Data Centre (GRDC) in Koblenz, Germany. An overview of the current floods in Europe is provided through the European Terrestrial Network for River Discharge. The overview map is based on near-real-time river measurements, automatically transferred by the National Hydrological Centres, via the GRDC, to the Joint Research Centre. The map shows the locations where river levels exceed critical thresholds (figure 5.5). More information available at: <http://floods.jrc.ec.europa.eu/>.

**FIGURE 5.6. FORECAST OF CHANCE OF EXCEEDING TRIMESTRAL MEDIAN RAINFALL (JUNE TO AUGUST, 2012) IN AUSTRALIA (LEFT PANEL) AND HISTORICAL CONSISTENCY OF THE FORECASTING SCHEME (RIGHT PANEL)**



Right panel: Color scheme indicates percentage of times the scheme has forecasted correctly.

## RAINFALL SEASONAL FORECAST (AUSTRALIA AND INTERNATIONAL)

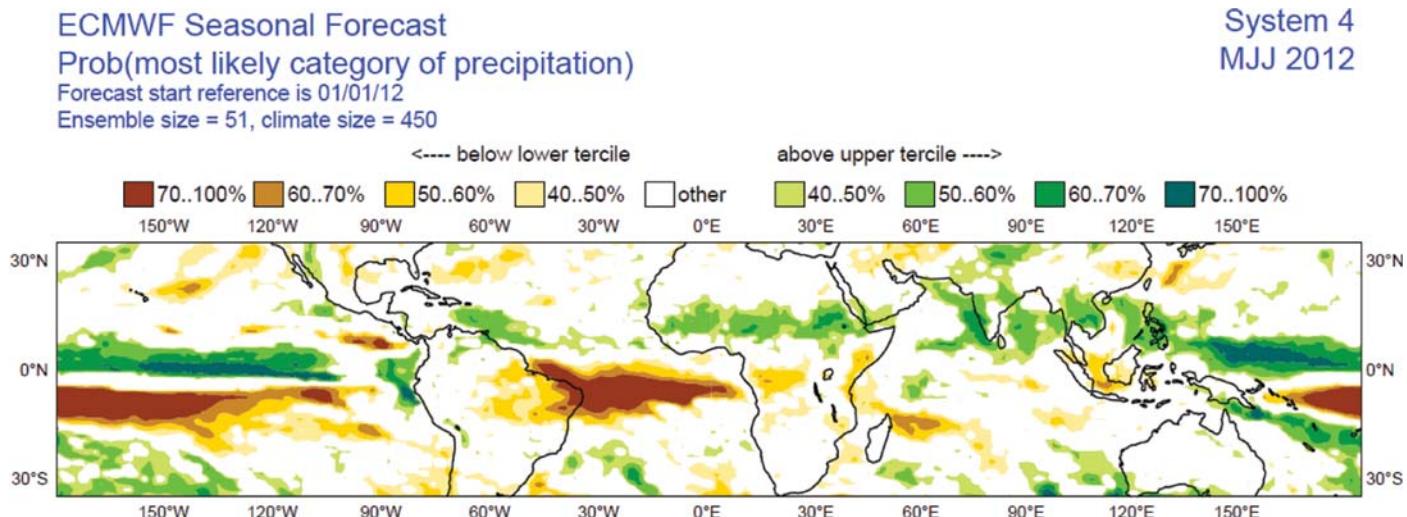
The Australian Bureau of Meteorology issues general statements about the probability of wetter- or drier-than-average weather over future 3-month periods (figure 5.6, left panel). The Bureau also issues average, maximum, and minimum temperatures for the entire 3-month outlook period. These outlooks are based on the sea surface temperature records for the tropical Pacific and Indian oceans and the Southern Oscillation Index (SOI), which is calculated using the barometric pressure difference between Tahiti and Darwin. The SOI is one indicator of the stage of El Niño or La Niña events in the tropical Pacific Ocean. For example, a moderate to strongly negative SOI (persistently below  $-10$ ) is usually characteristic of El Niño, which is often associated with below-average rainfall over eastern Australia, and a weaker-than-normal monsoon in the north.

An important part of the forecasts is the evaluation. Forecasts carry a certain amount of uncertainty. It is important to inform stakeholders as to the historical performance of the forecast system. In the case of Australia, consistency maps are generated regularly (figure 5.6, right panel). Strong

consistency means that tests of the model on historical data show a high correlation between the most likely outlook category (above/below median) and the verifying observation (above/below median). In this situation relatively high confidence can be placed in the outlook probabilities. On the other hand, low consistency means the historical relationship, and therefore outlook confidence, is weak. More information available at: <http://www.bom.gov.au/climate/outlooks/#/overview/summary>.

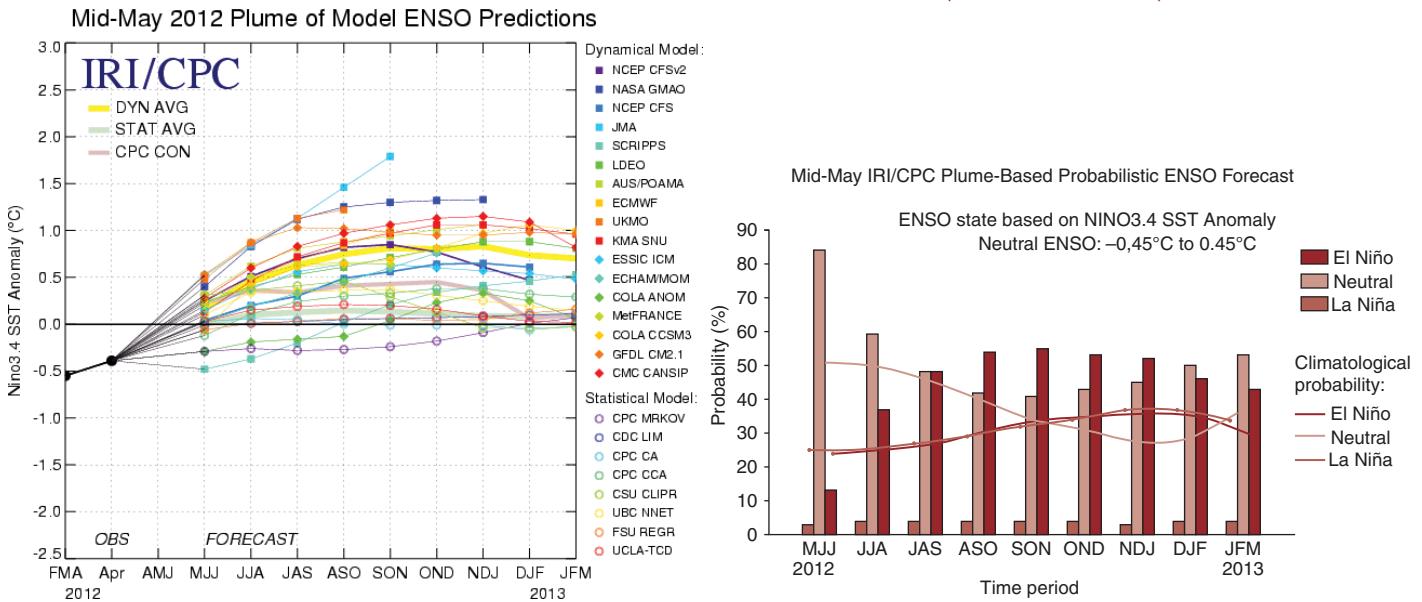
Forecast systems developed regionally, such as that from Australia, usually allow higher resolution, accuracy, and flexibility in the presentation of the results for both developers and users. However, technical challenges usually prevent their emergence in developing countries. In those cases, the users can rely on third-party forecasts from recognized institutions like the European Centre for Mid-Range Weather Forecasts (ECMWF), which perhaps has the best simulation systems in the world. Figure 5.7 shows the precipitation forecasts for May, June, and July in 2012. In this case, unlike the case of Australia, the forecast is estimated based on late-generation numerical weather prediction models. These forecasts are available online in a low-resolution format, but national weather services can have access to these high-resolution forecasts in the original data format so they can focus on the

**FIGURE 5.7. TRIMESTRAL FORECAST (MAY-JULY, 2012) OF PROBABILITY OF MOST LIKELY CATEGORY OF PRECIPITATION FROM THE ECMWF**



Source: International Resource Institute, Columbia University.

**FIGURE 5.8. ENSO FORECAST FROM DIFFERENT CLIMATIC CENTERS AROUND THE WORLD COLLECTED AND PUBLISHED BY IRI (LEFT PANEL) AND PROBABILITIES OF HAVING EL NIÑO, LA NIÑA, OR A NEUTRAL YEAR (RIGHT PANEL)**



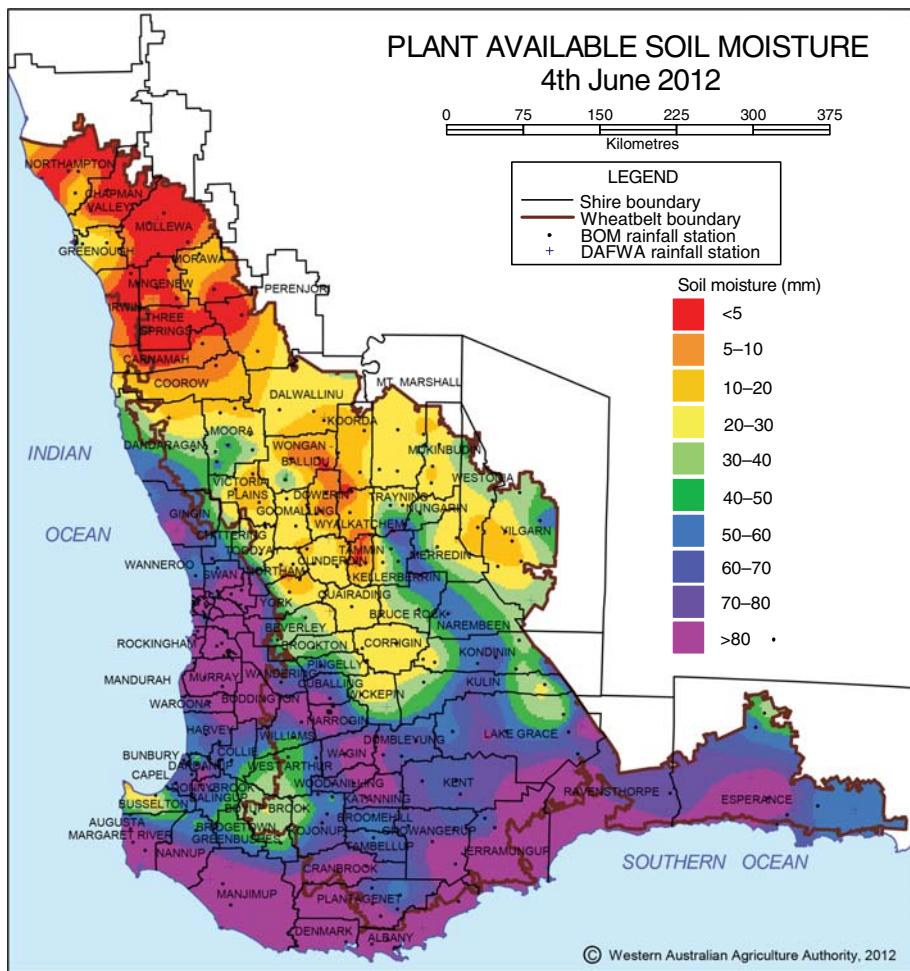
Source: Consensus Forecast of the International Resource Institute, Columbia University, and the Climate Prediction Center, National Weather Service.

processing of these forecasts for their specific needs. One of the potential and expected applications of these forecasts is downscaling, which allows local calibration and resolution increase. More information available at: <http://www.ecmwf.int/en/forecasts/charts>.

