

## Managing Climatic Risks for Enhanced Food Security: Key Information Capabilities

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### Abstract

Food security is expected to face increasing challenges from climatic risks that are more and more exacerbated by climate change, especially in the developing world. This document lists some of the main capabilities that have been recently developed, especially in the area of operational agroclimatology, for an efficient use of natural resources and a better management of climatic risks. Many countries, including the developing world, now benefit from well-trained staff in the use of climate data, physical and biological information and knowledge to reduce negative climate impacts. A significant volume of data and knowledge about climate–agriculture relationships is now available and used by students, scientists, technicians, agronomists, decision-makers and farmers alike, particularly in the areas of climate characterization, land suitability and agroecological zoning, seasonal climate forecasts, drought early warning systems and operational crop forecasting systems.

Climate variability has been extensively modelled, capturing important features of the climate through applied statistical procedures, agroclimatic indices derived from raw climatic data and from remote sensing. Predictions of climate at seasonal to interannual timescales are helping decision-makers in the agricultural sector to deal more effectively with the effects of climate variability. Land suitability and agroclimatic zoning have been used in many countries for agricultural planning, thanks to the availability of new and comprehensive methodologies; developments in climate, soil and remote sensing data collection and analysis; and improved applications in geographic information systems (GIS).

Drought early warning systems are available worldwide at both national and international levels. These systems are helping decision-makers and farmers to take appropriate decisions to adapt to short-term climatic risks. Also, operational crop forecasting systems are now becoming available at the regional and national levels. In some developed countries, several efficient and well tested tools are now available for optimizing on-farm decisions based on the combination of crop simulation models and seasonal forecasts. However, in developing countries few tools have been developed to efficiently manage crops at the farm level to cope with climate variability and climate risks. Climate change impacts on agriculture and food security have been assessed in international studies using specific and efficient methodologies and tools. Adaptation to climate change and variability can also be facilitated through effective planning and implementation of strategies at the political level. The role of technological progress, risk transfer mechanisms and financial instruments and their easy accessibility to rural people are critical elements of climate risk management.

*Keywords:* Agroclimatic information; characterization of resource base; climate forecasts; simulation models; satellite technology

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### 1. Introduction

The discussion of the links between climate and food security must take into account the four dimensions of food security: availability, access, stability and utilization. These are sometimes, referred to as “the four pillars of food security”.

All of them are somehow climate dependent. Availability of food refers to the actual production of food, which in turn depends on efficient use of resources such as crop varieties, land and water; availability of inputs and management skills; and competition for the use of the same resources from other sectors such as livestock and fisheries. Access to food refers to people’s economic ability to access food as well as their ability to overcome barriers that stem from physical remoteness, social marginalization or discrimination.

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It also depends on people's access to the resources that sustain agricultural production, particularly land and water, the agricultural technologies and financial services and the markets for agricultural inputs and produce [1]. Stability refers to the continuity over time of availability and access of food supplies. Stability can be threatened by erratic climate, economic and political factors and several changes that gradually affect agricultural activities (such as land use, loss of labour or increasing prices). Utilization of food refers to people's ability to absorb nutrients. This is closely linked to health and nutrition factors.

This document lists some of the main capabilities that have been recently developed, especially in the area of agricultural climatology, a scientific field that combines the knowledge of agronomy and climatology, in order to understand the complex mechanisms by which climatic resources (mainly heat, solar energy and rainfall) are processed into crop production. Efficient management of climatic variability and the associated risks requires that these complex mechanisms are well understood and modelled by the scientific community in order to develop decision support tools for decision-makers, agronomists and, most importantly, for the farmers. Developments in communications and electronic media, in particular the ever-expanding cyberspace linkages through the Internet and World Wide Web are changing the way farmers view information dissemination and exchange.

This document lists some of the capabilities available to practitioners and decision-makers, starting with the dissemination of agroclimatic data analyses and advice. The next section covers the characterization of the climatic, environmental and agroecological resource base, which is a necessary step in order to quantify agroclimatic resources, plan for their optimal use and describe climatic risk patterns for crop insurance and long-term agricultural and food security planning. Developments in seasonal climate forecasting and their applications are described in the following section. This is followed by a section which deals with crop simulation models and satellite technology for crop monitoring and early warning systems. It covers two types of applications: the well established ground-based agrometeorological techniques and remote sensing. The subsequent sections describe the tools available to assess and forecast impacts of climate variability and change to improve tactical planning, report on the technological progress, especially in information dissemination through the Internet, and discuss these developments along with local knowledge as key elements in adapting to climate change. The final section focuses on the role of institutions and governance in planning for adaptation to climatic risks.

