المعهد الوطني للبحث الزراعي
Institut National de la Recherche Agronomique

Agrometeorological Cereal Yield Forecasting in Morocco

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A word from the Director

Food security, in Morocco as in many parts of the world, relies heavily on cereal production which fluctuates depending on weather conditions. Cereal production in Morocco does not meet consumption needs of the ever growing population, leading to massive import of grain to fill the gap. The cost of imported grain is high and is expected to increase due to several factors: (1) the continuous rising of prices in conjunction with increasing world population and inputs prices, (2) the use of cereal grains for bio-fuel production, and (3) the negative impacts of climate change. In Morocco cereals are highly exposed to climatic risks, since they are mainly produced in arid and semi-arid lands, characterized by limited soil and water resources to satisfy crop growth requirements.

The Green Morocco Plan which is the strategy of the Government of Morocco for the agricultural sector, aims at insuring food security through a sustainable improvement of productivity while saving water and soil resources. It is an ambitious but achievable objective, given the range of available agricultural technologies and know-how developed at National Institute for Agronomic Research (INRA), in the field of adaptation to drought and land valorization. These include weather risk management tools for decision-making at both farm and policy levels, in addition to improved cultivars, agronomic and plant protection practices. Weather risk management refers to the drought issue in particular, for which INRA developed operational approaches and tools to monitor the season and forecast cereal yields, so as to timely undertake appropriate mitigation measures, and deal with the international cereal market. These achievements are the result of INRA's investment in the field of agrometeorology oriented toward operational cereal yield forecasting systems.

The present work is the result of a long term research programme started in the 1990s, sustained by our institution and involving committed human resources which are aware of the critical issues challenging the agricultural sector in Morocco. The research was supported by international cooperation with key European institutions (Ulg, JRC, VITO, Alterra, UNIMI). This research was fruitful, since a national cereal yield forecasting system called "**CGMS-MAROC**" was developed and implemented according to international quality standards. The system is currently operational, and a dedicated Web viewer was developed (www.cgms-maroc.ma). It is managed autonomously by a consortium composed of three national institutions (INRA, DMN, DSS) bound by a mutual strategic agreement. Cereal yields can presently be forecasted three months ahead of harvests, offering a large flexibility for decision making.

The document I have the pleasure to present, relates the history and findings of the operational agrometeorology research carried out at INRA.

Pr. Mohamed BADRAOUI

Director of INRA

Preface

The science of agrometeorological crop forecasting is also an art, because different experts come up with different solutions, where efficiency, accuracy and elegance all play a part. It is usually practiced in collaboration by several institutions, under the pressure of fixed deadlines, for mostly critical and demanding customers. Beyond the limitations that affect data, methods and models, the practitioners of this art have learned to provide crop yield estimates on time for decision making, and with acceptable errors.

Over the last fifteen or twenty years, due to significant advances in computer science and hardware, remote sensing, geo-statistics, and Geographic Information Systems, there has been a tendency to develop “industrial” or “brute-force” methods to monitoring crops and predicting yields. Some people are satisfied with the approach; they can easily be recognized: they produce semi-automatic graphs and maps of the current season based on satellite indices and compare them with a “historical average” assumed to represent “normal crop conditions.”

The authors of the present publication are of a different calibre. While using modern knowledge and techniques, they also know by experience that yield forecasting remains in essence an agronomic application. Beyond describing crop conditions, they emphasize the need to understand climate and its variability at all temporal and spatial scales relevant to agriculture, and the variability brought about by farming activities and practices, which are often controlled by economic or policy factors. This is what characterizes this little book: it explains the reasoning and the methods, ranging from traditional ones like frequency analysis of rainfall, to more advanced features like the use of satellite data and indices, and makes us understand why and how they can be used to quantify the effect of factors that affect crop yields.

I have known the authors for a long time. Their art of predicting crop harvests stems from experience in the real world. They do not neglect traditional techniques which are often ignored, or unknown to the practitioners of recent “industrial” approaches. One can be convinced by consulting the bibliography where classics like “De Martonne, Célérier and Charton (1924)” get along well with recent ones like “Bénichou and Le Breton (1987)” and “de Wit, Duveiller and Defourny (2012)”.

By their meticulous way of trying to understand, Riad Balaghi and his colleagues somehow remain traditional natural scientists. This can be seen in some of their empirical rules, like the one providing the level of accumulated rainfall above which the relation between yields and rainfall fades out. It can also be seen in numerous original figures that literally dissect data; they are unique and found nowhere else in the literature.

The work of Balaghi, Jlibene, Tychon and Eerens deserves ample diffusion, beyond Moroccan boundaries. First, in schools that teach crop yield forecasting, at various levels, under one name or another. Students will learn how to thoroughly observe data and extract **all relevant information** they contain. Second, and more importantly, professionals and practitioners, even experienced ones, will be surprised to find "know-how" and original analyzes that are overlooked in most texts.

As to me, I am delighted that such a publication of "advanced popular science" on crop yield forecasting is now made widely available. I have no doubt that it will meet the success that it deserves.

Dr. René GOMMES

Doctorate in bio-geochemistry (1977).
Agroclimatologist at FAO since 1980.
Coordinator of the Agrometeorology Group of FAO from 1994 to 2007, and Leader of the "Climate impact team" of FAO, from 2008 to 2010.
Senior scientist in the FoodSec Unit at the EC Joint Research Center at Ispra, from 2010 to 2012.
Since 2012, visiting professor at the Chinese Academy of Sciences.
Member of the European Society of Agronomy (ESA) and the International Society of Biometeorology (ISB).

Acknowledgement

Research on agro-meteorology was initiated at the Regional Agronomic Research Center of Meknes (INRA-Meknes), in 1992, as part of the research actions of the "High Rainfall Research Programme" (*Programme Bour Favorable*) coordinated then by Dr Mohammed Jlibene, until 2002. It has been later pursued under supervision of Dr Riad Balaghi, as head of the research unit "Agronomy and Plant Physiology" at INRA-Meknes, from 2002 to 2008, and as head of "Department of Environment and Natural Resources", at INRA-Rabat, from 2008 to date.

Since 2008, research in agrometeorology has received moral support from the Director of INRA, Pr Mohamed BADRAOUI, not just as a manager but also as a scientist convinced by the interest of supporting this research project for the benefit of food security in Morocco.