In addition to the European Centre for Mid-Range Weather Forecasts, there are also institutions like the

International Research Institute (IRI), which also issue regular forecasts. Finally, the Australian outlook relies upon on a numeric estimation of probabilities that is based on climate modes like El Niño-Southern Oscillation (ENSO). ENSO is an important climate regulator in many parts of the world. IRI collects ENSO forecasts from all over the world from recognized institutions, and distribute these forecasts in probabilistic form (figure 5.8).

**FIGURE 5.9. MAP FROM THE COVER OF AN AGROMETEOROLOGICAL BULLETIN**



Department of Agriculture and Food



Source: Copyright © Western Australian Agriculture Authority.

These forecasts can be very useful for regional climatologists once the impact of ENSO in the region has been documented. More information available at: <http://iri.columbia.edu/climate/ENSO/currentinfo/QuickLook.html>.

## AGROMETEOROLOGICAL BULLETINS

Agrometeorological bulletins are perhaps the most appropriate means to distribute most of the products presented in this document. Figure 5.9 shows the cover of an agrometeorological bulletin from the Department of Agriculture and Food from the state government of Western Australia.

An agrometeorological bulletin is issued for a user community, so it must meet their needs. A good practice is to prepare the bulletin jointly between national agrometeorological services, extension agents, researchers, and so on. The bulletin should be published regularly (every 7–10 days). A good approach is to publish detailed monthly bulletins, with updates in between (for example, every week).

Such a bulletin should have a one-page summary, with two components: (1) a box with text, and a map of the country showing areas where problems occurred or are likely to occur, and (2) a weather analysis summarizing the current weather for the period of interest. It is also important to compare the current period with the long-term

average and the previous season, for comparison purposes. A “snapshot” of agriculture is needed to understand the impact of weather.

Qualitative information about crops, livestock, pests, and diseases should also be included (for example, crop stages, development stages of pests, estimated soil moisture). A number of useful maps could be included to cover these topics, and a description of how weather has affected agriculture is important. Yield maps can be included, if available. The bulletin should focus on the effect of the weather. For example:

- » Lack of rainfall at the time of flowering of maize is likely to reduce yields.
- » Unusually high temperatures at the time of flowing of rice will probably reduce pollination.
- » The combined effect of high moisture and low temperature has certainly favored the development of black spot disease.
- » Abundant rain in the northern region has created good breeding grounds for desert locusts but rangeland production has improved.

Prospects describing what will happen between the current time and harvest, including considerations of actual and future conditions, should be included. This may be based on climatology, weather forecasts, or seasonal forecasts, plus additional relevant information (for example, market and road conditions).

The back cover could contain glossaries or generic information, for instance a map showing the main agro-ecological zones of the country, or explain which crops are “native” and which are “exotic,” and so on. More information about bulletins and examples can be obtained from:

<http://www.fao.org/NR/climpag/pub/AgrometeorologicalBulletinsTips.pdf>

[http://www.agric.wa.gov.au/PC\\_90647.html](http://www.agric.wa.gov.au/PC_90647.html)

<http://www.hydromet.gov.bz/monthly-argro-met-bulletin>

<http://63.175.159.26/~cimh/cami/files/dombulletin/sep2012.pdf>

<http://www.metmalawi.com/bulletins/bulletins.php>

# CHAPTER SIX

## AGRO-ECOLOGICAL ZONES



Agro-ecological zoning divides an area of land into smaller units, which have similar characteristics related to land suitability, potential production, and environmental impact (FAO/IIASA 1991). An agro-ecological zone (AEZ) is a mapping unit defined in terms of climate, soil, landform, and land cover with a specific range of potential and constraints for land use. The FAO Agro-ecological Zones Project (FAO 1978–81) was an early exercise in land evaluation at a continental scale. Results of the FAO AEZ project include land suitability, potential production, and population support capacity for 117 developing nations.

Agro-ecological zoning provides an assessment of the following issues:

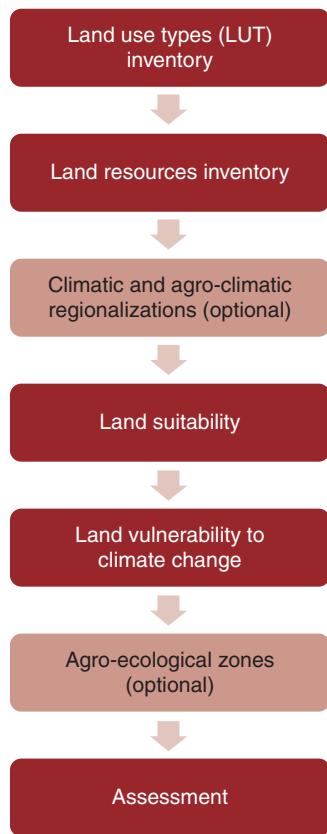
1. Distribution of land with different potentials and constraints
2. Response to improvements in inputs and management
3. Balance between population demand and land availability
4. Land use recommendations

In terms of land use recommendations, they benefit from policy formulations that include:

1. Specific extension support
2. Specific inputs and relief programs
3. Established research priorities
4. Defined development programs

The regionalization process depends on the information available, modeling capabilities, and objectives. Therefore, the methodologies applied regionally can have differences. However, in this section, we attempt to list and describe the common stages and order

## FIGURE 6.1. FLOWCHART OF A GENERAL AGRO-ECOLOGICAL ZONING PROCESS



necessary to develop an AEZ. In general terms, the zoning approach involves the following stages (see also figure 6.1):

1. Land use types (LUT)
2. Land resource inventory
3. Climatic and agro-climatic regionalizations (optional)
4. Land suitability
5. AEZ (optional)<sup>8</sup>
6. Analysis and recommendations

The vulnerability of crops to climate change is becoming an important assessment of agro-ecological zoning. However, given that even more methodologies and

models are being proposed involving an ever-increasing flow of complexities, climate change implications are not addressed in this paper, which is restricted to short-term weather risk assessment techniques. Each one of the methodology's stages is described individually in the following sub-sections. Subsequently, the stages are illustrated based on an agro-ecological zoning exercise implemented by the World Bank in Mozambique. Several examples of AEZs are provided in the last sections. The description in these cases is not exhaustive. The examples are only used to highlight regional challenges and solutions so the reader can appreciate that usually there are adaptations to solve regional challenges and needs. However, FAO Global Agro Ecological Zones (GAEZ) latest products have managed to achieve excellent quality, higher resolution, and cover a wide diversity of crops. This is an application that is readily available and useful.

## INVENTORY OF LAND USE TYPES

LUTs are representative combinations of crop(s), management system (operations and inputs), and socioeconomic settings. An inventory of the climatic, edaphic, and land-form requirements for each LUT is created. The level of detail depends on the databases available. This information is used to assess the climatic and edaphic suitability, as well as the potential yield calculation. In this activity, current or projected representative LUTs are selected for the analysis.

The crop climatic inventory should contain phonological requirement, such as thermal ranges, day length, and growth cycles (adaptation to climatic conditions). The soil inventory, on the other hand, should summarize the soil requirements of crops related to internal (for example, soil temperature, soil moisture soil aeration, natural fertility, soil depth) and external soil requirements (for example, slope, occurrence and depth of flooding, accessibility). Therefore, although in some AEZ reports an LUT inventory is listed after the land resources inventory, this document provides it first because the climate and soil information required will depend on the characteristics of the selected LUTs.

<sup>8</sup> As gridded datasets are becoming more popular, agro-ecological zoning has evolved into point analysis so that regionalizations and zonifications are no longer essential. The topic has historically been named agro-ecological zoning; even though zonifications are not longer the final objective, the name is still preserved. The objective is evolving toward the assessments of land suitability and vulnerability to climate change. Regionalizations can still be useful for planning purposes and policy definition and implementation, but they are optional.

**TABLE 6.1. LIMITING CROP FACTORS AND THEIR RELATIONSHIP WITH POTENTIAL, ATTAINABLE, AND ACTUAL YIELDS**

Factor	Potential Yield	Attainable Yield	Actual Yield
CO <sub>2</sub>	X	X	X
Solar Radiation	X	X	X
Temperature	X	X	X
Genotype	X	X	X
Plant Density	X	X	X
Water Supply		X	X
Any other limiting factor (pests, weeds, diseases, and so on)			

## COMPILATION OF LAND RESOURCES INVENTORY

At this stage, all datasets relevant for production are compiled. The most important information is related to climate, soil, and topography. However, additional datasets can be useful like land use and protected areas to identify and exclude urban areas or water bodies, for example, which are not suitable for agricultural use.

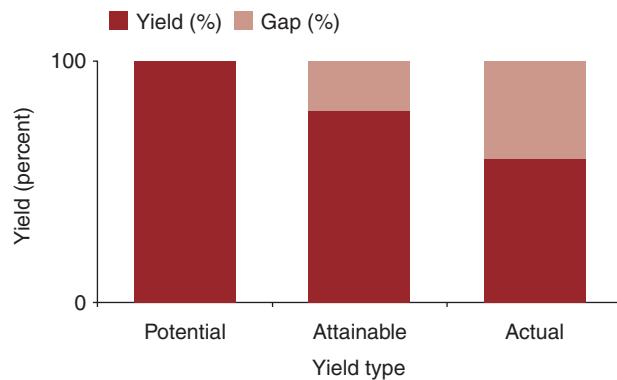
## CLIMATIC AND AGRO-CLIMATIC REGIONALIZATIONS (OPTIONAL)

Based on the factors previously described, climatic and agro-climatic regionalizations can be generated. The differences between these two types of regionalizations are basically the input data. Climatic regionalizations depend only on climatic information while agro-climatic regionalizations add agronomy or farming systems to the climatic database. The statistical analyses used to define climatic regions have been described on pages 24–25. The same statistical methods can be used to develop agro-climatic regionalizations with the corresponding input data.

## LAND SUITABILITY

The most recent agro-ecological zoning exercises focus on land suitability, which is defined in terms of potential, attainable, and actual yields. Potential yield is defined by the amount of CO<sub>2</sub>, solar radiation, temperature, genotype, and plant density (table 6.1). Nutrients and water are assumed to be nonlimiting, and additional

**FIGURE 6.2. YIELD AND GAPS OF POTENTIAL, ATTAINABLE, AND ACTUAL PRODUCTION**



limiting factors such as pests and diseases are not taken into account to estimate the potential yield. Attainable yield, on the other hand, adds available water supply to the factors implemented for the estimation of potential yield. Finally, actual yield adds all additional limiting factors like pests, diseases, nutrients, weeds, and so on. Clearly, potential and attainable yields are more easily estimated from models, while actual yields are derived from observational information (for example, national production statistics).