## 2. Making agroclimatic information available to users

A significant volume of knowledge about climate and agriculture is currently available, and to convert this knowledge into action, it must be communicated to various types of users, from scientists and technicians to those involved in operational aspects of agriculture – production, storage of products, trading and similar activities. Communication about all weather-dependent aspects of crop and animal production, food and non-food forest products, as well as fisheries, can help improve food security or incomes through the exchange of messages (data, information, knowledge), with feedback between a producer and a target or audience. Types of audiences (clients) vary and the messages must be customized and refined by experience to achieve maximum impact. This also applies to the communication media. Messages can vary from awareness creation and advocacy to on-farm management advice, warnings, knowledge and information useful for planning at the level of individuals, institutions and government. Efficient communication relies on reliable and up-to-date data and information. Use of indigenous knowledge can lead to an easier adoption of the message. Modern communications technology, including the Internet and wireless telephones, offer potential to improve climate communication and data use, such as the establishment of Farm Adaptive Dynamic Optimization (FADO) schemes. The FADO approach is based on the real-time collection of on-farm information such as weather and phenology and the off-site processing of the information in order to derive farm management options that are fed back to the village.

Many countries, including developing ones, now benefit from staff well trained in the use of climate data, information and knowledge to reduce negative climate impacts on the four dimensions of food security, and to make better use of climate resources. Next to universities, much training is dispensed by specialized schools operated by national meteorological services. Of particular relevance are regional centres, some of them established thirty years ago, which continue to train technicians, engineers and scientists. One of them is the Regional Training Centre for Agrometeorology and Operational Hydrology (AGRHYMET) in Niamey, Niger, which was established by the Permanent Inter-State Committee for Drought Control in the Sahel (CILSS) following World Meteorological Organization (WMO) Expert Missions in 1972 in response to the Sahelian droughts.

## 3. Characterization of the climatic, environmental and agroecological resource base

Climate is now mostly regarded as a hazard, due to the political visibility of climate change and media coverage of atmospheric extreme events. However, there is a lot to be gained from looking at climate not only as a natural hazard, but also as a resource. Resources must be known, assessed in quantitative terms and properly managed if they are to be used sustainably, and climate is no exception [2]. Magalhaes [3] argues that climate should be treated as a component of the natural capital endowment of the region and as a factor that may trigger crises that impact people, economic and social activities and the environment. It remains that climate is the first natural resource [4][5] as it provides water, heat, and solar energy, without even mentioning many benefits such as wind pollination and wind power. However, unlike soil and other natural resources, most climate resources are variable over space and time, thus introducing the risk component inherent in climate. For this reason, climate variability has been modelled in accordance with agroclimatic indices, statistical procedures and local knowledge in order to capture average patterns.

The strong impact of weather on crops in the world led to the development of locally adapted agroclimatic indices. One of these indices is the well known Penman-FAO index [6][7] which is strongly related to crop yields in many arid and semi-arid regions of the world. (FAO is the Food and Agriculture Organization of the United Nations.) Recent developments in satellite imagery have allowed the derivation of new agroclimatic indices from vegetation reflectance measures, which are better related to crops in many cases, particularly in arid and semi-arid regions. The Normalized Difference Vegetation Index (NDVI), as registered since 1980 by the AVHRR (Advanced Very High Resolution Radiometer) sensor, is one of these satellite indices. The AVHRR sensor is a broad-band, 4- or 5-channel scanning radiometer, sensing in the visible, near-infrared and thermal infrared portions of the electromagnetic spectrum. The NDVI has been extensively used in vegetation monitoring, crop yield assessment and forecasting [8][9][10][11]. Most

statistical procedures rely on relatively simple frequency analysis of time series at decadal, monthly and annual levels as well as spatial interpolation. However, statistical analysis of climate remains an expert knowledge art that is very specific to local conditions.

As with climate, the characterization of all environmental categories that include climate is variable in space and especially in time. For instance, climate classification maps and agroclimatic suitability maps describe the “usual” or “average” conditions. It may even happen that “average” never occurs in practice, such as in climates characterized by the bimodal distribution of variables. For instance in some areas at the border between temperate weather systems and monsoon systems (for example, part of Southern Africa), the average climatic conditions seldom occur. Similarly, the timing of the “first rainy season” and the “second rainy season”, separated by a dry season and characteristic of many climates, is highly variable. In practice, either the first or the second dominates, which makes agricultural planning very difficult and often results in the not so intuitive cropping patterns developed by farmers over the centuries to minimize risk – planting at the end of the first rainy season, for example [12].

A systematic effort in land-use planning is an appropriate way to assure sustainable agricultural development and efficient use of natural resources. Agroecological zoning (AEZ) is used to characterize geographic areas based on climate, soil, biological and yield information [13][14][15]. Agroecological zoning offers much scope for developing strategies for efficient natural resource management and in this context, recent advances in remote sensing and geographic information systems have made the task of integration and mapping of a wide range of databases much easier. There is, for example, a need to reduce the farmer’s risk when introducing a new crop. Both satellite and ground information are essential to the development of advisory systems and planning strategies for new crop farming investments.