This research project needed considerable amount of agro-meteorological and agronomical databases, as well as scientific and technical help from national and international cooperation. Institutions involved in the project were: "Direction de la Stratégie et des Statistiques" (DSS, Morocco), "Direction de la Météorologie Nationale (DMN, Morocco), "University of Liege (Arlon Campus Environnement, former Fondation Universitaire Luxembourgeoise, ULg - Belgium)", "Joint Research Centre of the European Commission " (JRC, Italy), "Flemish institute for technological research" (VITO, Belgium) and "Food and Agriculture Organization of the United Nations" (FAO, Italy).

The project was partly financed by the Belgium Agency of Development" (CTB, Belgium) as well as the European Union thanks to the Seventh Framework Programme (FP7 - Project « Crop Monitoring as an E-Agricultural Tool for Developing Countries », E-AGRI).

The idea of this research project has matured with the help and perseverance of INRA researchers who can identify themselves and find the expression of their common output. Researchers of great scientific and technical quality have contributed to this achievement with varying degrees:

Mr. Moha MARGHI, former Director of "Direction Provinciale de l'Agriculture de Meknes" and later former general secretary of the Ministry of Agriculture and Marine Fishery (MAPM), was the first official to have requested INRA-Meknes to present scenarios of drought consequences on cereal production in the Meknes region during the dry season of 1994-1995. By approaching us, he inspired us with the idea of investing in research for forecasting cereal yields.

From the Joint Research Centre of the European Commission (JRC): Dr. Giampiero GENOVESE, Dr. Bettina BARUTH, Dr. Mohamed EL AYDAM, Dr Giovanni NARCISO, have supported the research agreement between JRC and INRA in the field of harvest forecasting as well as the E-AGRI research project.

From the "Direction de la Stratégie et des Statistiques" (DSS, Rabat): Mr. Redouane ARRACH and Mr. Mustafa TAHRI, who were committed to provide agricultural statistical data and helped with the research collaboration agreement between DSS, INRA and DMN, as part of the E-AGRI project.

From the “Direction de la Météorologie Nationale” (DMN, Casablanca): Mr. Tarik EL HAIRECH and Mr. Rachid SEBBARI have concretized the research agreement between DMN and INRA and were formally committed to the E-AGRI project.

From the E-AGRI: Dr. Qinghan DONG, Dr. Allard DE WITT, Mr. Steven HOEX, helped in the adaptation of “CGMS” to Moroccan context. Dr Mouanis LAHLOU, from Institute of Agronomy and Veterinary Hassan II, developed the Web viewer of the “CGMS-MAROC” forecasting system.

From INRA: Dr. Rachid MRABET, Mr. Hassan BENAOUDA, Dr. Hamid MAHYOU, Dr. Sliman ELHANI, Dr. Rachid DAHAN, Dr. Hassan OUABBOU and Mr. Mohamed BOUGHLALA have exchanged data and information with us and participated in different research projects some of which were not directly related to yield forecasting per se.

The authors would also like to thank all colleagues who directly or indirectly contributed in our research work, either by providing agro-climatic data or contributing to the overall thinking process, particularly: Mr. Abdelaziz EL OUALI (former Head Agrometeorology Service at DMN), for his advice on climatology in Morocco; Mr. Wolfgang GÖBEL (former researcher at INRA) for exchange information on agro-meteorology and for common publications on the “Atlas Agroclimatique du Maroc”; Dr. Mohamed EL MOURID (former researcher and research manager at INRA) who initiated the first research studies on crop modelling at INRA; Mr. Hamid FELLOUN and Ms. Fatiha SELOUANI (MAPM) who provided us with climatic data of the Ministry of Agriculture and Marine Fishery.

Least but not last, thanks go also to Mr. Chafik KRADI, head of the “Division de l’Information et de la Communication” at INRA and his staff, particularly Mr. Reddad TIRAZI who helped in the diffusion of this document.

Our special thank goes to Dr. René GOMMES, ex senior scientist at FAO with whom we were honored to work on several occasions on operational agro-meteorology and climate change and who was kind to preface this document.

The authors

SUMMARY

The present document provides a summary of research work carried out, at National Institute for Agronomic Research of Morocco (in French, Institut National de la Recherche Agronomique - INRA), since early 1990s, in the area of operational agrometeorology oriented toward forecasting crop harvests. Forecasting the production of crops early before harvest allows decision makers to be prepared in advance for eventual consequences of abnormal deviations of the climate, particularly for strategic commodity crops to food security like cereals. To our knowledge, to date there is no official method to forecast cereal production in Morocco on the basis of agrometeorological data. However, cereal productions are estimated based on a sampling method some weeks before harvest, every year by the Ministry of Agriculture and Marine Fishery (MAPM) through the Direction of Strategy and Statistics (in French, Direction de la Stratégie et des Statistiques - DSS). It is a direct method, precise, and applied directly before harvest, but requires consequent human and financial resources. The need to elaborate an indirect method to early forecast yields that is fast and economical, has been understood at INRA as early as in 1995, triggered by the severe drought of that particular season, described as the worst dry season of the 20th century in Morocco. Neither the classical frequency analyses of the climate used to identify seasons of close similarity to 1994-1995 season, nor the available mechanistic models for crop forecasting used in developed countries, have been able to monitor crop development during that season and a fortiori predict the catastrophic harvest of 1995. Therefore, it became necessary to come up with a new approach for forecasting cereal yields using an innovative methodology which combines empirical and statistical approaches with agronomic and meteorological expertise. First we had to study the interaction between the climate and the cereal crops behaviors, particularly climatic and crop cycles were analyzed together in a series of long term data, initially for Meknes region where the first two authors were posted, extended later to other regions of Morocco. Preliminary results indicated for the first time in Morocco that inter-annual variation of cereals yields could be explained by variation in the amount of rainfall cumulated during the crop cycle, with a relatively high accuracy. The relationship could be enhanced by partitioning the season into three or more phases. In collaboration with the University of Liège (ULg, Belgium) and later with the Joint Research Centre of the European Commission (JRC), a new indicator was identified as highly correlated to cereal yields, which is the Normalized Difference Vegetation Index (NDVI) derived from satellite images. Unlike many European countries, this index was highly correlated to cereal yields in Morocco, mainly due to the aridity of Moroccan climate and the predominating coverage of cereals of agricultural areas. NDVI is correlated with cereal yields as long as cropping season rainfall did not exceed 550 mm, which explains the irrelevance of NDVI to forecast crop yields in Northern Europe. The combination of both rainfall and NDVI allowed forecasting of cereal yields as early as March, three months before harvest, and at a low cost, with a level of accuracy similar to the one of the direct sampling method used at crop maturity by DSS. These astonishing results have led INRA to publish for the first time in Morocco three crop forecasting bulletins between 2009 and 2011, in collaboration with JRC. In these bulletins, an approach combining four individual approaches was used: (1) similarity approach using rainfall and/or NDVI as criteria of comparison, (2) regression models using rainfall and NDVI as predictors of cereal yields, and (3) the JRC approach which is based on a simulation model of crop growth called WOFOST. The deterministic model WOFOST is now being adapted to the Moroccan agro-climatic context and incorporated in an operational forecasting system. To ensure durability of the system, a strategic partnership between INRA, DSS and DMN was formalized in addition to that bounding INRA and JRC. This new collaboration has allowed establishment of the first national cereal yields forecasting system named "CGMS-MAROC", based on the combined approach developed in the present document. The system is carried out by the three national institutions (INRA, DSS and DMN), leading to the edition of a fourth bulletin of cereal yields forecasts issued for the 2012 season. The combined approach can be extended to forecast yields for other crops in morocco as well as in countries of similar climatic pattern, provided some adjustments. In parallel to yield forecasting, a new field of research can be explored, dealing with estimating cropped areas, using low resolution and inexpensive satellite images.