Potential and attainable yields are used to benchmark actual yields and, therefore, suitability. Potential yield is the maximum possible yield, while attainable yield is the second-highest due to the impact of water supply, and actual yield is the lowest. The differences between yields are known as gaps (figure 6.2). The larger the attainable yield, the more suitable the region; the larger the gap, the more unsuitable the region. Thus, attainable yields and gaps can be used to identify the most suitable crops for a

given region. In addition, the analysis can be performed for several crops to identify the most profitable combinations and distributions.

## AGRO-ECOLOGICAL ZONING

The differences between climatic, agro-climatic, and agro-ecological zonings (or regionalizations) are basically characterized by the input data, which increase for each one of these regionalizations. In addition to climate and farming systems, agro-ecological zoning includes additional environmental factors. The objective is to group units with similar land suitability, potential production, and environmental impact. It is important to note that although the name of all the products described in this chapter fall under the term agro-ecological zoning, the latest exercises by FAO do not actually define zones. The use of gridded datasets allows point analyses (that is, pixel based) that have rendered regionalizations less common and useful. However, regionalizations can still be useful for planning purposes and policy definition and implementation.

## ASSESSMENT

The result from the land suitability assessment is a classification of crops grown in different land units. Each land suitability class reflects a range of anticipated yields. This information generates the following assessments, which are the final products expected from the AEZ analysis:

**1. Potential Land Productivity:** The assessment allows the selection of crops for each agro-ecological cell (AEC) based on potential yield. The determination of land productivity requires the following steps:

(a) Formulate cropping pattern options: Sequential cropping increases land productivity but it is only possible when the available growing period exceeds the duration of the growth cycle of a single crop. If the length of growing period (LGP) is less than 120 days, for example, a single short duration crop is feasible. On the other hand, if the LGP is greater than 270 days, crop mixtures with different maturation periods are common.

(b) Formulate crop rotations: This is achieved by taking into account fallow requirements of the selected cropping pattern. It is calculated based on the requirement of humus levels, and expressed as the percentage of time the land is under fallow. At intermediate input levels, fallow requirements are 33 percent of those at low input levels while at high inputs, fallow requirements are only 10 percent.

(c) Impact of soil erosion on productivity: The impact is addressed in three stages: (1) estimation of the potential soil erosion, (2) net soil loss estimated by taking the difference between potential soil erosion and the rate of soil formation, and (3) estimated limits of tolerable soil loss under different options of cropping patterns and define measures for soil conservation.

**2. Estimation of Potential Rain-fed Arable Land:** Whenever possible or appropriate, combinations of crops have been constructed. Suitability classes are defined relating average single crop suitability to maximum attainable yield. Arable extents estimation is applied in three stages:

(a) Determination of the crop combinations that perform best under the worst climatic conditions;

(b) Selection of crop combinations with production stability; and

(c) Among all qualifying crops, a selection of the combination that maximizes the sum of extensions weighted by productivity to describe the arable land potential.

**3. Spatial resource allocation (optimizing land use):** The optimization can address single or multiple factors simultaneously:

(a) Food output (average yield or minimum yield in bad years)

(b) Net revenue

(c) Production costs

(d) Gross value

(e) Arable land area

(f) Harvested area

(g) Maximum or net erosion

(h) Self-sufficiency ratio (minimum of the individual commodity group self-sufficiency ratios)

## CHAPTER SEVEN

# WORLD BANK CASE OF STUDY: AGRO-ECOLOGICAL ZONING IN MOZAMBIQUE<sup>9</sup>

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## OBJECTIVES

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The overarching aim of this project was to develop initial analysis and mapping products to begin to build a framework for addressing agricultural risks from adverse weather and climate variability. A central goal was to identify crop risks from weather and map vulnerability.

The technical objectives were:

1. Map climate and agroclimate zones
2. Characterize crop suitability for major cash and food crops
3. Assess crop vulnerability to weather conditions
4. Carry out a field campaign to integrate calibration information

## METHODOLOGY

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The methodology is, in general terms, in agreement with the general steps described in chapter 6. The following tasks were performed: (1) mapped climatic and agro-climatic zones based on remote sensing and geographic methods, (2) compiled agronomic and bioclimate datasets for use with Geographic Information Science (GISc) and biogeochemical modeling to generate crop suitability indices, (3) modeled yields of major cash and food crops using climate scenarios to generate crop vulnerability indices and risk maps, and (4) carried out field validation and surveys and iteratively utilized feedback to improve the precision of the crop risk maps.

## COMPILATION OF LAND RESOURCES

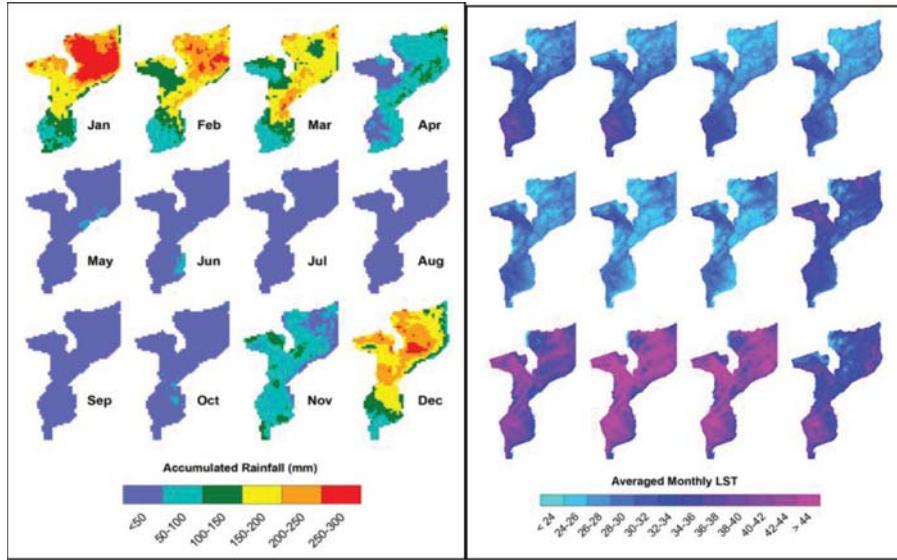
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Satellite-observed rainfall and temperature data were obtained and analyzed to map spatiotemporal trends and homogenous weather and agroclimate zones. Precipitation

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<sup>9</sup>This entire chapter is a summary from the following report: *Mozambique: Agriculture Weather Risk Mapping*, Final Report, World Bank Project # 7159460. Project PI: Nathan M. Torbick; World Bank POC: Carlos E. Arce.

**FIGURE 7.1. MONTHLY AVERAGE ACCUMULATED RAINFALL**



Left panel: Observed from TRMM and monthly average land surface temperature. Right panel: Observed from MODIS in Mozambique from 2002 to 2010. Generally, the remotely sensed climate products capture distinct seasons across Mozambique; a relatively wet and cooler season from November to April and a relatively dry and hot season from May to September.

data were derived from the Tropical Rainfall Measuring Mission (TRMM) and temperature data from MODIS MYD11C3. Both datasets were processed to generate gridded monthly averages at  $0.05^{\circ}$  ( $\sim 6$  km). Diverse climatological products were also developed: for example, monthly climatologies of precipitation and temperatures (figure 7.1), wettest and driest months, and hottest and coolest months.

Weather station data were received and quality controlled. Secondary quality control processing eliminated stations with more than 50 percent of missing data. This data was used to calibrate and validate the remote sensing data. The TRMM datasets were aggregated over time to reflect 10-year average annual precipitation and 10-year average seasonal precipitation (months DJF, MAM, JJA, SON). Station data sets were also aggregated. Coefficients of correlation between TRMM and stations ranged from 0.75 to 0.89. Regression modeling was completed to identify the best models for predicting average annual and average seasonal precipitation measurements (box 7.1). Independent variables that were considered included: elevation, aspect, slope, longitudinal convexity, maximum curvature, and remotely sensed TRMM precipitation and

MODIS LST at corresponding time periods (annual or seasonal 10-year averages). Slope and aspect data were combined to calculate the eastern and northern components of the unit normal vector for inclusion in the regression analysis following established guidelines (Hutchinson 1998). These components were calculated at multiple scales (see Digital Elevation Model derivatives, Chapter 3, page 11).

## ZONAL MAPPING

Zonal mapping relied on the available input parameters to delineate homogenous weather zones and agroclimate zones for Mozambique. A suite of zonal products was generated using climate and agricultural spatio-temporal information. Variables were primarily derived from the remotely sensed weather information (that is, TRMM PPT and MODIS LST), soils, and topographic modeling.

To integrate soils information into the zonal mapping and to parameterize the crop model, the Harmonized World Soil Database (FAO/IIASA/ISRIC/ISS/CAS/JRC 2009; see page 11) was utilized. Spatial soil information

## BOX 7.1. UNIVERSAL KRIGING (UK)

Overall  $R^2$  were relatively high, indicating that regression models using the remotely sensed TRMM data are able to represent a large portion of the variability observed in precipitation at station locations. Finally, universal kriging (UK) (interpolation methodology) of precipitation data was completed using the independent identified variables. The ability to predict station observations with the universal kriging was evaluated using root mean squared errors (RMSEs) and maps of significant error terms. UK provided the lowest RMSE for average annual precipitation over the 10-year time period. RMSEs for the seasonal data sets were lowest in comparison directly to the TRMM data and predictions obtained through UK. When using an “average annual” for modeling, UK has the optimal results for predicting station data. The MODIS LST data followed a similar calibration process. The maps of residuals for UK consistently identify fewer significant error terms than the maps for ordinary kriging, at least for station locations. However, both the ordinary kriging and UK do a poor job at capturing the spatial patterns observed by the remote sensing observation due to the sparsely populated coverage of the station locations.

was extracted and gridded to identical modeling units as the remotely sensed cells. Topographic information was obtained from the SRTM (see page 11). As input into the zonal mapping procedures, a suite of topographic indices (for example, slope, aspect, and so on) were generated that were scaled to the identical modeling units for further analyses.