The environments represented by agroecological zones are often associated with distinct farming systems and land-use and settlement patterns. Maps of agroecological zones have been used in many countries for different agricultural planning applications ranging from the physical location of research stations; the introduction of particular crops, cultivars and technologies to suit the conditions in different areas; the allocation of water resources to agriculture; fertilizer recommendations; policies and regulations for rural land use; inputs and technology subsidies; and others. These applications illustrate the attractiveness of the AEZ concept to planners and decision-makers of different stripes and colours: the bird’s-eye view of agricultural potential and constraints offered by integrating the key components of the agricultural environments is much easier to understand than a stack of single-theme maps.

Whereas in the past the manual integration of spatial data from different disciplines, at different scales and accuracies, was a major bottleneck in developing AEZ maps, GIS technology makes this now perfectly practicable. The feasibility of rapidly defining agroecological zones by the combination of climatic, land use/land cover, terrain, soil and other data using GIS procedures has been demonstrated in the last few years through a number of regional and country studies. The integrating principle of the AEZ concept and the ease of linking AEZ mapping units to single-theme GIS layers, including climate risk maps, make it perfectly suitable for undertaking a SWOT analysis of well defined agricultural environments in relation to food security. SWOT analysis is a strategic planning method used to evaluate the Strengths, Weaknesses, Opportunities, and Threats involved in a project or in a business venture. It has been well established that access to and stability of the natural resource capital – particularly natural vegetation, climate, soil, irrigation water and biodiversity – are major determinants of the resilience of rural livelihood systems against climatic risk.

Understanding the underlying causes of vulnerability resulting from changes in the stability of the natural resource base requires an integrated approach, which considers both the differences in agroecological and socio-economic characteristics between different areas. Themes of “agro-eco-socio-economic” zones based on GIS make a lot of sense in assessing structural vulnerabilities of rural populations to climatic and other resource-related risks to their livelihoods. Although thus far little progress has been made in developing integrated spatial frameworks combining both biophysical and socio-economic themes, the feasibility of this approach has been improved over the last decade thanks to the vast numbers of climatic, soil, terrain, land cover and remote sensing datasets that have been made available to the public at large.

Needless to say, more detailed and accurate analyses also require more detailed and accurate data on weather, soils, land cover and other factors. Many of the improved tools can avail themselves of better data, including remote sensing and new sensors such as those used to measure soil moisture of leaf wetness, a crucial variable in the simulation of disease impacts.

#### **4. Seasonal climate forecasts and their applications**

Year-to-year variability of climate significantly affects the agricultural fortunes of most farmers. For example, the all-Australian crop value fluctuates by as much as 6 billion Australian dollars from year to year, and these fluctuations are highly correlated with seasonal ocean temperature changes [16]. Farmers have to take a number of crucial land and water management decisions during the growing season, based on climatic conditions, and sometimes these decisions have to be taken several weeks in advance.

The past two decades have seen significant improvements in the forecasting of climate variability, based on advances in our understanding of ocean–atmosphere interactions. Such improvements permit the development of applications that predict climate at seasonal-to-interannual timescales, helping decision-makers in the agricultural sector to deal more effectively with the effects of climate variability [17].

Until 20 years ago, seasonal climate predictions were based exclusively on empirical-statistical techniques that provided little understanding of the physical mechanisms responsible for relationships between current conditions and the climate anomalies (departures from normal) in subsequent seasons. Mathematical models analogous to those used in numerical weather prediction, but including representation of atmosphere–ocean interactions, are now being used to an increasing extent in conjunction with, or as an alternative to, empirical methods [18].

A wide range of forecast methods, both empirical-statistical techniques and dynamical methods, are employed in climate forecasting at regional and national levels [19]. Empirical-statistical methods in use at various centres include analysis of general

circulation patterns; analogue methods; time series, correlation, discriminant and canonical correlation analyses; multiple linear regression; optimal climate normals; and analysis of climatic anomalies associated with El Niño–Southern Oscillation (ENSO) events. Dynamical methods (used principally in major global prediction centres) are model-based, using atmospheric General Circulation Models (GCMs), coupled atmosphere–ocean GCMs (CGCMs) and 2-tiered models. Hybrid models, such as a simple dynamical or statistical model of the atmosphere coupled with an ocean dynamical model, are not being used operationally by any National Meteorological and Hydrological Service (NMHS) at the present.

A recent trend is to examine the potential use of Regional Climate Models (RCMs). These are complex atmospheric models that handle only a relatively small region (approximately the size of Europe) but with far more resolution than is possible using present global models, and that use boundary conditions supplied by a pre-run of a global model [20]. It is hoped that outputs from such models will provide greater temporal and spatial detail than is available from the global models. Relatively cheap workstations, and even Pentium 4-equipped PCs, are all that is required to run an RCM, and a number of experimental systems are running in various countries with and without other numerical capabilities using boundary conditions supplied by a global centre.