Key words: Agrometeorology, yield forecasting, similarity analysis, NDVI, rainfall, temperature, cereals, soft wheat, durum wheat, barley, drought, Morocco, INRA.

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ACRONYMES

°C	Degree Celsius
AFI	Area Fraction Image
AGRIMA	Agriculture Maroc
AgroMetShell	FAO tool for monitoring crops ftp://ext-ftp.fao.org/sd/reserved/agromet/AgroMetShell/
Alterra	Research Institute at the University of Wageningen, Netherlands http://www.alterra.wur.nl
AURELHY	Analysis Using RELief for Hydro-meteorology
AVHRR	Advanced Very High Resolution Radiometer
CGMS	Crop Growth Monitoring System www.marsop.info/marsopdoc/cgms92/1_en.htm
CRTS	Centre Royal de Télédétection Spatiale www.crts.gov.ma
CST	CGMS Statistical Toolbox http://e-agri.wikispaces.com/CGMSStatTool
CV	Coefficient of Variation (%)
DMN	Direction de la Météorologie Nationale www.marocmeteo.ma
DMP	Dry Matter Productivity www.geoland2.eu
DPA	Direction Provinciale de l'Agriculture
DPAE	Direction de la Programmation et des Affaires Économiques, currently DSS
DSS	Direction de la Stratégie et des Statistiques www.agriculture.gov.ma
E-AGRI	A research Project on Crop Monitoring as an E-agriculture tool in Developing Countries www.e-agri.info
ENSO	El Niño–Southern Oscillation or El Niño/La Niña–Southern Oscillation
ENVISAT	Environment Satellite, European satellite launched in 2002 to observe Earth
ETa	Actual Evapotranspiration
ETP	Potential Evapotranspiration
EU	European Union
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization of the United Nations: http://www.fao.org

FAOCLIM	FAO database of monthly agro-climatic observed and calculated parameters http://www.fao.org/nr/climpag/pub/EN1102_en.asp
fAPAR	Fraction of solar radiation absorbed by plants
g	Gram, unit of weight
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GLC2000	Global Land Cover for the year 2000
GlCropV2	Land cover map made of in collaboration with VITO
ha	Hectare (1 hectare = 10.000 m²)
INRA	National Institute for Agronomic Research: www.inra.org.ma
JRC	Joint Research Center: http://ec.europa.eu/dgs/jrc/index.cfm
Kg	Kilogram
Km	Kilometer = 1000 meters
l	Liter (1 l = 1 dm^3)
LAI	Leaf Area Index
MAPM	Ministry of Agriculture and Marine Fishery www.agriculture.gov.ma
MARS	Monitoring Agricultural ResourceS mars.jrc.ec.europa.eu
MERIS	Medium Resolution Imaging Spectrometer
MIAC	Mid America International Agricultural Consortium
mm	Millimeter rainfall (1mm=1 liter per square meter)
MODIS	Moderate Resolution Imaging Spectro-radiometer http://modis.gsfc.nasa.gov/
NAO	North Atlantic Oscillation
NDVI	Normalized Difference Vegetation Index
NOAA-AVHRR	The Advanced Very High Resolution Radiometer sensor carried by the National Oceanic and Atmospheric Administration satellite
ONICL	Office National Interprofessionnel des Céréales et Légumineuses www.onicl.org.ma
ONSSA	Office National de la Sécurité Sanitaire des produits Alimentaires www.onssa.gov.ma
ORMVA	Office Régional de Mise en Valeur Agricole
PCA	Principal Component Analysis
PROBA-V	Project for On-Board Autonomy – VEGETATION sensor to be launched in 2013 http://www.vgt.vito.be/
PSDA	Projet de Soutien au Développement Agricole dans les ORMVA

Q	Quintal (1 quintal = 100 Kg)
R^2	Coefficient of determination
RWP	Rain Water Productivity
RWUE	Rain Water Use Efficiency
SEEE	Secrétariat d'État chargé de l'Eau et de l'Environnement http://www.minenv.gov.ma
SPOT-VEGETATION	Programme conceived to allow daily monitoring of terrestrial vegetation cover through remote sensing, at regional to global scales http://www.vgt.vito.be/pages/mission.htm
SRTM	Shuttle Radar Topography Mission: www2.jpl.nasa.gov/srtm
ULg	University of Liege (Arlon Campus Environnement) http://www.facsc.ulg.ac.be/cms/c_636656/en/arlon-campus-environnement-home
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
VITO	Flemish institute for technological research, Belgium www.vito.be
WMO	World Meteorological Organization http://www.wmo.int
WOFOST	WOrld FOod STudies is a simulation model for the quantitative analysis of the growth and production of annual field crops http://www.wageningenur.nl/en/Expertise-Services/Research-Institutes/alterra/Facilities-Products/Software/WOFOST.htm

I. INTRODUCTION

The main authors' interest, in studying the climate and its impact on cereal production with the aim of yield forecasting was sparked by the major drought that occurred during the 1994-1995 growing season in Meknes region. Scenarios of the prospective consequences of drought on cereal yields were analyzed by identifying, from the historical climatic and crop database, similar seasons to 1994-1995 in terms of cumulative rainfall over the period of September-January. While similar cropping seasons could be identified from early rainfall distribution, it turned out later as the season evolved, that the season of 1994-1995 was exceptional, far away from recorded past seasons. The severe drought during this unexpected season was about to cause an economic disaster in Morocco, narrowly averted by the bumper harvests of the following season (1995-1996). Analysis of historical data since 1960 indicated that the climate in Morocco was relatively stable until 1980 from where a change had occurred, expressed in lower rainfall and higher temperatures during the next three decades. Also, higher intra and inter annual variations tended to increase. Frequency and severity of climatic hazards were amplified with negative consequences on water resources and agriculture, and ultimately on the whole economy of the country. It then became necessary to invest in agrometeorological research science in order to develop effective methods and rapid tools capable of forecasting cereal yields early in the season. The present document reports the thinking process and research work done at National Institute for Agronomic Research that led to the development of a global approach of cereal yields forecasting in Morocco. The document provides also some ideas worth exploring to improve precision and accuracy of the forecasts.