A set of hierarchical zonal maps was generated to identify homogenous climate zones and identify agroclimate zones. The zonal mapping procedure used Principal Components Analysis (PCA; see page 24) as a method to reduce data dimensionality and extract unique maximum information. The summary procedures for the zonal mapping of homogenous climate zones were as follows:

1. Ran PCA for 10-year average annual, DJF, MAM, JJA, and SON climate variables with elevation derivatives
2. Identified five components for each. Component definitions varied by season

3. Ran K-means clustering algorithm on selected subset of components for annual and each season
4. Mapped cluster identifications for each

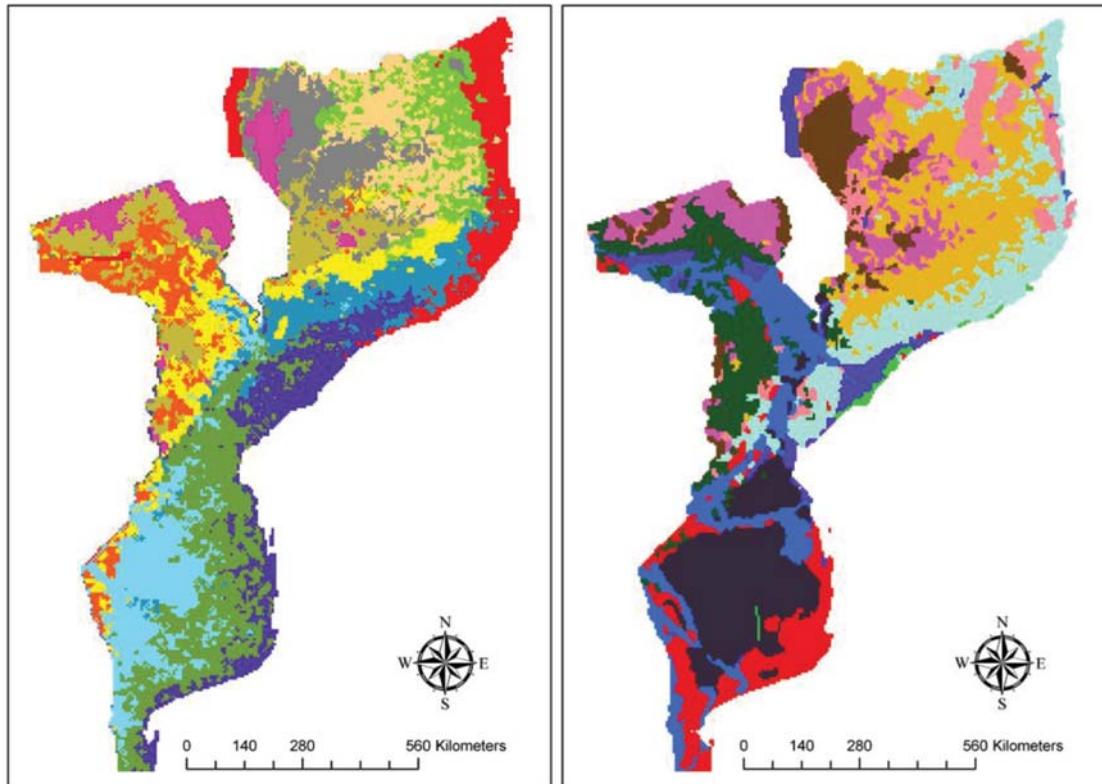
The summary procedures for the zonal mapping of homogenous agroclimate zones were as follows:

1. Ran PCA for soil variables only and identified three components
2. Ran PCA for climate and soil variables together, using only those soil variables that loaded with the three components identified above
3. Ran K-means clustering algorithm on two subsets of components: 1234 and 1245
4. Mapped cluster identifications for both

To smooth out the agro-climatic maps, a generalization scheme was run by applying a majority filter and small pixel grouping sieve filter.

The homogenous weather maps and the agroclimate maps have similarities and differences. The PCA analysis found that elevation, rainfall, location, and temperature were the most statistically important variables used to determine the homogenous weather regions by explaining 35 percent, 23 percent, 12 percent, and 11 percent of the variation in the component loadings. The PCA factors across seasons were similar except for LST becoming more influential in the drier periods (although elevation was always the predominant factor). As expected, the elevation gradients can be seen in both the weather and agroclimate zonal map products, which was shown in the PCA results to be a driver of zones. Soil composition, soil moisture attributes, and soil conductivity/mobility were the major component loadings for the soil dataset. The drier seasonal climate has some influence on the agroclimate zonal maps as seen by the representation of southern features in Gaza and Inhambane relative to the weather zonal map with a stronger coastal factor present likely influenced by the Inter Tropical Convergence Zone and Indian Ocean temperatures. The final zonal map products were smoothed using a generalization majority filter. The maps were generated in a hierarchical fashion with 375 individual zones and 11 major agroclimate clusters that are statistically unique (figure 7.2). To simplify and provide general details, short, interpretive titles are provided in table 7.1.

**FIGURE 7.2. FINAL MAP PRODUCT**



(Left panel) For homogenous weather zones for Mozambique utilizing 10 year monthly average satellite remote sensing weather inputs and geostatistical methodologies. Final map product illustrated for agro-climate clusters map product (right panel) were designed in a hierarchical (scaled) approach with 375 individual zones and eleven major agro-climate clusters that are statistically unique.

## ASSESS LAND SUITABILITY

A process-based agricultural productivity model was utilized to generate crop yield distributions and develop crop suitability index maps. In preparation for quantitative analyses of crop susceptibility to climate variability and drought, crop suitability was modeled across Mozambique using the Denitrification-Decomposition agro-ecological model (DNDC; see page 13). Suitability was modeled and mapped for all major crops including: beans, cassava, cotton, groundnut, maize, millet, potato, paddy rice, rain-fed rice, sorghum, and tobacco.

A Crop Suitability Index (CSI) for Mozambique was developed by using DNDC to understand agricultural risks due to weather fluctuations and climate change. It was achieved by modeling crop suitability

by agroclimate zone and scaled up to the cluster within Mozambique via DNDC crop yield modeling results. To answer the question “how well does this crop perform, on average, within this zone and within this cluster?” for each crop of concern it assumed a wall-to-wall distribution of crops in that respective modeling unit and ran DNDC using 2010 climate data. Then DNDC was performed in two modes: one using conventional fertilization (that is, best information on actual fertilizer N applications) and one using “optimal” fertilization (that is, fertilizer N is applied whenever soil N falls below crop demand). The first mode addresses the likely situation that crops are farmed using standard N inputs (which are typically low in Mozambique). The second mode sidesteps the vexing question of whether suitability is actually related to underlying geography or low N inputs, and facilitates

**TABLE 7.1. MAJOR AGRO-CLIMATE CLUSTER NAMES IDENTIFIED FROM BIOCLIMATIC AND AGRICULTURAL FACTORS**

Cluster #	Descriptive Name
1	Dry hot semiarid southern lowlands
2	<b>Tropical central coast with dry periods</b>
3	Dry seasonally hot southlands
4	<b>Semi-tropical wet season with dry periods</b>
5	Tropical wet coastal and wet north-central lowlands
6	<b>Northern mid-elevations with cooler rain season</b>
7	West-central mid-elevation with cooler wet sea son
8	<b>Seasonal valley regions</b>
9	Semi-tropical wet highlands
10	<b>Northern moist cool season</b>
11	High elevation with cooler tropical wet

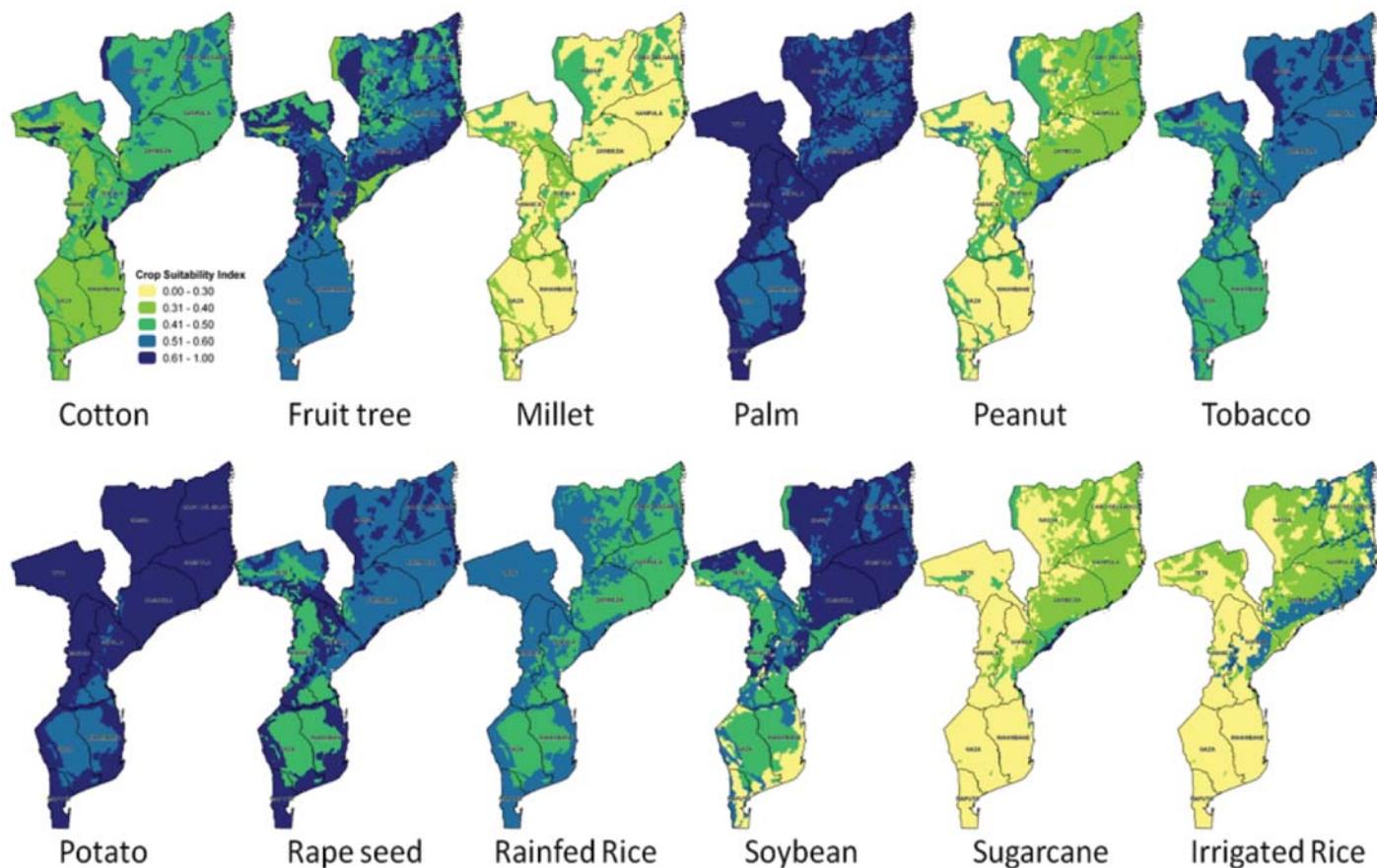
interpretation of other important variables (for example, soil texture or annual precipitation).

The cropping calendar was based on expert knowledge and FAO Crop Calendar input (<http://www.fao.org/agriculture/seed/cropcalendar/>). For soil inputs, the Harmonized World Soils Database was applied. For each unit in the modeling scheme, the area-weighted mean value was calculated for four soil attributes: clay fraction (percent of weight, a proxy for soil texture), bulk density (g/cm<sup>3</sup>), pH, and organic matter content (percent of weight). Nitrogen deposition data were based on the values in the original DNDC embedded grid. For 2010 climate data we relied on daily meteorological data (maximum and minimum temperature in °C and precipitation in cm) derived from the NASA Modern Era Retrospective-Analysis for Research and Applications dataset (MERRA; see page 10) to drive daily climate input requirements. MERRA reanalysis is considered among the best and most current multidimensional climate data available. MERRA was qualitatively assessed using the TRMM and LST products and was found to be satisfactory and acceptable for this analysis.