In several regions of the world, interpretation and delivery of the climate prediction information has been promoted more through the development of Regional Climate Outlook Forums (RCOFs) initiated by WMO, NMHSs, regional institutions and other international organizations. These are forums that bring together the experts from a climatologically homogeneous region and provide climate predictions and information usually for the season having critical socio-economic significance. These forums bring together national, regional and international climate experts, on an operational basis, to produce regional climate outlooks based on consensus agreement among coupled ocean–atmosphere model forecasts, physically based statistical models, results of diagnosis analysis and published research on climate variability over the region and expert interpretation of this information in the context of the current situation [21]. By bringing together countries having common climatological characteristics, the forums ensure consistency in the access to and interpretation of climate information. Through interaction with sectoral users, extension agencies and policymakers, RCOFs assess the likely implications of the outlooks on the most pertinent socio-economic sectors in the given region, and explore the ways in which these outlooks could be used. Regional agriculture and food security outlooks are now regularly produced based on the climate outlooks after the RCOFs in some regions.

The first International Workshop on Climate Prediction and Agriculture, held at the World Meteorological Organization in Geneva, Switzerland, in September 1999 [22] considered a number of important issues relating to climate prediction applications in agriculture: capabilities in long-term weather forecasting for agricultural production; downscaling; scaling-up crop models for climate prediction applications; use of weather generators in crop modelling; economic impacts of shifts in ENSO event frequency; and strengths and economic value of climate forecasts for agricultural systems. As part of the broader Task Force on Climate Prediction and Agriculture (CLIMAG) program, the Asia-Pacific Network for Global Change Research (APN) and SysTem for Analysis, Research and Training (START) supported a multidisciplinary research project to assess the potential for seasonal climate forecasts to reduce vulnerability to climate variability in south Asia. By using a systems analytical approach in southern India and northern Pakistan, the project demonstrated how cropping systems management can be altered by adapting to the underlying climatic variability.

The Agricultural Production Systems Research Unit (APSRU) in Queensland has developed a software tool, "Whopper Cropper", to help predict the production risk faced by growers [23]. This combines seasonal climate forecasting with cropping systems modelling to help producers choose the best management options [24]. Farmers can investigate the impact of changing sowing dates, plant populations, nitrogen fertilizer rates and other variables.

## **5. Crop simulation models and satellite technology for crop monitoring and early warning systems**

### *5.1 Agricultural meteorology and ground-based approaches*

Drought is largely a social construct representing the risk of agricultural activity being substantially disrupted by spatial and temporal variation in rainfall and temperature [25]. A critical component of planning for drought is the provision of timely and reliable climate information, including seasonal forecasts, to aid decision-makers at all levels in making critical management decisions. This information, if properly applied, can reduce the impacts of drought [26]. Drought early warning systems help decision-makers and farmers to take appropriate decisions to adapt and mitigate climatic risks well in advance. Thanks to early information, decision-makers can warn farmers well in advance of likely drops in yields due to unfavourable weather conditions. Such systems are available at the international level (GIEWS (Global Information and Early Warning System of FAO), FEWS (Famine Early Warning System of USAID ([www.fews.net/](http://www.fews.net/))), and others) and at the regional level (AGRHYMET – EWS (Early Warning System)). Depending on data availability, each country can develop its own system using, for instance, the FAO approach [27], which aims to optimize the combination of several kinds of data: punctual (meteorological) or continuous (satellite) data, and historical or real-time data, in order to achieve reliable and accurate yield forecasts [28].

Today, some operational forecasting systems are available worldwide at country and sub-national levels. Among the most important systems we can mention are GIEWS and Monitoring Agriculture with Remote Sensing (MARS) managed by the European Commission. These forecasting systems are based on agrometeorological models with various levels of complexity and empiricism. Currently, most operational climate impact models use mathematical techniques that were developed in the 1970s and 1980s.

Agrometeorological models are used throughout the world to understand the crop response to weather and soils [29]. These models rely on accurate input data on weather, soils and crops, and require the fitting of many parameters – both difficult requirements, particularly in developing countries. They were elaborated when remote sensing (RS) technology was in its infancy. For example, both GIEWS and MARS try to improve their yield forecasts by using the low-resolution imagery registered by synoptic earth observation systems, such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), active since about 1980, and SPOT (Satellite Earth Observation System) –VEGETATION (Multi-spectral

scanning radiometer (on board SPOT 4 and 5 satellites) acquiring images in 4 channels with 1 km spatial resolution) since 1998. (See, for example, the MARS Bulletin for Morocco <http://mars.jrc.it/mars/Bulletins-Publications>) Remote sensing is particularly useful in semi-arid regions where the state of the vegetation shows high year-to-year variations in relation with weather variability – as is the case for the Mediterranean countries which face high climatic risks due to drought and climate change [8].