Crops evolve under the direct influence of agrometeorological factors such as temperature, moisture, sunlight and radiation, or hygrometry. The development of methods for crop yield forecasting, requires a thorough understanding of the interaction between these factors and the crops. The study of these interactions is the result of a maturing process of an emerging science termed "Agrometeorology" stemming from "Biogeography" and later from "Bioclimatology". The term agrometeorology[1], meaning meteorology applied to agriculture, emerged during the 1920s (WMO, 2006), and developed as a recognized and established science in the 1950s (Seemann *et al.*, 1979). The objective of operational agrometeorology is to predict the response of crops to external conditions of natural (climate, soil, diseases, parasites, etc.) or human origins (cultural practices, prices, etc.).

Research on operational agrometeorology at National Institute for Agronomic Research of Morocco (INRA), precisely at its Regional Agronomic Research Centre of Meknes, was triggered by the

[1] Agricultural meteorology can be defined in large terms as « a scientific discipline that is concerned with the study on heat, air and biomass inside and above ground, in areas devoted to agricultural production, in addition to the incidence of parasites and diseases on crops and animals which also depend on these factors for their expression" (WMO, 2006).

extreme drought that happened during the cropping season of 1994-1995. This drought sparked the awareness of the need to forecast crop yields. Cumulated rainfall over the cereal cropping cycle (September till May) in Meknes region, as example, was less than half (43%) the amount of an average season (530 mm). The season started with a 33% deficit in rainfall (September till November) as compared to the long term average (126.5 mm) and stayed dry until February, receiving practically no rainfall during three months (7.6 mm). Between the months of February and May, rainfall was low and insufficient (134.8 mm) to help crop rebound.

Alarmed by the persistent drought during December 1994 and January 1995, the representative of the Department of Agriculture in the province of Meknes (Direction Provinciale de l'Agriculture de Meknes) requested the Regional Research Centre of INRA in Meknes to provide scenarios of prospective developments of the season. Due to lack of established methodologies and forecasting tools for cereal forecasting at that time, distribution of rainfall of the season of 1994-1995 was compared to historical weather data available at the National Meteorological Service since 1960, using frequency analysis method[2]. Based on this type of analysis, it appeared that season of 1974-1975 was displaying a rainfall pattern similar to that of 1994-1995. During season of 1974-1975, despite early drought the total amount of rainfall was close to average in the region. Hence, frequency analysis of rainfall indicated that expected total season rainfall would be greater than 445 mm, with 90% probability, and greater than long term average with 50% probability. On the basis of these two scenarios (50% and 90% probabilities), two figures of expected yields were proposed. Considering the scenario of 90% probability, expected yields of soft wheat would be 11 Quintals per hectare (Q/ha) at the national level and 22 Q/ha at Meknes. Based on the scenario of 50%, expected yields would be 14 Q/ha at the national level and 27 Q/ha at Meknes. Finally at the end of the season, none of the two scenarios has helped to provide yield forecasts for the season of 1994-1995. The reason is that this season was particular, with no similarity in both rainfall amount and distribution with past recorded seasons since 1960. The drought period lasted long, covering two thirds of the cereal cropping cycle. Final yields of soft wheat (official statistics of the MAPM), were 4.79 and 5.70 Q/ha at the national and regional levels, respectively, which was an unprecedented situation.

From the unexpected results, it was understood that the hypothesis of a stationary climate in Morocco was no longer holding, that is historical rainfall frequencies have changed as a result of a change in the climate since 1980. Other methods and tools for cereal yield forecasting had to be invented based on an agro-meteorological approach resulting from a fine study of the climate and its interaction with cereals development.

[2] Frequency analysis is a statistical methodology that quantifies probabilities of a hazardous event like climate or hydrology, based on past recorded events. It relies on the hypothesis of stationary or homogeneous distribution of the time series.

Preliminary analysis indicates that, in general characteristics, Moroccan climate is of Mediterranean[3] type with major influences of the ocean, the desert and the mountains, determined basically by its extended latitude (between 21°N and 36°N), sea shore, Sahara desert and Atlas mountains. The latitude determines temperature due to the curving of the globe and the inclination of solar rays, as compared to the tropics, resulting in a decrease of temperature from south to north. The Mediterranean Sea in the North, with 512 Km of coast from Saïdia East to Cap Spartel West, and the Atlantic Ocean to the west, with a longer coast of 2934 Km, from Cap Spartel north to Lagouira South, attenuate temperature variation and temper the seasons. During summer, temperatures are mild, similar to those on the Mountain, and moderate in the winter, creating an environment of low temperature amplitude. The climate becomes continental from the Ocean toward East, and temperature becomes cooler with altitude. The Sahara desert south of the country, which has an arid climate (< 150 mm) influences inland climate through the movement of tropical dry and hot air masses moving from south to north and from East to West. In the Atlas and Rif mountains temperature is cooler due to elevation. Due to low temperature in mountains, moisture precipitates as snow during winter and sometimes during spring.

The Azores anticyclone located in the Atlantic Ocean near Portugal, and the Saharan depression in the south, exert antagonistic actions on the Moroccan climate. Humid and cold air masses reaching Morocco from the Atlantic Ocean are accompanied with rainfall and snow in high elevation, When the Azores anticyclone moves to the west or south west. During spring and summer, the Azores moves up to high latitudes, pushing perturbations to the 45th parallel North. At the same time, tropical dry and hot air moves up from south, leading to a net decrease in precipitation. Other anticyclones of less importance influence Moroccan climate as well, particularly the Atlantic one and the Mediterranean one.