**TABLE 7.2. DNDC CROP MODEL INPUT PARAMETERIZATION FOR GENERATING CROP SUITABILITY INDEX**

Input Parameters	Output Parameters
Climate – Daily max and min air temperature – Precipitation – Solar radiation – Atmospheric N deposition	Crop Scheme – Photosynthesis – Respiration – Water demand and transpiration – N demands/uptake
Soil – Bulk density – Texture (clay fraction) – Organic C content	Soil – C allocation – Yield and litter production – Temperature profile – Moisture profile
Human Activities or Managements – pH – Tillage – Irrigation – Runoff/Fertilization – Manure amendment – Grass cutting	– pH profile – Eh profile – Evaporation – Water leaching and runoff – SOC dynamics – N leaching – Emissions of N <sub>2</sub> O, NO, N <sub>2</sub> , NH <sub>3</sub> , CH <sub>4</sub> and CO <sub>2</sub>

**FIGURE 7.3. CROP SUITABILITY INDEX FOR SELECTED FOOD AND CASH CROPS WITH CONVENTIONAL FERTILIZATION SHOWN AND 2010 WEATHER DRIVERS**



Millet and sugarcane tend to have relatively moderate to low suitability. Peanut, sugarcane, and irrigated rice have clusters in the north with higher suitability.

To express the results of this analysis, a simple index was used to indicate how well a crop grows relative to “best” yield within Mozambique:

$$\text{yield}_{\text{cluster}} / \text{high yield}$$

where “high yield” is the 95th percentile of yield within Mozambique.

Maps of crop suitability index were developed for all crops and with conventional and optimal fertilization. Figure 7.3 shows some of the suitability maps.

The selected suitability maps by top areal crop coverage show ranging crop suitability based on crop type and agro-climate clusters. The suitability indices provide a powerful tool to compare across crop types, management practices, and geography. In general, CSI is higher in the northern

and coastal properties. This pattern is highlighted in the figure for beans and cassava. These suitability maps generally agree with actual production and mean yields across Nampula and Zembezi, and portions of Cabo Delgado, Niassa, and Tete. Beans tend to have a smaller range of suitability as indicated by the CSI maps when compared to cassava with similar high suitability regions but lower CSI in the south and coastal areas of Inhambane and Maputo. The increase in drought tolerant varieties of beans has improved the suitability of beans across Mozambique.

The CSI readings for maize and sorghum have very similar suitability based on the DNDC simulations with 2010 data inputs. The highest suitability categories tend to occur in patchy locations primarily in the central and northern regions of Mozambique. These maize patterns generally match agricultural census information for Mozambique. There is a notable increase in suitability in the north and

coastal regions with optimized fertilizations methods, with the south remaining less suited for maize.

It is worth noting that the crop suitability index is not production-based and does not imply that a location with “more optimal” or “higher” suitability delineates a location where high yields will automatically occur nor zones where high yields do occur in reality. Rather, this is a normalized map showing the relative mean difference from a highly suitable growing possibility (“higher”) and the relative mean difference for a given crop at a given location. “Other factors” (that is, road networks, distance to market, conflicts, market price, inflation, management, adaptations, fertilizers, and technology) will influence cropping suitability decisions and ultimate suitability. In Mozambique most farmers do not achieve optimal yields due to a variety of factors (AFTS 2006; Coughlin 2006; INGC 2009; Loening and Perumalpillai-Essex 2005; PEDSA 2010). The crop suitability map that was generated is a relative quantitative index to provide guidance on relative yields based on agroclimate conditions with all “other factors” being equal.

## CROP VULNERABILITY

Crop vulnerability and risk to weather was assessed at the agroclimate zone scale in Mozambique using yield from the crop model. Other vulnerabilities were also run and stored in a GIS. Three strategic scenarios were simulated

**TABLE 7.3. CLIMATE SCENARIOS FOR CROP VULNERABILITY ASSESSMENT**

Scenario	Annual Temperature (°C)	Annual Precipitation
Baseline	no change	no change
1	+1	-5%
2	+2.5	-10%
3	+5	-15%

based on generally accepted climate projections from dynamic and downscaled models, the geostatistical relationships constructed in this project between temperature and precipitation, and historical and current trends in Mozambique and the region. This approach integrates the strengths of models, expert knowledge, and current findings. See table 7.3 for the scenarios.

The crop model was run in both conventional and optimized fertilization (where fertilizer N is applied when available soil N drops below crop demand) modes. To express the results of this analysis we created a simple vulnerability index which indicates each crop’s performance relative to the 2010 baseline within each agroclimate cluster (see table 7.4):

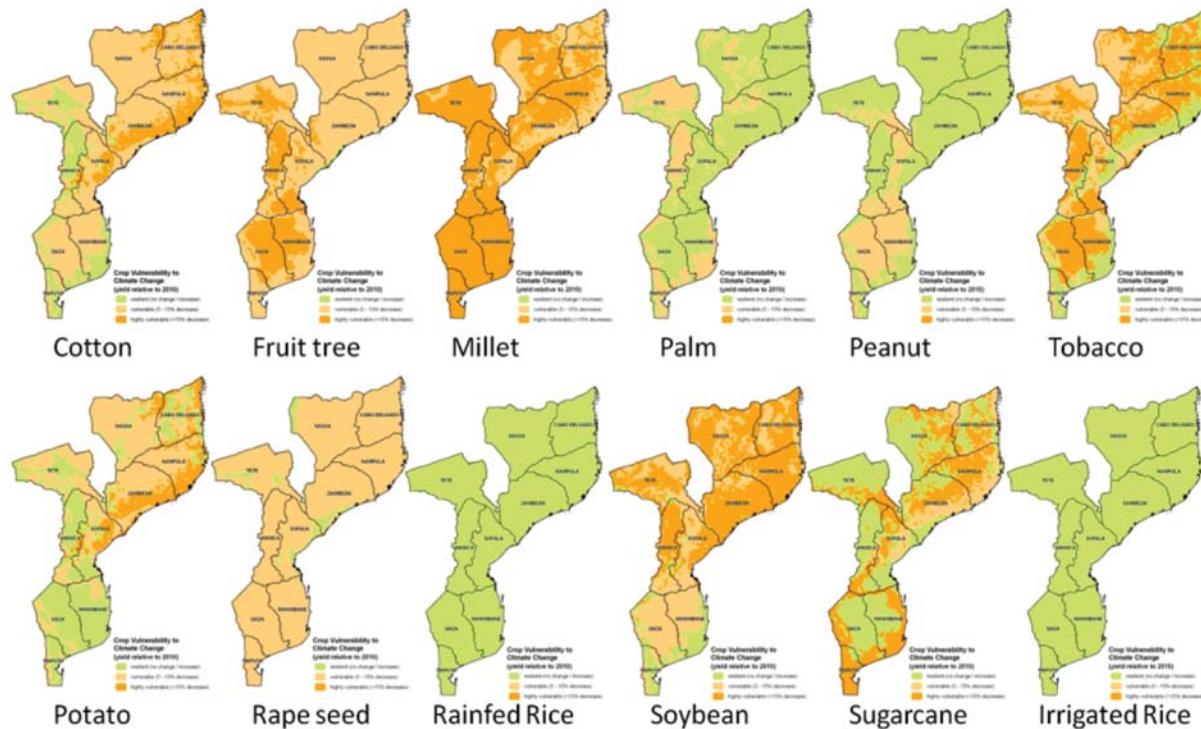
$$100 \times \text{mean rate}_{ij} / \text{mean baseline rate}$$

where i is the climate scenario and j is the fertilization mode.

**TABLE 7.4. VULNERABILITY OF ALL CROPS TO CLIMATE CHANGE BY AGRO-CLIMATIC CLUSTER (REGION OR ZONE)**

	Conventional Fertilization				Optimal Fertilization			
	2010 Climate	+1°/ -5%ppt	+2.5°C/ -10%ppt	+5°C/ -15%ppt	2010 Climate	+1°/ -5%ppt	+2.5°C/ -10%ppt	+5°C/ -5%ppt
Cluster 1	100%	84%	84%	93%	100%	82%	84%	105%
Cluster 2	100%	92%	90%	84%	100%	92%	91%	92%
Cluster 4	100%	98%	94%	91%	100%	97%	88%	78%
Cluster 5	100%	96%	90%	85%	100%	97%	93%	91%
Cluster 6	100%	96%	89%	83%	100%	90%	79%	71%
Cluster 7	100%	107%	104%	100%	100%	105%	97%	92%
Cluster 8	100%	128%	127%	135%	100%	122%	125%	134%
Cluster 9	100%	100%	93%	83%	100%	103%	93%	86%
Cluster 10	100%	107%	135%	160%	100%	105%	131%	159%
Cluster 11	100%	99%	89%	82%	100%	100%	92%	86%
Cluster 12	100%	97%	106%	98%	100%	98%	112%	107%

**FIGURE 7.4. CROP VULNERABILITY INDEX (CVI) FOR SELECTED FOOD AND CASH CROPS WITH CONVENTIONAL FERTILIZATION AND CLIMATE SCENARIO 2 SHOWN COMPARED TO 2010 WEATHER DRIVERS AND YIELD BASELINES**



Millet, tobacco, soybean, sugarcane, and fruit tree have the largest area of increase in relatively higher vulnerability. Climate Scenario 2 = +2.5 degrees Celsius and -10% total PPT.

The vulnerability maps indicate that, in general, clusters in the south-central region of Mozambique and covering large regions of Gaza and Inhambane are highly vulnerable, with 15–30 percent reductions in yield compared to baselines. In the most extreme scenario, these same clusters show less vulnerability due to the complexity of the processes that are occurring. In addition, these areas have a relatively small amount of crop area and not much absolute change (although there was some relative change), thereby causing an artifact in the map result (figure 7.4).

With an increase of 2.5°C in temperature, a reduction of 10 percent in total rainfall, and using conventional fertilization, the agroclimate zones along the coast and central Mozambique have a decrease of 5 percent to 15 percent in yield compared to baseline yields and therefore become vulnerable. This represents a large sector of the agricultural industry in Mozambique. In the optimized fertilization scenarios, the coastal agroclimate clusters and south-central clusters become highly vulnerable, with an