Several efficient and well-tested tools are now available for optimizing on-farm decisions based on the combination of crop simulation models and seasonal forecasts. The tools apply at the farm level and where seasonal forecasts based on ENSO have good predictive power, such as in Australia. Whopper Cropper [30] was developed because climate and market risks threaten the efficiency and sustainability of cropping systems in the grain/cotton belt of northern New South Wales and Queensland where the semi-arid climate is extremely variable. The mean sorghum yield associated with a positive Southern Oscillation Index (SOI) phase for September/October is 1 000 kg/ha greater than that for a negative SOI. Whopper Cropper is designed to provide distributions of crop yields that enable the likely impact of management options to be rapidly evaluated. It was developed using an iterative process that involved extension professionals and the target user group. (See <http://www.bom.gov.au/climate/cli2000/rNelson.html>.)

## 5.2 Remote sensing

Indices derived from RS (NDVI, EVI (Enhanced Vegetation Index), and others) are used directly in statistical models to forecast crop yields at large scale. However, most models can use RS data as input in various stages of the modelling process (parameters, input or driving variable), and it has been demonstrated that the performance of the models can be readily improved when RS data are combined with crop models [31][32][33][34].

Operational application of RS in agrometeorological modelling systems for crop yield prediction is however, very limited today. Various reasons have played a role with regard to the applicability of RS data in agrometeorological crop models. Difficult access to RS data in near real time has, up to recently, been one of the reasons. Pre-processing complexity and analysis have also surely played their roles. However, one of the main obstacles so far has been the disparity in scale between the process (crop growth on small fields) and the type of satellite observing system that can be used operationally and economically over large areas with high temporal frequency. This basically means that satellite sensors which fit the operational constraints (operational, economical and available) do not observe individual crop fields in many parts of the world with high enough spatial resolution (usually 1 x 1 km). This means that crop specific biophysical parameters are difficult to extract from these types of satellite data, which makes it difficult to use them in a crop-specific agrometeorological model. Also, maybe the last reason why RS was not included in agrometeorological crop models comes from the fact that most developed countries are located in the northern hemisphere where persistent cloud cover is a constraint to the use of remote-sensing images.

In recent years, the advancement of satellite sensor technology has gradually improved the spatial resolution of polar orbiting satellite sensors that can cover large areas with high temporal frequency (such as MODIS (Moderate Resolution Imaging Spectroradiometer (<http://modis.gsfc.nasa.gov/>)) and MERIS (MEdium Resolution Imaging Spectrometer. MERIS is a programmable, medium-spectral resolution, imaging spectrometer operating in the solar reflective spectral range). These sensors can now observe the Earth with a spatial resolution of 250 to 300 meters with high temporal frequency (daily). This spatial resolution is still too coarse to observe individual crop fields in many parts of Europe. However, it is likely that there will be at least some pixels where the fractional coverage of a single crop within the pixel is high. It is therefore necessary to obtain so-called "vegetation continuous fields" [35], also called Area Fraction Images (AFI) that can be used to find those pixels and extract crop specific biophysical parameters from them.

By using this approach, we can estimate crop biophysical variables (Leaf area index (LAI), the Fraction of Absorbed Photosynthetically Active Radiation (fAPAR), Biomass, the fraction of green vegetation covering a unit area of horizontal soil (fCover), and others) for specific crops directly through remote sensing. The basic hypothesis stated here is that it may be possible to simplify agrometeorological models conceptually by replacing some of their parts (modules) with remote-sensing data. The simplification notion is especially useful when applying heavy models with, say, more than 100 parameters, in which case it is never possible to have a complete adjustment of all parameters, which in turn leads to errors and difficulties in making estimates.

The measurement of biophysical variables with RS also presents two other important advantages. Present agrometeorological models only give outputs at meteorological stations or they make simplification assumptions on the spatial homogeneity of meteorological, plant and soil conditions. This approach often leads to lack of precision as most meteorological networks are very scattered especially in developing countries. In addition, the RS estimates of biophysical variables contain information – such as fertilization level and pest and disease pressures – beyond what is currently taken into account by most agrometeorological models. With these RS biophysical estimates, we could roughly estimate yield factors unknown in the present agrometeorological models. This advance could lead to model improvements or to better model robustness resulting in better exportability of these models to areas where they have not been calibrated.