Total annual precipitations in Morocco increase along latitude from south to north and along longitude from east to west. Water supply in Morocco is entirely dependent on precipitations, unlike countries of the Middle East, Eastern and central Africa. There are no supplied water sources outside the boundaries of the country, unlike some other countries such as Egypt whose water supply is dependent on the Nile River or Syria or Iraq who depend on the Euphrates River, or the central African counties who are sharing the great lakes. Therefore, because of the total dependence of Moroccan agriculture on precipitation, any sudden deficit has immediate negative impact on agriculture and water resources, and consequently on the economy of the country as a whole. This great dependence of Moroccan economy on rainfall was understood early by Marchal Louis Hubert Lyautey whose famous statement "*Governing Morocco is raining*" is still at date.

[3] The Mediterranean climate is characterized by a rainy season in autumn and winter seasons, hot and dry summers, and cool winter temperatures.

The gradient of moisture from south to north is so large that six relatively homogeneous agro-ecological zones could be distinguished (Table 1):

- Saharan desert zone, with less than 150 mm of annual rainfall ;
- Pre- Saharan zone, with annual rainfall in the range of 151-250 mm ;
- Arid zone, where annual rainfall in the range of 251 and 350 mm ;
- Semi-arid zone, with annual rainfall in the range of 351 and 450 mm ;
- Sub-humid zone, with annual rainfall in the range of 451-550 mm ;
- Humid zone, with annual rainfall above 550 mm.

Table 1: Classes of rainfall and corresponding aridity levels with administrative provinces included in each class. Rainfall data are averages of 1988-2005.

Annual rainfall (mm)	Aridity level	Province
<150	Sahara	Dakhla, Lâayoune, Tantan, Errachidia, Ouarzazate, Bouarfa, Tiznit, Sidi Ifni
151-250	Pre Sahara	Midelt, Taroudante, Marrakech, Oujda, Agadir
251-350	Arid	Settat, Nador, Al Hoceima, Essaouira, Beni Mellal, Nouasser, Khouribga, Kasba Tadla
351-450	Semi-arid	El Jadida, Safi, Casablanca, Sidi Slimane
451-550	Sub-humid	Rabat-Sale, Kenitra, Tounate, Meknes, Fes, Taza
> 551	Humid	Larache, Tetouan, Tangier, Chefchaouen, Ifrane

The Atlas Mountains lanyard the country diagonally, along the axis north-east to south-west. They act as a natural barrier against desert influence from its Southern side and against moisture originating from the Ocean from its Western side. The blocked oceanic moisture by the Atlas Mountain chains precipitates as snow or rainfall depending on the harshness of winter temperatures (Figure 10). Because of its natural geography, the Atlas Mountains are assimilated to the national water reservoir. Elevation peaks at 4,165 meters above sea level at Jbel Toubkal Mountain. Beyond this natural barrier, climate is therefore arid and pre-Saharan. Water masses, coming from runoff of rain water and melting of the snow, in the mountainous chains, feed the major rivers of the country, which flow to the ocean for most of them (Loukkos, Bouregreg, Sebou, Oum Er-Rbia, Souss), to the Mediterranean Sea (Moulouya) or to the Sahara (Ziz and Draâ). The Middle Atlas, a mountainous range stretching from south-east to north-west along 350 km, is the North African Mountain most covered with moist areas, mainly natural lakes, rivers and fresh springs.

Due to its geographic configuration, agriculture in Morocco, is confined within the borders of the Mountains and the Seas, and is highly influenced by climatic factors, mainly rainfall. Availability of water, which is the most vital factor to agriculture, is shrinking due to the growing pressure of demand for water for urban, industrial and touristic development, and to the negative impact of climate change on rainfall. Major expected expressions of climate change in Morocco include reduced precipitations, increased temperatures, and intensified extreme hazards like drought, heat waves, frost, flooding, etc. (SEEE, 2010).

The economic weight of agriculture on the Moroccan economy (15 to 20% of GDP and 40% employment) is so high that any temporal or seasonal variation of the climate will immediately affect agricultural production, particularly that involving crops used as the basis of food security like cereals. Rainfall variation between the successive cropping seasons of 1994-1995 and 1995-1996, in a ratio of 1 to 3, affected cereal yields in a ratio of 1 to 3.61 and production in 1 to 5.74. Comparison between the seasons of 1994-1995 and 1995-1996, indicates a cumulated rainfall over the crop cycle (September till May) of 198 mm vs. 591 mm, and yield a of 4.79 Q/ha vs. 17.27 Q/ha, and a production of 17 vs. 98 million quintals. The unpredicted harvest of 1994-1995 could have led to an economic disaster if the next season didn't happen to be rainy and productive.

Cereal imports were consistent since 1980, representing nearly half (48.7%) of the cereal production and most of imported food products and import cost. Annual cereal imports amounts to 2.6 million tons on average for the period of 1980-1981 till 2010-2011 (ONICL, 2012), most of it composed of soft wheat which accounts for 77%, followed by durum wheat (12%) and barley (11%). Cereal imports are in constant progression since early 1990s, fluctuating over time and ranging from 10% of average cereal production (during season of 1994-1995) following the good harvest of 1993-1994 to 244% during 2000-2001 following the dry season of 1999-2000. However, cereals are imported even during record productive seasons like during 2008-2009 (10.2 million tons of production), where significant quantity was imported during the next season (2.56 million tons), that is 25% of the 2008-2009 total cereal production. Total cereal supply, as the sum of production and import, without accounting for stocks, which may represents total needs for food and feed, increases over years with a rate of 0.16 million ton per year since the 1990s. This high dependence on imported cereals is associated with risks of short supplies and high prices in the international market which may result from the variation in global production, embargos on imports and speculation.

The 5.3 million hectares of cereal land have been, by commodity, subdivided by the MAPM into six agro-ecological zones: *Favorable*, *Intermediate*, *Unfavorable South*, *Unfavorable East*, Mountainous and *Saharan*. The favorable zone is located in the northern parts of Morocco, starting at its southern limit at the Kenitra-Taza line. The *Intermediate* zone is located in the center of the country north of the Casa-Benslimane line. The *Unfavorable South* zone is located between the Casablanca-Benslimane line and Agadir province, while the *Unfavorable East* zone is located in the eastern parts of the country. The *Saharan* zone is located South of Agadir province. The Mountainous zone is mainly located in the Atlas Mountains. The *Favorable*, *Intermediate* and *Unfavorable South* account for 75% of total cereal production and 75% of total area. The Mountainous zone contributes to total cereal production and total cereal area by 12% and 10%, respectively. Yields are higher in the *Mountain* zone with an average of 1.41 ton per hectare for the period 1991-2011 (DSS), followed by the *Favorable* zone (1.39 tons per hectare), *Intermediate* zone (1.19 t/ha) and *Unfavorable South* (0.76 t/ha).