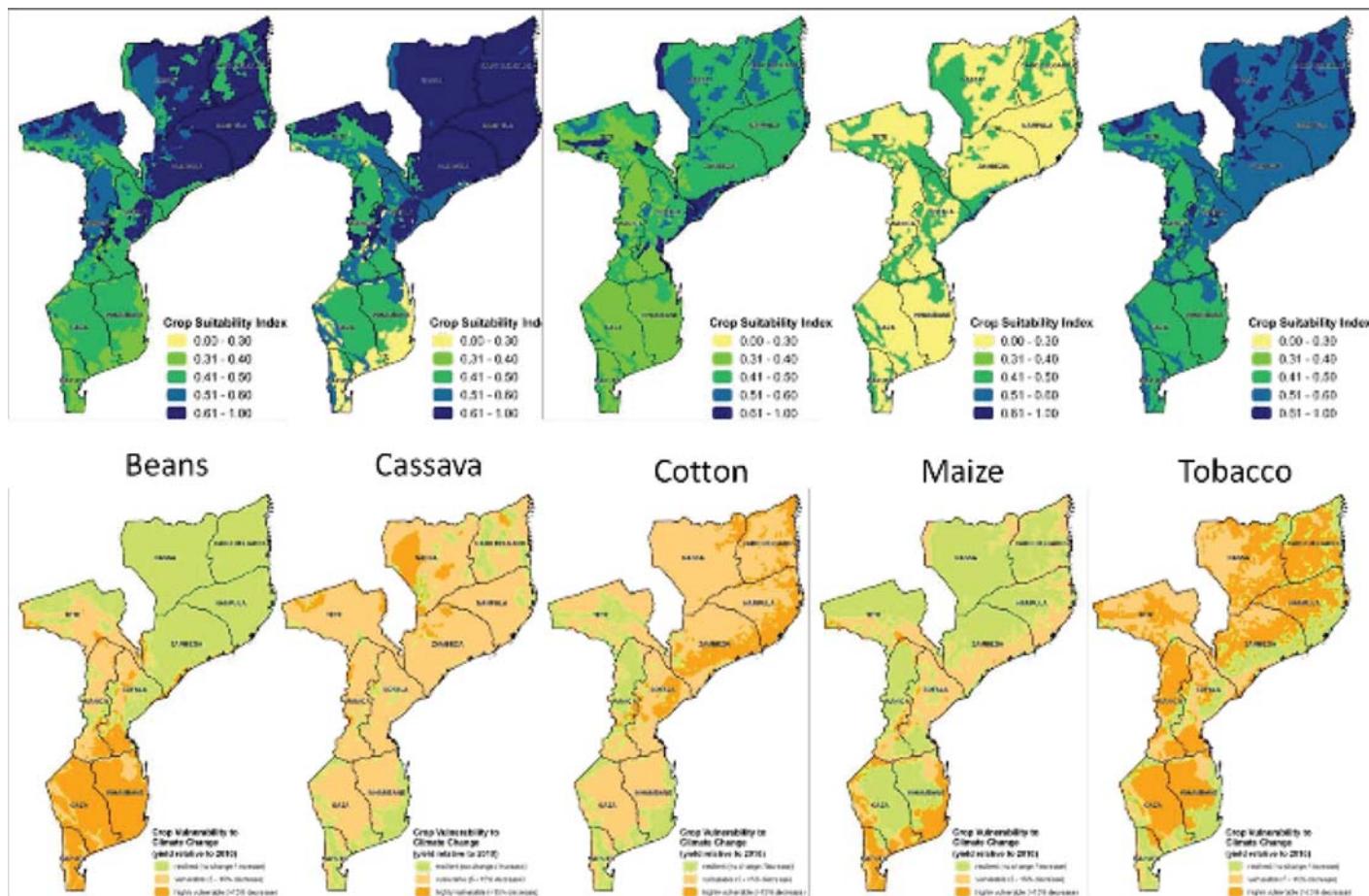
increase of 2.5°C and a 10 percent reduction in precipitation compared to the 2010 baseline. This does not imply that the optimized yields are lower than the conventional yields for the same climate scenario; rather, that yields are lower compared to the relative baseline and in fact the highly vulnerable optimized fertilizations yields are typically higher than the conventional fertilizations yields for the same zone (figures 7.5 and 7.6).

## ADDITIONAL EXAMPLES OF AGRO-ECOLOGICAL ZONING

### AGRO-ECOLOGICAL ZONES, BANGLADESH

The most important factors in the definition of agro-ecological zoning in Bangladesh are: physiography, soils, and land level in relation to flooding. Floods represented a particular challenge, so they played an important part of the regionalization. Flood levels were categorized as follows: (1) highlands (land normally above flood level

**FIGURE 7.5.** CVI (BOTTOM) FOR CLIMATE SCENARIO 2 AND CSI (TOP) UNDER CONVENTIONAL FERTILIZER FOR KEY CROPS IN MOZAMBIQUE COMPARED TO 2010 WEATHER DRIVERS AND YIELD BASELINES



Spatial comparisons show relatively high suitability cotton clusters become highly vulnerable. Tobacco tends to have substantial area to become highly vulnerable throughout Mozambique. Climate Scenario 2 = +2.5 degrees C and -10 Percent Total PPT.

during the flood season), (2) medium highland (land normally flooded up to 90 cm), (3) medium lowland (land normally flooded between 90–180 cm), (4) lowland (land normally flooded between 180–300 cm), and (5) very lowland (land normally flooded deeper than 300 cm during the flood season) and bottomland (sites that remain wet throughout the year).

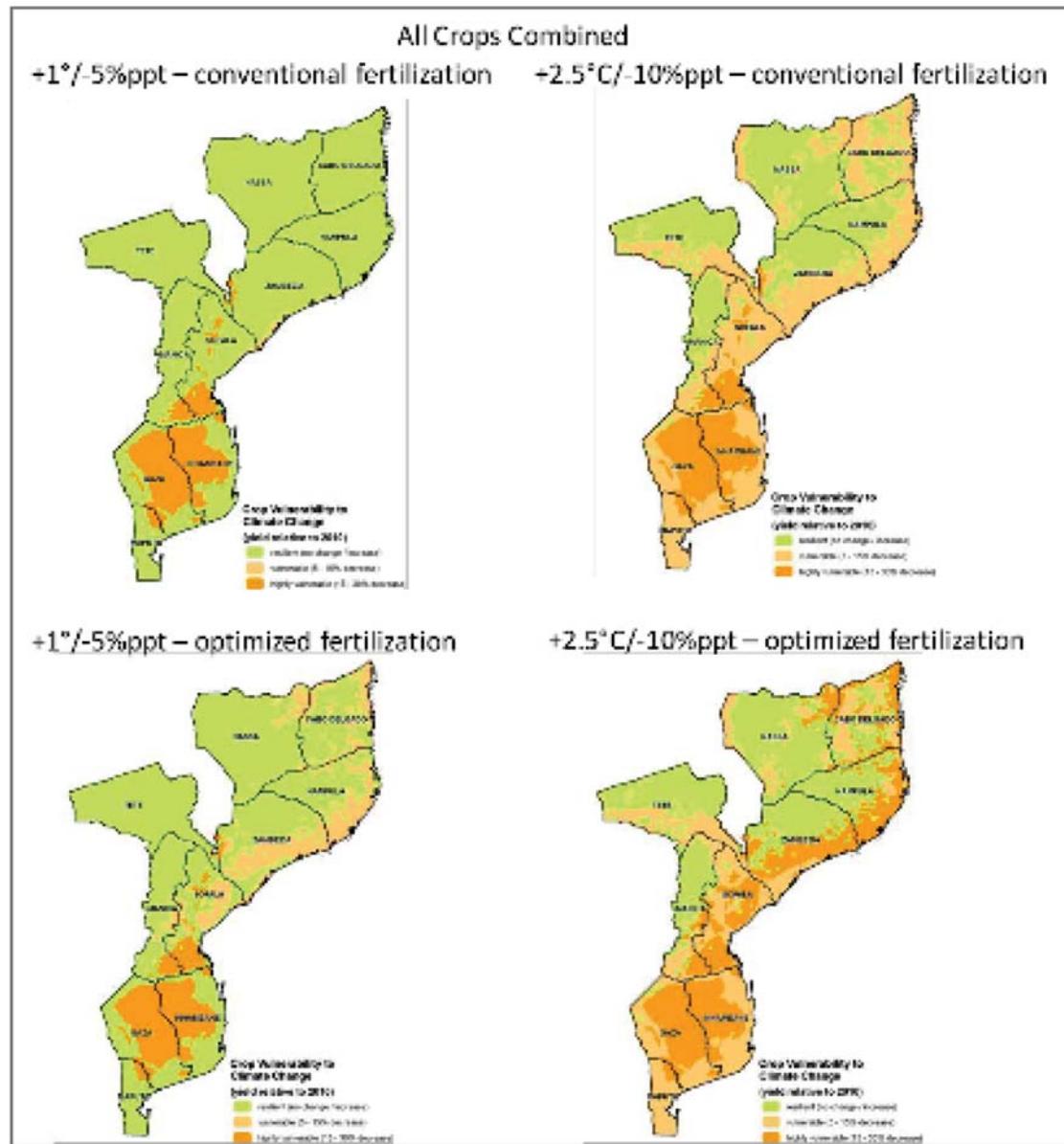
Highland, for example, is considered appropriate for perennial dryland crops if the soils are permeable. Impermeable soils may be suitable for transplanted varieties of rice if bunds retain precipitation on the fields. The analysis identified 30 agro-ecological zones (figure 7.7), which are subdivided into 88 agro-ecological subregions, which have been further subdivided into 535 agro-ecological units. Agroecological zoning is used extensively for planning

purposes, technology transfer, and specific bio-physical resource utilization activities. More information available at: [http://www.banglapedia.org/HT/A\\_0083.htm](http://www.banglapedia.org/HT/A_0083.htm).

#### AGROECOLOGICAL ZONING IN THE ILAVE-HUENQUE WATERSHED OF THE ANDEAN HIGH PLATEAU

This regionalization had the challenge of addressing a mountainous area, requiring a high density of meteorological stations to capture the spatial variability. In this particular case, the analysis relied on several satellite sources of information (Geostationary Satellite System, Landsat TM, and NOAA/Advanced Very High Resolution Radiometer [AVHRR]). Four agro-ecological zones resulted: (1) aptitude for crop and pasture, (2) livestock

**FIGURE 7.6.** ALL CROPS COMBINED FOR THE SCENARIO 1 (LEFT) AND 2 (RIGHT) ARE HIGHLIGHTED FOR CONVENTIONAL (TOP) AND OPTIMIZED (BOTTOM) CVI

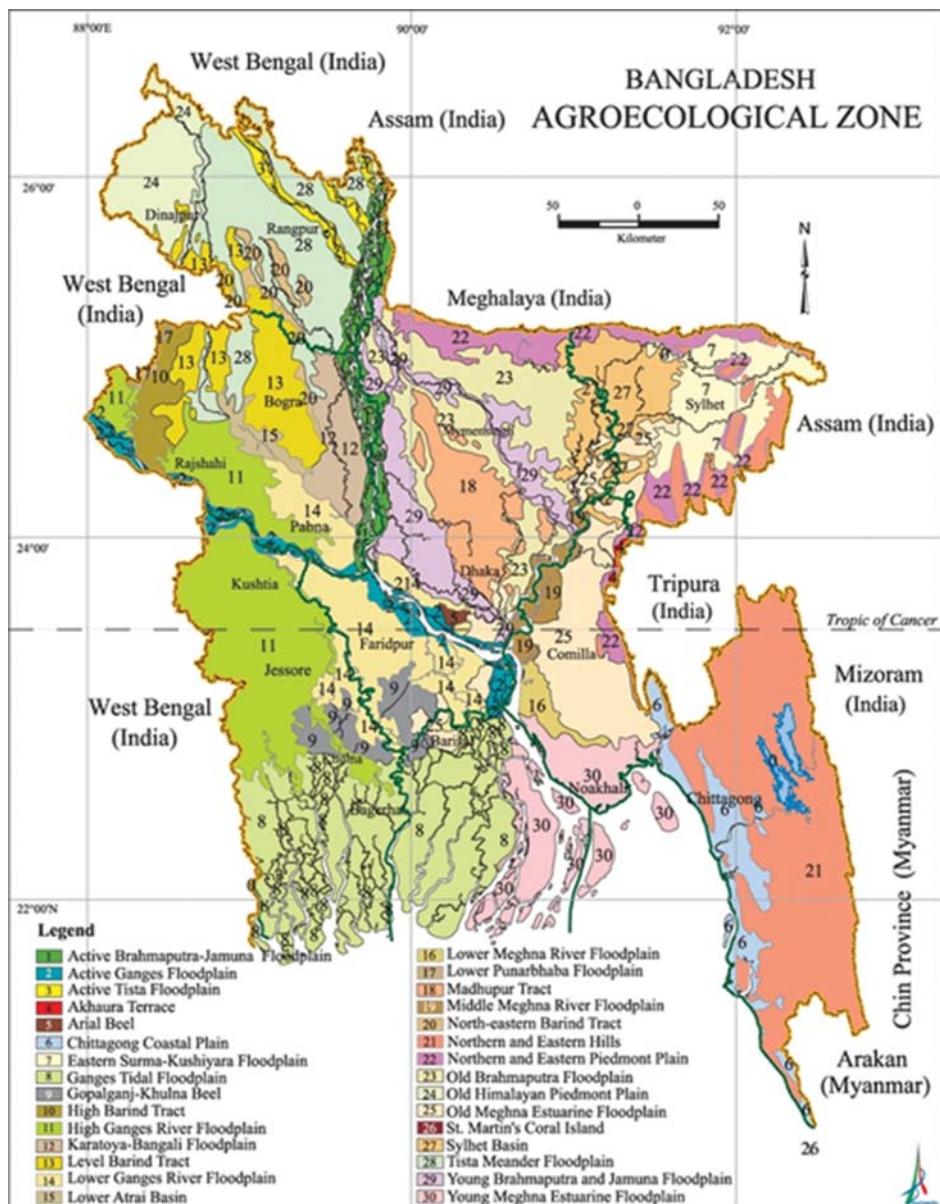


In general, clusters in the south and coastal regions are most susceptible to becoming highly vulnerable with warming temperatures and decreases in rainfall.