## 6. Tools to assess impact of climate variability and change

Climate change projections point to the development of more arid conditions in most parts of the world, except in the northern countries. Climatologists calculate projections from atmospheric models which transform assumptions of greenhouse gas emissions (in particular, carbon dioxide) into climate projections. The models are simplified and easily managed representations of the Earth's atmosphere calculated on a global scale, using atmospheric grid-boxes of approximately 250 x 250 km. Climate projections are based on representations of the world as it might be to the year 2100. The Intergovernmental Panel on Climate Change (IPCC) refers to these representations of the future as scenarios, each of which leads to a different trajectory for worldwide greenhouse gas emissions. It should, however, be well understood that the scenarios are neither predictions nor forecasts. The scenarios are families of possible futures; they cover the range of atmospheric conditions which will result from our policy choices, ranging from drastic measures for emissions reduction that would follow rapid adoption of renewable energy, to an acceleration of fossil fuels use, in particular in developing countries. However, climate projections are based on physical models which are better at forecasting mean values of rainfall and temperature than their extremes. It follows that the impacts forecast for the future represent averages of values which can

sometimes strongly fluctuate from one year to another. Uncertainties related to impact projections are mainly due to our difficulty in imagining the world of tomorrow, to the imperfections of climate models and to downscaling techniques regarding the statistical errors inherent in the baseline statistical data. In particular, uncertainties in average growing season temperature changes and the crop responses to these changes represent a greater source of uncertainty for future impacts than do associated changes in precipitation [36].

Despite all these uncertainties, the scientific community as well as policymakers now agree that the world is facing a warming climate. Climate change poses an increasing threat for food security, especially in the developing countries. At lower latitudes, especially seasonally dry and tropical regions, crop productivity is projected to decrease for small local temperature increases of 1° or 2° Celsius, and would increase the risk of hunger [37]. Large displacements in agricultural production patterns are expected, both continentally and regionally. In Europe, winners will be most abundant in north-western Europe and losers most abundant in southern Europe. Many of the effects are mediated through effects on water availability and water quality. According to the IPCC, vulnerability is likely to increase in the margins of arid and semi-arid areas in particular. Arable land area, crop yield potential and the length of the crop growing season are expected to decrease. In some African countries, yields from rainfed agriculture could decrease by 50 per cent by 2020 [37]. Similarly, a recent study examining the vulnerability of 132 national economies to expected climate change impacts on their capture fisheries, using an indicator-based approach, found that the most vulnerable nations were mainly located in Africa [38]. And FAO [39] outlines the need for a shift towards practices that enable vulnerable people to safeguard existing rural livelihood systems and make them more resilient to climate change.

There are two main approaches [40] to estimate quantitatively the impacts of climate change on agriculture: the agro-economic and the Ricardian approach [41]. The former attempts to estimate directly, through crop models or statistical methods, the impacts of climate change on crop yields [42], and then feed the results into behavioural models that simulate farmers' adaptation, so that effects on farm income or welfare can be evaluated. The Ricardian approach (see, for example, Mendelsohn et al.[43]) purports to isolate, through econometric analysis of time series and cross-sectional data, the effects of climate on farm income and land value, after controlling for other relevant explanatory variables (such as factor endowment, proximity to markets). Since it is assumed that farms have been adapting optimally to climate in the observed past, the regression coefficients estimating the marginal impacts on output of future temperature or precipitation changes already incorporate farmers' adaptive response, which therefore does not need to be modelled explicitly.

It is worth noting that climate–fish yield relationships in the fisheries and aquaculture sector are not as well understood due to the multiplicity of ocean and hydrological parameters and their diverse interactions. This poses significant challenges when conducting impact assessments, and more research is needed towards understanding these relationships. The impact of climate variability and change on food security will be significant and diverse. Changes in food availability and in food affordability due to climatic disturbances may add an additional health burden to households and communities [44]. Across fishing communities, in a scenario of decreased catches due to climatic events, the risk of malnutrition and under-nutrition for communities highly dependent on fish for a source of protein [45], combined with changes in diet (reduction of protein from a fisheries source), are some of the possible effects. This is of particular relevance for Asian and sub-Saharan African countries where nutritional reliance on fish as a source of animal protein is greatest [38]. Reductions in fishery-dependent incomes can also reduce the ability to purchase store-bought food during periods of natural resource scarcity. Securing local food supplies and livelihoods in the face of climate variability (such as increased frequency of droughts, floods and extreme weather events) will be of strategic importance. Additionally, infrastructure damages due to extreme events or flooding can diminish access to local markets, reducing the availability of food products as well as increasing their prices [46][47].

## **7. Adapting to climate change**

Various types of adaptation can be distinguished, including anticipatory (before impacts), autonomous (spontaneous) and planned adaptation (result of a deliberate policy decisions) and can occur at different scales – household, private sector, government institutions, local, national [37]. Adaptive management deals with the unpredictable interactions between people and ecosystems, emphasizing the importance of feedbacks from the environment in shaping policy [48] and of the ability to learn, experiment and be flexible. Knowledge-building – whether scientific, technological or traditional – as well as institutional learning and innovation, are necessary for institutions to design adaptive management strategies.

Adapting small-scale and rainfed agriculture to seasonal climatic variability could be ensured through effective quick-fix response strategies (autonomous adaptation) that are often the answer to short-term impacts of climatic variability [49]. Autonomous adaptation may take several forms in terms of soil and land management, water management and conservation of agro-biodiversity. Autonomous adaptation to climate change will rely mainly on technological progress (agricultural yield improvements in arid and semi-arid conditions), irrigation (water management at the level of agricultural plot, catchment area and region) and land use according to agricultural suitability [42].