Yields at the country level are low, half of those obtained in research experiments at the INRA experiment stations (Jlibene, 2009), indicating that there is still important room for cereal yields improvement in Morocco. National yields have slightly improved over the years. For example, soft wheat yields evolved from 0.7 t/ha in the 1940s, to 0.9 t/ha in the 1950s and remained unchanged during the 1960s and the 1970s, despite large scale state development programs: "plowing", "fertilizers", and "seed" (Jlibene, 2009). During the next three decennials (1980s, 1990s, 2000s) country average yields improved to 1.4 t/ha despite a decrease in rainfall and frequent drought episodes. However, this improvement was yet insufficient to cover the fast growing population needs. Imports rocketed from 0.9 million ton in the 1970s to more than 2.0 in the 2010s, with peaks of 5.0 million tons in extremely dry year.

Episodes of drought can occur early in the cropping season, in the middle or at the end of the season, or in combination of two out of three periods, in association with variation of temperature and biotic stresses (insects and fungi). Rainfall variation, in amount and distribution within the season, in addition to temperature variation and biotic stresses, creates a multitude of agro-climatic situations which appear difficult to model.

Studies on the behavior of cereals in interaction with the climate in Morocco are scattered and lack precise data and consistent monitoring of both the climate and plant parameters along the cycle. Grain yield is the most often studied variable in relation to rainfall which is considered as by far the most important climatic variable. The influence of climate on cereal growth and production is a reality traditionally known to Moroccan farmers and students, becoming almost a faith not worth investigating. Farmers usually wait for the first rain storms of September and October to prepare the soil for planting before the rainy season in November and December, and entertain the crop during spring before harvest in the summer. This is an ancestral practice that was perpetuated over centuries. As a consequence, research studies have focused mainly on means to improve yields instead of understanding their formation in relation to climate. Without understanding the interaction between crops and the climate, yields forecasting would be unrealistic.

Crop harvest forecasting[4] provides the opportunity to become prepared for consequences of any shortage in production through actions to reduce vulnerability to climatic risks. It is hence a valuable tool for decision making in agriculture, allowing for planning in advance actions like aids to farmers, or cereal imports. It also allows quantifying drought impacts needed by institutions like agricultural insurance company. Harvest forecasting evolved from applied research status to an operational one, due to INRA research efforts in collaboration with partner institutions national and international.

[4] Crop forecasting is a science that permits to foresee crop yields using mathematical models.

From a practical point of view, harvest forecasting can be realized at different spatial scales, ranging from farmer's level to country level. Approaches to use for crop forecasting depend on the scale, available basic data, and the required precision. From a scientific point of view, approaches can be grouped into three categories depending on the level of conceptualization (Gommes *et al.*, 2010):

- Expert approach is based either on experience or opinions of the investigator or farmers when economic factors are at stake. This is the case of Delphi approach for predicting harvests (Moricochi *et al*., 1994) ;
- Extrapolation approach is based on diverse statistical analyses (simple or multiple regression, principal component analysis, neuronal net, etc.) of agricultural production and environmental factors (climate, fertilizers, prices, etc.) or semi-empirical models and simulation[5] models. This approach is often used in operational agrometeorology ;
- Intermediary approach, which is a combination of expertise and extrapolation approaches.

Empirical approaches are often based on statistical relations between the climate and vegetation, whether it is natural or grown. These relations can also be studied using directly measured climatic parameters by the parametric approach, or by subjective appreciations of the cropping seasons by an expert agricultural scientist. Relations that use empirical approaches are valid only for contexts similar to the one that led to their development. Statistical approaches are quite important because they are practical; they can rapidly recognize relevant climatic element that effect crops. However, they are valid only for stationary phenomena in time, that is, when climatic phenomena stay unchanged over the period under consideration. In Morocco, we have observed since early 1980s a change in climate leading to more frequent droughts and increased aridity. Statistical approaches can be used only for series of climatic data recorded after the change point.

Agrometeorological forecasting of crop harvests, at the country or the region levels, which is a branch of operational agrometeorology, refers to two main schools of thought: the school of modelling approach of interactions between crops and their environment (water balance, physiology processes, energy absorption, etc.) and the school that can be qualified as "pragmatic" which relies on methods using statistical models linking crop production to agronomic factors, climatic, environmental, or economical indices[6].

The pragmatic approach has been adopted by FAO for forecasting crop harvests worldwide due to its effectiveness and relative simplicity to implement (Gommes, 2001). Agro-meteorological forecasting approach of crop harvests adopted by the World Meteorology Organization is a combination of simulation models and statistical models (WMO, 2010). Likewise, the approach

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[5] Agro-meteorological simulations models of growth and crop development allow understand the response of plants to variations of the environment.

[6] Indices are useful for modelling because they constitute an integrative or a combination of a range of environmental parameters (rainfall, temperature, moisture, hygrometry of soil, etc.) which explain the behavior of plants. An index is a practical way of simplifying the plant environment.

used by FAO to estimate crop yields, relies on linear regressions between official statistics and outputs of a model named AgroMetShell[7] which calculates water balance of cultivated soils. Outputs of this model are regressed linearly to agricultural statistics, which accounts for technology improvement, real field conditions of farmers, and resolves the problem of spatial resolution[8], and the bias of simulation models. The pragmatic approach has also been used to propose indicial systems to manage agricultural insurance for cereals (Skees *et al*., 2001; Stoppa and Hess, 2003) and sugar beet (Koch, 2011) in Morocco.

Operational forecasting of cereal yields has been attempted for the first time in Morocco in 1994 (Bazza and Tayaa, 1998), for the province of Settat, as a part of AGRIMA (Agriculture Maroc) project, launched jointly by the MAPM, the Royal Centre of Spatial Remote Sensing (CRTS) with assistance from the United Nation Development Program (UNDP). In this project, proposed statistical models for forecasting cereal yields used actual evapotranspiration (ETa) as the predicting variable for Settat province. To generalize this model to other regions, a simulation model of evapotranspiration was tested. However, this experience was carried out for only one year, and could not be conclusive.

At the research level, numerous studies have tested simulation models developed in other countries in varietal selection to identify criteria of selection for wheat (Confalonieri *et al*., 2012), in agronomy research to simulate grain yields of cereals at research experiment plots (El Mourid, 1991; Bennani *et al*., 1993), in risk analysis of climatic risk in relation with choice of barley cultivar and planting date (Hanchane, 1998 and 2009), in improving wheat productivity through management of genotype and irrigation (Debaeke and Aboudrare, 2004), in irrigation management of wheat (Hadria *et al*., 2006) or sugar beet productions (Taky, 2008), etc.