with potential increase, (3) extensive livestock production, and (4) barren land and areas under grazing with very shallow soils (figure 7.8). For the first zone, crop simulations suggest that productivity can be significantly increased with the help of technology. For example, rain-fed potato production could be increased from 5–12t/ha to 18t/ha with irrigation. Suggestions for zone two

include, for example: substituting bofedales for alpaca; using sheep as a flexible alternative; increasing productivity through good quality pasture (alfalfa, ryegrass and white clover), which could feasibly generate increases of 40–50 percent in gross income. The study assessed several alternatives to improve the management of natural resources. The involvement of local experts in the analysis

**FIGURE 7.7. AEZs OF BANGLADESH**



Source: Banglapedia.

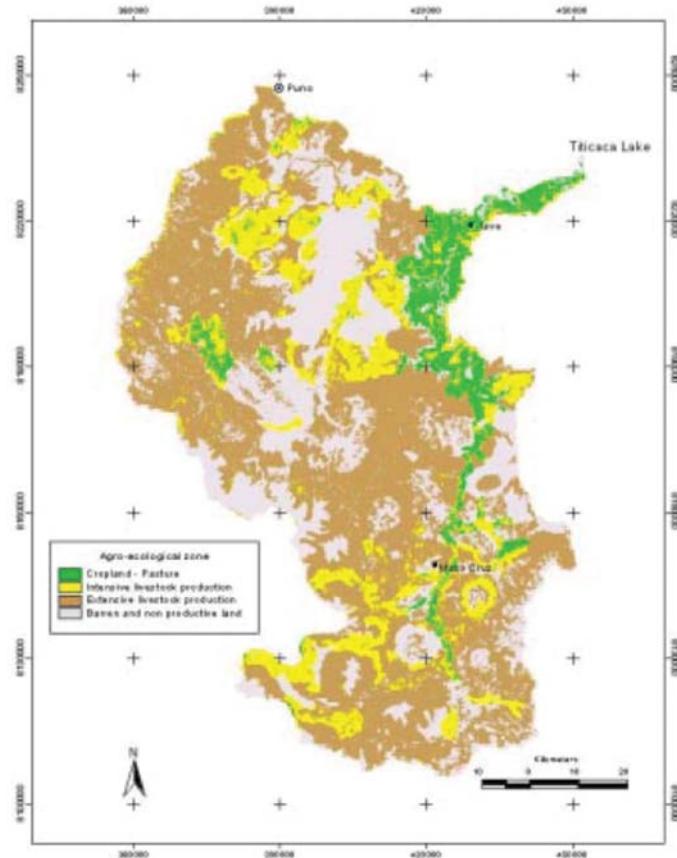
should improve the chances that these suggestions will be finally implemented. More information available at: <http://inrm.cip.cgiar.org/home/publicat/01cpb028.pdf>.

### AGRO-ECOLOGICAL ZONES, THEIR SOIL RESOURCE, AND CROPPING SYSTEMS—INDIA

The objectives were to (1) assess yield potentials of different crops and combinations; (2) plan crop diversification; (3) plan research and technological dissemination; and

(4) determine crop suitability for optimization of land use. The methodology was based on four basic maps: soil, physiography, LGP, and bioclimate. The country is grouped in 20 agro-ecological regions (figure 7.9) and 60 agro-ecological sub-regions. Constraints and potentials were described for each region. Cropping systems were planned to minimize deterioration of land quality (soil physical conditions, nutrient availability, and organic carbon pool). More information available at <http://agricoop.nic.in/Farm%20Mech.%20PDF/05024-01.pdf>.

**FIGURE 7.8. AEZs OF ILAVE-HUENQUE WATERSHED**



Source: CGIAR.

**FIGURE 7.9. AEZs OF INDIA**



Source: National Bureau of Soil Survey and Land Use Planning, Government of India.

# CHAPTER EIGHT

## CONCLUSIONS



As stated at the introduction to this document, agro-ecological zoning and, consequently, weather risk mapping are becoming increasingly useful techniques in the design of agricultural risk management strategies, and in guiding informed investment decisions. However, the proliferation of different applications and the attendant degree of sophistication are making it increasingly difficult for development practitioners to keep abreast of current developments. This overview of agriculture risk mapping techniques aims to serve as an illustrative introduction of the current state of knowledge and practice.

There are an increasing number of approaches and models to design risk mappings in agriculture. These are becoming rather complex, given the challenges in modeling the behavior of living plants as they are submitted to various weather conditions. Success in achieving accurate results largely depends on the quality of the data used, the predicting ability of the models, and the chosen time horizon. Scientists and organizations are undertaking serious efforts to improve the predictability of the applications, hopefully leading to a rapid evolution of such applications in the near future.

This document offers a deliberately circumscribed illustration of the various methods that are available, as well as the sources of data that can be used with some degree of confidence, and those products that are highly valuable for the purposes they were designed to serve. The picture that emerges is by no means exhaustive, but hopefully it captures the array of applications in the agricultural sector.

The authors hope that this document will help those development practitioners interested in this subject become familiar with the technical aspects involved in the design of these products, and their potential practical uses.



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## APPENDIX A

# EXAMPLE OF TERMS OF REFERENCE FOR AGRO-ECOLOGICAL ZONES

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## INTRODUCTION

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These terms of reference detail the objectives, scope of work, and products for hiring a consulting firm (the Firm) to conduct a risk mapping assessment of the agricultural sector. The findings of the tasks detailed here will serve as inputs for the Government of Mozambique (GOM) for the structuring of a risk management strategy to protect small farmers. Findings of this exercise will also be used by the donor community to identify possible areas of development investment opportunities to promote agricultural productivity.

## BACKGROUND AND OBJECTIVE

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The Agricultural Risk Management Team (ARMT) of the Agriculture and Rural Development Department (ARD) of the World Bank has agreed with the Ministry of Agriculture (MOA) of Mozambique to provide technical assistance in various aspects related to agriculture risk management. The technical assistance that the World Bank is planning to provide to the MOA needs to serve as the basis for the government and private sectors to identify and put in place measures to start managing agricultural risks in a more informed manner and under an agreed framework.

The Agricultural Census 2008 (TIA 2008) shows that farmers face production risks related to floods, droughts, cyclones, and wild animals, and it provides some dimension of importance for various agricultural regions. It does not, however, delve into the details to specify those risks by crops. A recent risk assessment on the cotton supply chain also revealed that pest and diseases are important risks facing smallholder farming in the country. Despite the recognized importance of identified production risks, preliminary discussions with various stakeholders in the agricultural sector revealed that there is hardly any technical analysis done in risk identification and risk exposure in agriculture, nor any systematic attempt at quantifying the losses produced by the occurrences of those risks. This situation makes it difficult for the authorities and even the private sector to begin introducing appropriate risk management practices.

Whenever an adverse catastrophic event has taken place in the past, the MOA has relied on an ad-hoc system to collect financing from Ministry of Finance and donors to make available a pool of resources to deliver support to affected farmers. The MOA is therefore much interested in identifying and designing a risk management framework that will allow the public sector to implement risk management measures in a more planned manner and in partnership with the private sector to start managing identified agricultural risks.

The World Bank seeks to hire a firm that will undertake a risk mapping assessment of the agricultural sector in Mozambique with the objective to aid policy makers and planners to identify the key crops and exposures to loss and which might be selected for designing a national agricultural risk management strategy and for future pilot crop insurance programs.

## SCOPE OF WORK/ACTIVITIES

The Firm will conduct a risk assessment mapping of production risks for major cash and food crops at the district level, taking into account the 10 agro-ecological zones used by the MOA. The assessment will provide spatially referenced information on production systems, production hazards, location of agricultural assets (crops), and farmers' characteristics. The highest spatial and temporal resolution (that is, the lowest possible level of aggregation) permitted by the availability and quality of data will be used for the hazard mapping. In order to proceed with the required assignment, the Firm will undertake the following key activities:

### COMPONENT 1: MAPPING HOMOGENOUS WEATHER ZONES

The Firm will analyze meteorological time-series, particularly rainfall and temperature, in order to propose relevant homogenous weather zones for agricultural production in Mozambique. The classification of the homogeneous weather zones should be based on agronomic criteria. To conduct this activity, the Firm will also need to conduct the following activities:

- » Acquire long-term historical rainfall and temperature databases (minimum of 20 years).
- » Perform quality control to the database.

- » Define agronomic thresholds to classify Mozambique into agricultural homogenous weather zones.
- » Define homogenous weather zones.

### COMPONENT 2: CROP SUITABILITY

The Firm will define and classify crop suitability zones for major crops (cash crops and food crops). The result of this component is a suitability map that will identify optimal agricultural investments. The Firm will provide estimates of potential productivity for each land unit. This component involves but is not limited to the following activities:

- » Collect and analyze the following information: soil types; bioclimatic and soil requirements; water requirements indices (WRSI); topography; and marginal and optimal conditions.
- » Define suitability zones for crops based on the previous information.
- » Implement information, results, and degrees of suitability for each crop in a (Geographic Information System (GIS).

Identify areas for optimum productivity for food and cash crops based on bioclimatic (that is, altitude, average temperature, average rainfall, rainfall seasonality, others), soil (that is, effective soil depth, soil texture, slope), and water availability. This activity should be based on the following information: soil, topography, climate, and productivity of crops.

### COMPONENT 3: WEATHER VULNERABILITY ANALYSIS AND MAPPING

A vulnerability map will be defined based on the comparison of suitability zones with actual land use. For the conduction of this exercise, the Firm will need to:

- » Analyze actual land use and land cover data.
- » Contrast actual land use with suitability zones.
- » Define vulnerability zones per crop.
- » Propose and apply a methodology to estimate variations in relation to the average historical yield.
- » Quantify the areas exposed, number of producers per crop exposed, and value at risk per crop season.

After the completion of this exercise, the use of GIS must be used to present the results.