While technological innovation is an important aspect of adaptation to climate change, local practices can also inform planned adaptation. In the agricultural sector, traditional knowledge is an important element of climate risk management. Farmers' local adaptation already happens and could provide a basis for effective strategies. These are mainly autonomous in nature and driven by risk-based approaches. Local knowledge and innovation are often the basis for spontaneous responses to extreme events. At the same time farmers and artisanal fishers will also find that their traditional knowledge about local agroclimatic conditions may lose its value and relevance under changing weather patterns [50]. Therefore, local coping responses should be systematically embedded in overarching adaptation strategies, development programs and local planning processes. To be effective, local knowledge and technological innovation could be combined with structural adjustments (such as growth promotion and diversification of the economic activities), scientific knowledge and risk pooling mechanisms including social safety nets for the poorer to further reduce vulnerability.

## **8. The role of institutions and governance**

Coping more effectively with climate change and variability requires governance systems and policies that foster flexibility [51][52][53]. Success of adaptation planning in agriculture also depends on local and national institutions and the degree of coordination of responsibilities among and within organizations. As noted by Cleveringa et al. [54], “centralized regulations and financing mechanisms must be combined with decentralized planning, management and services” in order to be effective. In the fisheries sector climate variability and change can affect the distribution and abundance of fish stock. Changes in geographical distribution of marine resources will require a redefinition of boundaries and access rights for fisheries resources. This will pose new challenges to institutional design and policy, calling for flexible institutions (Badjeck et al.[44]). For all sectors (fisheries, forestry, agriculture, water) institutions that efficiently manage natural resources and promote good governance and policies that reduce the vulnerability of resource-dependent communities to multiple stressors, including climate change, are needed.

Strengthening institutions for natural resource management is crucial to adaptation and must build on principles such as participation of civil society and gender equality. In addition, addressing issues such as rural poverty, overexploitations of fisheries stocks, water stress, deforestation and land degradation will lead to more resilient livelihood systems as well as to a reduction in vulnerability to climate change. Institution-building for intersectoral good governance and integrated natural resource management are thus the building blocks of successful adaptation. The development of integrated agriculture–aquaculture (IAA) farming systems to increase water productivity illustrates this point. In Malawi, farmers set aside a small amount of their land for fish farming. Those who adopted IAA were able to increase their net farm income and be more productive, especially in period of droughts, thus increasing farm resilience and food security [55].

The role of financial services and their accessibility by rural people are also critical elements of climate risk management. Financial products tailored to the needs of rural people can offer innovative options to respond to climate change impacts. The range of different risks that agriculture faces, as well as their different predictability require different responses. Risk transfer mechanisms and financial instruments are promising adaptation strategies in the agriculture sector. Combined with targeted risk reduction initiatives, products such as weather-related insurance for agriculture represent an attractive alternative for reducing weather risk in agriculture.

Weather-related insurance constitutes a risk-spreading mechanism through which the cost of weather-related events is distributed among other sectors and throughout society. Weather-related insurance products for managing risk in the agricultural sector are still in their nascent stages. Pilot programs conducted in several developing countries have proven the feasibility and affordability of such products. In particular, Index-Based Weather Insurance (IBWI) products are relatively inexpensive regional insurance systems based on a simple and objective index (cumulative rainfall during the cropping season, for example) that can be used as proxy measures of the countrywide exposure of farmers to risk; hence IBWI can serve as a nationwide food security indicator on which an insurance agreements can be based. The index should be strongly related to risk, based on easily available data at an acceptable spatial resolution, easy to compute and easily understandable by customers.

Insurance in the agricultural sector is better accepted by farmers in the areas with higher temporal rainfall variability, and where limited evidence suggests that farmers may be subject to less basis risk [56][57]. The major issue related with IBWI has to do with equity, that is, the possibility that farmers have lost their crops locally while the regional index shows average conditions. In relation to IBWI, data availability is also an important element. For this reason, the design of IBWI requires the presence of a dense, secure and high quality weather station network in order to interpolate as accurately as possible the weather index. Also, more sophisticated tools can be used instead of weather indices. Simple empirical forecasting models and crop simulation models that use very few input parameters can be highly suitable in developing countries. (See, for example, AgrometShell model <http://www.hoefslout.com/agrometshell.htm>.) It remains that IBWI and more traditional weather insurance schemes have a good potential of spreading the risk associated with farming and, thereby, improve food security. (See, for instance, the case of Malawi [ftp://ext-ftp.fao.org/SD/Reserved/Agromet/Malawi\\_WYX/MYZ\\_report.pdf](ftp://ext-ftp.fao.org/SD/Reserved/Agromet/Malawi_WYX/MYZ_report.pdf) and Morocco <http://www.ifpri.org/sites/default/files/publications/eptdp106.pdf>.)