Now a day, the only public institutions that realize operational agrometeorological cereal yield forecasting at the country level are from one side the consortium composed of INRA, DSS and DMN, and the other the central bank of Morocco (Bank Al Maghrib http://www.bkam.ma/). Both institutions are using pragmatic approach with different methods and tools.

The objective of the present document is to summarize research works on agrometeorological cereal yield forecasting in Morocco, including both the thinking process and the results elaborated by the authors.

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[7] AgroMetShell is a tool for monitoring and forecasting crops, developed by FAO (ftp://ext-ftp.fao.org/sd/reserved/agromet/AgroMetShell/)

[8] Major problem concerning agrometeorological simulation models is the scaling up from the experiment station field to the administrative province or region. Most variables used in modelling are obtained in small plots controlled experiments, and are difficult to find or measure on larger scales.

II. APPROCHES OF ANALYSIS

To develop a cereal yields forecasting approach, two things were needed: (1) assembling and managing a data base on meteorological, biological, agricultural, geographical, satellite and administrative variables, and (2) identifying agro-climatic indicators that correlate to yields. Satellite data were provided by our European partners, while other types of data were available in Morocco, but raw and often fragmented and discontinuous, requiring preliminary treatments. Search of yield correlating agro-meteorological indicators was first limited to indicators derived from temperature and rainfall data, independently from the cereal crops, particularly statistics of means and variances of inter region, inter and intra season variations, or else probability of occurrence of a fixed rainfall amount. Similar to climatic analyses, indicators of cereal crop production were also studied independent from climate variation. Likewise, means and variances across regions and years were computed. These analyses remained descriptive, suggesting search and validation of other indicators which integrate both the climate and the crop. New indicators of cereal yields forecasting highly correlated to yields, were explored, mainly water balance indices and vegetation indices derived from satellite imagery. Normalized Difference Vegetation index (NDVI) is delivered as an image in a "raster" format (pixel), with no distinction among the numerous land covers. Therefore, a specific land cover map was developed for Morocco, by compiling various maps available at the global level, and which were improved by adding extra information reflecting the importance of agricultural land in each pixel. Recent development of computer science tools, particularly the geographic information system, and the availability of satellite images of high resolution at low price, have opened new direction toward analyzing interactions of crops with the climate, in general and toward forecasting cereal yields in particular.

1. DATA BASE SETS USED

Agrometeorology requires compilation of data sets of different types: meteorology, soil, hydrology, biology, agronomy, satellite, geography, etc. These data sets have to be satisfactory in quality and quantity, so as to detect interrelations among agricultural environment and crop behavior. The different data sets must inter cross, spatially and temporally, so as to be able to be cross analyzed. Compilation of data, its storage, data updating including quality control, are all part of required upstream work[9].

Data sets used in this document include:

[9] Gathering and managing agro-meteorological data bases (climatic, satellite imagery, geographical, soil, etc.) need an inter-institutional effort to develop operational agro-meteorology.

- Meteorological data, mainly rainfall, solar radiation, air temperature, air moisture, wind speed and direction ;
- Satellite imagery data provided by Flemish Institute of Technology Research (VITO, Belgium) ;
- Historical data on North Atlantic Oscillation Index[10] (Hurrell, 1995) ;
- Administrative boundaries in GIS vector format of the country, the regions, the agro-ecological zones and provinces ;
- Agricultural land cover map "GICropV2" developed in collaboration with VITO in 2012 ;
- Agricultural statistical data, involving historical series of yields and areas of cereals by province.

All these data sets were compiled in a new data set entertained at the Environment and Natural Resources Department of INRA.

1.1. CLIMATIC DATA

Data sets on climate used in this document, are of different sources:

- Historical set of 35 synoptic stations, available at the Ministry of Agriculture and Marine Fishery (MAPM). These stations are part of the 44 synoptic stations of the "Direction de la Meteorologie Nationale" (DMN). Data include rainfall data from 1987 till 2011, and decadal temperature data (minimum and maximum) for the period of 1999-2009. The 35 stations are localized each in one of the provinces, the reason why their names are the same as those of the provinces. The synoptic stations of DMN operate day long for most of them (24h/24h) and produce hourly observations on main meteorological variables: atmospheric pressure, temperature, relative humidity, strength and direction of the wind, cloudiness, quantity and intensity of precipitations, insulation time, and radiation. However, these stations cover mostly costal zones, and less mountainous, Eastern and Saharan regions ;
- Long term daily historical data on rainfall and temperature from some synoptic stations, provided by DMN. Some of these data date back to the start of last century ;
- Data of Global Historical Climatology Network (GHCN, http://www.ncdc.noaa.gov/ghcnm/) (Peterson and Vose, 1997). This network provides daily temperature, precipitation and air pressure. It is managed by the National Climatic Data Center at the University of Arizona (USA). Data are collected continuously from a

[10] North Atlantic Oscillation index is generally calculated as the difference in air pressure at sea level, between two meteorological stations localized respectively at the Island depression and Azores anticyclone.

great number of fixed stations on the surface of the globe (approximately 6,000 stations for temperature, 7,500 stations for rainfall, and 2,000 stations for air pressure) ;

- Daily climatic data on rainfall, temperature max and min, sped of wind, and relative humidity, provided by the web site www.tutiempo.net which reuse data of the GHCN network ;
- FAO climatic data “FAOCLIM 2.0” (http://www.fao.org/nr/climpag/pub/en1102_en.asp; FAO, 2001). This website contain daily climatic data worldwide, including Morocco, over the period of 1960-1990 ;
- Dekadal meteorological data over a 70 years period for the rural district of Arbaoua, kindly supplied by the “Office Regional de Mise en Valeur Agricole de Loukkos” (ORMVA-L) for the PSDA project (Jlibene and Chafai, 2002). These data were used to determine periods of cultural interventions for the Loukkos region using the FAO method (FAO, 1978) ;
- World climatic data (www.worldclim.org/; Hijmans *et al*., 2005), containing among others, monthly precipitation and temperature (mean, max and min) for the 1950-2000 period, interpolated at a spatial resolution of 1x1 km ;
- Meteorological data provided by INRA automated stations, particularly the one of Meknes regional research center, for the period of 1995-2000. Hourly data were recorded in this station on rainfall, temperature, relative humidity, wind speed and direction, dew point and solar radiation.