## COMPONENT 4: FIELD VALIDATION

The objective for this component is to validate findings by obtaining feedback with samples of producers in various parts of Mozambique. Some of the activities that may be carried out by the Firm include the following:

- » Conduct interviews and focus groups with farmers and local experts to identify climatic hazards, growing periods, crops' potential productivity, crops' best and worst yields, crops' production systems, and production areas.
- » Identify those food and cash crops that are most suitable to produce on each homogeneous zone. Adjusted crop yield values are expected to be estimated by the Firm as well as yield variation due to changes on optimal agro-climatic conditions (that is, unreliability of rainfall).

## DATA FORMATS AND REQUIREMENTS

All data products are required to have detailed metadata following the World Bank's metadata standards (ISO 19115 metadata standard).

All spatial data formats shall comply with the Open Geospatial Consortium standards. It is strongly preferred that the vector data be delivered as shape files with associated OpenGIS® Styled Layer Descriptor (SLD) and the Raster data be delivered in the GeoTiff format. All data should be geo referenced and projected in WGS 84 UTM zones.

All databases and catalogues shall be delivered as either Excel 2007 files or Post GIS databases where appropriate.

All data shall be delivered on hard disk to the World Bank in a format that will allow their transfer to the Government of Mozambique.

The findings will be presented in a single document that contains the following structure:

Contents

Executive Summary

Chapter 1. Introduction

Chapter 2. Methodology

Chapter 3. Weather Homogenous Zoning

Chapter 4. Crop Suitability Mapping

Chapter 5. Vulnerability

Chapter 6. Conclusions

## PRODUCTS/DELIVERABLES

The deliverables from this contract are:

- » A methodology and work plan for organizing the weather risk analysis to accomplish the objectives based on the key components described (15 days after contract signature). The Firm is expected to present the methodology and technical details related to the agrometeorological zoning.
- » An Intermediate Report including the zoning of weather homogenous areas and crop suitability mapping (3 months after contract signature).
- » A Final Report, at the satisfaction of the World Bank (5 months after contract signature).

## TIMESCALE AND COSTS/BUDGET

The Firm will conduct the activities for this assignment in a period of 5 months counted from contract signature. The contract costs will be decided after submission of a technical and financial proposal to the World Bank.

## RESPONSIBILITY AND CONTRACT PAYMENTS

Marc Sadler, Leader of the ARMT, will be responsible on behalf of the World Bank for managing and supervising this contract.

The World Bank will schedule three payments for delivery of the products in the following manner:

1. 20 percent at the delivery of a work plan agreed with the World Bank
2. 50 percent at the delivery of the Draft Report in reference to 4.3 above, at the satisfaction of the World Bank
3. 30 percent at the delivery of the Final Report in reference to 4.4 above, at the satisfaction of the World Bank

## FIRM QUALIFICATION

The World Bank seeks to contract a Firm that has the following qualities:

- » Proven experience to conduct agriculture production analysis in East and Southern African region, preferably Mozambique

- » Capacity and experience in using GIS techniques for analyzing agriculture/rural-related activities
- » Capacity to conduct risk analysis to estimate value-at-risk and expected losses, as used by the insurance industry

## APPENDIX B

# EXAMPLE OF TERMS OF REFERENCE FOR GRIDDED ANALYSES OF METEOROLOGICAL VARIABLES

## BACKGROUND AND DESCRIPTION OF THE CONSULTANCY

Guided by their technical experience the Consultant must (1) assess the feasibility and (2) create a gridded (that is, mesh-based) product of rainfall, maximum and minimum temperature, potential evapotranspiration (Hargreaves), and relative humidity in Nicaragua that could be used by the local insurance industry there to develop an index-based weather insurance market for agriculture.

The objective of such a product would be to enable better risk mapping and greater access to risk transfer products in areas with inadequate weather infrastructure. The Consultant should assess the feasibility of creating the data grid to address these specific needs, outlining the steps that would be required to produce such a product if considered feasible. The methodology to assess this feasibility and ultimately to create such a product should be based, but not limited to, the methodology already used to develop a gridded climatological database for index-based insurance purposes in Mexico (Cressman 1959).

The consultant will assess the feasibility of creating gridded weather data products in Nicaragua (a feasibility study has already been developed for Guatemala and Honduras) based on a blend of existing station data and existing gridded data products (for example, NARR, NOAA's Climate Prediction Centre datasets, the NCEP/NCAR Reanalysis) to support the weather station-based data observations, and on the performance of a quality control process to weather datasets. The Consultant must describe the steps that would be required to perform a quality control process and to identify valid records for Nicaragua weather datasets. The methodology to be applied for the detection of discrepancies on climate datasets and a consistent weather datasets, based

on valid records should be structured, described and provided. The methodology will allow the elimination of outliers, climatic inconsistencies, negative precipitation and minimum temperature greater than maximum temperature based on technical and subjective considerations of the expert.

The World Bank (The Bank) will provide the Consultant with an inventory of weather stations and station data in the countries and any other information that is required by the Firm to complete the feasibility study.

The minimum information for the study includes:

- » Station Catalogue: Station ID, latitude and longitude of the stations
- » Dataset: ID, date and readings of precipitation, maximum and minimum temperatures and, if feasible, any available readings of relative humidity

## DELIVERABLES AND WORK DAYS

The deliverables of the study are the following:

i. A (1) report that:

- a. Describes the procedure followed by the Consultant to conduct the process of data quality control and identification of valid records in Nicaragua for rainfall, temperature (minimum and maximum temperature). Examples to support the consultant's findings will be required.

The estimation of the percentage of valid records for individual stations should be delivered in a shapefile, geo referenced and projected to WGS 84. A database with the valid records should be structured, described, and delivered in text format.

- b. Summarizes the feasibility of creating gridded analysis (precipitation, maximum and minimum temperatures, and evapotranspiration) suitable for weather risk index insurance development. Evidence and explanation to support this conclusion will be required. If deemed feasible, the methodology to be used to construct the gridded product and its characteristics should be outlined. If deemed infeasible, suggestions on how the spatial coverage of weather information in Nicaragua could be improved,

and what investments could be made to do so, is requested. Deliverable should be submitted in Spanish.

The characteristics of the gridded product to be defined include:

- » Interpolation methodology and technical details
- » Temporal resolution
- » Spatial resolution, which is determined based on the spatial distribution of the meteorological stations
- » Geographic domain
- » Initial and Final date

Under these Terms of Reference (ToR), the consultancy related to the First Stage is expected to require \_\_\_\_ consultant-days.

- ii. In case the gridded product is determined to be feasible, the second step will consist of creating the product for Nicaragua. It will be attempted to reproduce Cressman Modified methodology (1959) using NARR observations in the generation of their gridded dataset and evaluating its precision. The consultant will provide grounds for the use of Cressman products based on scientific literature and its application around the world.

The gridded analysis used by the Consultant will be based on the Cressman methodology (Cressman 1959). The methodology consists of correcting a preliminary field based on observations. The preliminary fields used by the Consultant will be the North American Regional Reanalysis (NARR; Messinger et al. 2006) developed by the National Oceanic and Atmospheric Administration (NOAA). The Consultant will include a gridded analysis for the following variables: (1) Precipitation, (2) Maximum Temperature, (3) Minimum Temperature, (4) Potential Evapotranspiration by Hargreaves Method, and (5) Relative Humidity. The last two variables will be estimated directly from NARR (that is, no application of the Cressman analysis since the meteorological records of these variables are scarce in Nicaragua). The only process involved in these particular cases is the estimation of daily data (from NARR's three hourly reports) and interpolation to match the spatial resolution of the other grids.

The evaluation will consist of comparing the gridded dataset with climatological dataset from meteorological stations to estimate the error associated with the interpolation. A discussion on how the interpolation introduces data artifacts (for example, “smoothing” of the original values) will be provided by the Consultant. The World Bank and the Inter-American Federation of Insurance Companies (FIDES, acronym in Spanish) can select up to two temporal resolutions (for example, daily, monthly, and so on) for the evaluation.

Finally, a Graphic User Interface (GUI) will be created to acquire individual time series from the gridded dataset for Nicaragua. The user will be able to define interactively the following parameters:

- (a) The pixel of interest by geographic coordinates, averaged over a geographic area defined by a GIS shapefile or an ASCII file with geographic coordinates
- (b) Variable of interest
- (c) Period of interest

Additionally, the GUI will provide the following mean statistics:

- » Basic Statistics: Mean, Median, Minimum value, Maximum value, Standard Deviation, Variance, a user defined percentile, a time series plot

The GUI will be designed so it can be installed and executed on any PC with Windows XP without the acquisition of any additional software by the Bank. The selection of the development environment for the GUI depends entirely on the Consultant.

The deliverables of the second stage include the gridded dataset in text format (ASCII), and a report, installation discs, and tutorial of the GUI. No source codes are part of the deliverables.

The consultancy related to the Second Stage is expected to require \_\_\_ consultant-days work. However, total consultant-days work for completing the consultancy (First Stage: Feasibility Study; and Second Stage: Generation of

grid and Graphic User Interface) is of \_\_\_. The number of days will start to run once the meteorological dataset is delivered.

Deliverables are to be submitted in Spanish.

## DURATION AND PAYMENTS

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The consultancy expected start date and end date is \_\_\_ and \_\_\_ respectively.

A trip to Nicaragua to present the analysis and procedures followed in the generation of the gridded products and results will be conducted by the Consultant.

Payments will be done as per number of days worked with corresponding evidence of accepted reports and documents.

FIDES will support the review of the products.

## CONSULTANT PROFILE

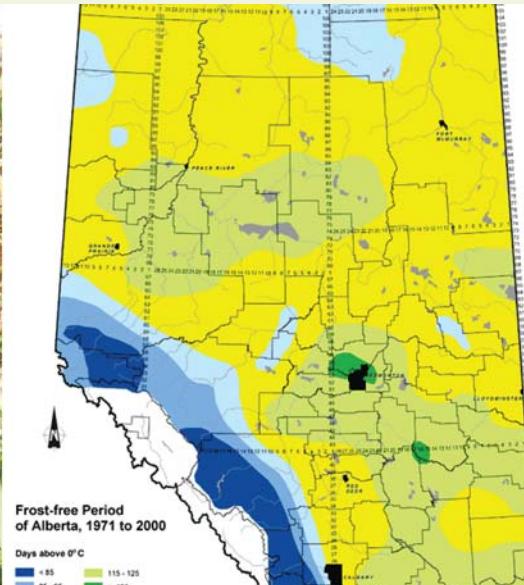
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The consultancy requires the candidate to have an educational background in Statistics, Agricultural Insurance, or in a related field. The Consultant should have at least eight years of experience and outstanding expertise in the use and applications of gridded data made by NOAA, and must have experience in weather data analysis and managing extensive weather stations datasets and weather data grids. The Consultant should have worked in Latin American countries, preferably in Central America, and have a working knowledge of Spanish and English (spoken and written, particularly). Finally, the Consultant should have knowledge of computer applications related to the legible presentation of complex weather data that will serve for analytic purposes by insurance companies.

## RESPONSIBILITY

Technical responsibility and supervision for this consultancy will be done by \_\_\_.

## AGRICULTURE GLOBAL PRACTICE TECHNICAL ASSISTANCE PAPER



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