Despite the fact that fisheries and aquaculture activities are located in areas highly susceptible to the impacts of climate variability and changes (coastal and inland areas subject to droughts, floods, sea-level rise and other extreme events), the access to financial services and weather insurance products to manage risk in this sector has not been fully explored. The FAO has already undertaken several studies on risk management in aquaculture [58][59], and pilot studies at the local level based on this information and the experience gained in the agricultural sector should be undertaken.

## 9. Conclusions

The science of agricultural meteorology has made considerable efforts to capture the important features of the climate in order to optimally manage crops depending on available natural resources. However, the increasing variability of the climate during the last decades is forcing the scientific community to place food production into a climatic risk perspective. In recent decades there have been significant improvements in the scientific understanding and methodologies that support the development of national strategies to reduce the impacts of climate variability and extremes on food security and to make better use of climate resources. These improvements include new data sources (such as satellite data, with increasing spatial resolution); computer-based methods (such as crop simulation models, geographic information systems, geostatistical methods); automatic data collection and transmission; new types of data, including satellite-based vegetation indices; and new ground-based sensors. Moreover, the scientific community as well as operational agrometeorologists have gained experience in the applications of seasonal climate forecasts and in operational forecasting of crop response to weather and agronomic conditions, using computerized crop simulation models or simple statistical methods combined with a better local expertise and indigenous knowledge on relevant local environmental conditions.

Unfortunately, while the science and methods are well documented and are available at very low effective costs, their implementation is still far from optimal in many countries. One of the main reasons is the lack of effective national governance in promoting the use of climate information for insuring food security at the farm level. Most climatic risks could be mitigated if useful

information and advice were provided to farmers at the right time. Effective cooperation among meteorology, agriculture, forestry and agricultural research, as well as between nations and international institutions, is crucial for providing farmers with on-time useful information to cope with short-term agroclimatic risks (heat, frost, diseases, drought and others) in all phases of the cropping season.

Improvements in the scientific, physical and agronomic and communication tools have been complemented by the development of more complex mechanisms with a marked socio-economic component, as in monitoring and warning concepts and systems, now an integral part of agricultural and food security planning, crop insurance schemes and other approaches. In particular, drought risk insurance is essential in order to reduce vulnerability to climatic hazards and to promote investment in drought-prone environments.

Global warming and long-term climatic risk management are also an international concern as they are, at least partially, an expression of disturbances in global systems. Climate change poses an increasing threat for food security, particularly in developing countries where farmers are already adapting to adverse conditions. Agricultural research is providing farmers with drought-resistant technologies but, in the long term more investments in the research sectors are needed to provide agriculture with water efficient technologies.

## 10. Recommendations

- (a) Despite numerous scientific, technological and humanitarian efforts to address the issues of crop productivity, food insecurity in developing countries remains a critical concern. Since climate variability is a dominant factor influencing food production and food insecurity, concerted efforts should be made to factor climate information and climate risk management into the strategies to enhance food security.
- (b) Relevant and country-adapted information products should be prepared to advise decision-makers at the government and regional levels of the existence of powerful tools to manage climate resources and the associated risks, stressing their characteristics in terms of costs and benefits, as well as their potential to improve food security. Climate and agricultural data should be processed in such a manner that they are directly serviceable to the final users (farmers, decision-makers, non-governmental organizations, educational institutions) through dedicated models and other tools.
- (c) Farmers in developing countries should have access to products that increase crop production and reduce climatic risks (advice and structural and non-structural mechanisms, such as insurance). These products could be derived from the location-specific processing of weather and agricultural data or come from global weather information networks. This implies that local data collection, transmission, processing in simulation models and dissemination to the farming community should all be improved in a coordinated manner as part of an integrated advisory and warning system.
- (d) The most relevant agronomic and economic time horizon for the strategic planning of farming is one to five years and since this time horizon falls between seasonal forecasts and climate change scenarios, efforts must be made to enhance research efforts and financial inputs to address this issue.
- (e) “Hotspots” for climate applications should be identified based on a global assessment of the vulnerability at upmost scale for food security where climate forecast skills are high and where capacity exists to use climate information to manage risks.
- (f) Tools and methods should be developed and disseminated to make available detailed agroclimatic reference material (climatic risk maps, crop distribution maps) at a scale that is useful for local planning (village to district). The word "detailed" refers not only to the geographic scale, but also to the thematic resolution, such as local crops and breeds and farming practices.
- (g) In order to realize the potential value of seasonal climate forecasts in agriculture, linkages between producers of climate information and applications and various end-users should be enhanced through appropriate mechanisms such as capacity-building for intermediaries and end-users and strengthening institutional partnerships (meteorological, agriculture, remote sensing and statistic administrations in particular), especially in developing countries.

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