1.2. NORTH ATLANTIC OSCILLATION INDEX

History of the North Atlantic Oscillation Index (NAO) is available for download at the website of the University of East Anglia, England (http://www.cru.uea.ac.uk/ ~timo/datapages/naoi.htm). Data on this index are available for all months of the year without interruption since 1821, which allows for reconstitution of past climatic events. It was used to demonstrate the influence of NAO index on precipitation pattern in Morocco. NAO index links the intensity of Island depression to that of the Azores anticyclone. NAO fluctuations have direct consequences on Moroccan climate (Figure 1).

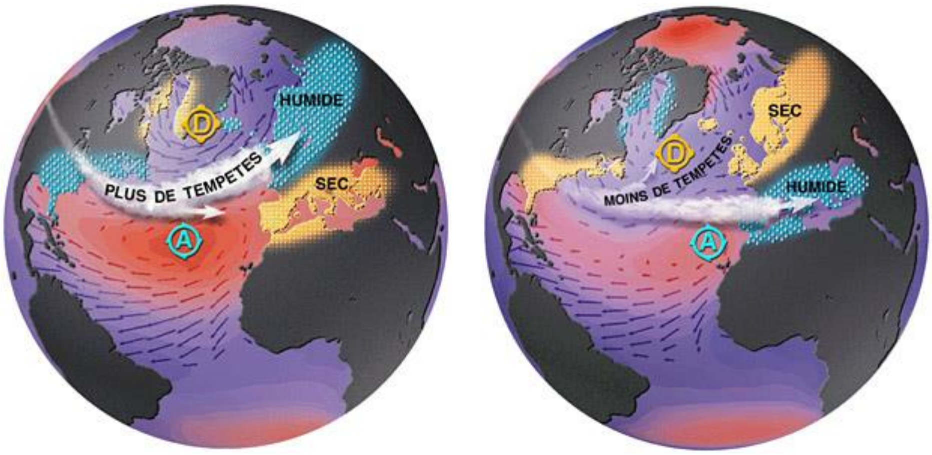


Figure 1: Positive phase (left) and negative one (right) of the North Atlantic Oscillation. At the positive phase, drought reigns over the Mediterranean region, while storms are frequent over Europe. On the contrary, at negative phase, the Mediterranean region enjoys a humid weather while Europe is less humid. ***(Source: http://www.ldeo.columbia.edu/res/pi/NAO/).***

1.3. VEGETATION INDEX FROM SATELLITE IMAGERY

With the development of satellite imagery, it was possible to develop agro-meteorological indices from the spectral reflectance of the vegetation. These indices can be used to forecast crop harvests, either directly as predicting factors in regression equations (Kogan, 2000; Maselli *et al.*, 2000; Balaghi *et al.*, 2008), or indirectly to estimate biophysical variables like LAI[11] or fAPAR[12] used as input variables to simulate growth of crops (Duchemin *et al.*, 2006; De Wit *et al.*, 2012). However, one of the major obstacles of using such indices in simulation models lies in the discrepancy between the spatial resolution of the geographic information and that of the physiological processes of photosynthesis. Physiological parameters are obtained in small experiment plots, while satellite imagery derived indices are obtained for large areas and in high frequency (dekadal) to allow agro-meteorological monitoring (Balaghi *et al.*, 2010).

Normalized Difference Vegetation Index or NDVI, as derived from NOAA-AVHRR sensor since 1980, SPOT-VEGETATION since 1988 or MODIS[13] since 2001, is one of the indices most used to measure the vitality of vegetation. NDVI has been largely used to monitor vegetation and forecast crop yields all over the world. It is computed as follows:

[11] Leaf Area Index (LAI) is the projected area of leaves in a unit area of soil surface (Watson, 1947).

[12] fAPAR is the fraction of solar radiation absorbed by plants, in the spectral range of photosynthesis.

[13] Moderate Resolution Imaging Spectroradiometry (MODIS) sensor is installed on board of satellite Terra and Aqua of the National Aeronautics and Space Administration (NASA), used for the follow up of vegetation (NDVI and EVI) at 250 meters spatial resolution.

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

Where, NIR and RED are respectively measures of reflected radiation in the near infra-red, the red.

NDVI increases progressively with increased vegetal density; from a value of 0.15 (average value) for bare soils, to a value of 0.75 (average value) for dense plant covers. One of the main benefits of using NDVI is the integration of environmental factors, in a sense that it reflects the state of global environmental stress of the vegetation, more than separate climatic variables or simulation models can do (Balaghi *et al.*, 2010). For example, water stress resulting from a prolonged deficient water balance is reflected by low NDVIs. Decreases of NDVI values can also be caused by abiotic stresses like mineral deficiency or toxicity or biotic stresses like epidemics of diseases and insects.

NDVI values are delivered on a 10-days basis for NOAA-AVHRR images since 1982 and SPOT-VEGETATION since 1999, and a 15-days basis for MODIS images since 2001. These images are pretreated by VITO before delivery, correcting for radiometric, geometric and atmospheric variations.

1.4. ADMINISTRATIVE BOUNDARIES OF MOROCCO IN GIS FORMAT

Official agricultural statistics are delivered on administrative province basis; which makes the province, the smallest territorial area for forecasting. Polygons delimiting provinces are available in a GIS format. The rural districts boundaries are also available in GIS format and can be used to forecast yields at this level when statistical yield data will made available.

1.5. LAND COVER MAPS

Different land cover maps issued from spatial remote sensing, are available for free use at the global level, with varied quality and precision. Global Land Cover-2000 (GLC2000 version 5.0, Mayaux *et al.*, 2004), CORINE-2000 and GlobCover (Tchuente *et al.*, 2010; Neumann *et al.*, 2011), were of particular interest to us. The European program CORINE Land Cover (CORINE-2000) is an inventory of 29 European states land cover from satellite images. It covers part of Morocco as well. The CORINE-2000 land cover map has a geometric precision greater than 100 m which allows for elaborating maps of less than 30 meters spatial resolution, has been updated in 2006 by the *Global Monitoring for Environment and Security* initiative (GMES) (http://sia.eionet.europa.eu/CLC2000). GlobCover initiative of the European Spatial Agency aims at producing a global map of land cover, using data of 300 meters of spatial resolution of MERIS sensor embarked on board of ENVISAT satellite platform (http://postel.mediasfrance.org/fr/PROJETS/Pre-operationnels-MES/GLOBCOVER/). Digital GlobCover land cover map elaborated in 2008 is the unique reference of intermediate resolution which covers Morocco. A land cover map for Africa is also made available for free use by the « Southern African Development Community (SADC) » (http://www.sadc.int/).

To develop a specific land cover map for Morocco, GlobCover V2.2, CORINE-2000, AfriCover[14], and SADC maps were all grouped in one map covering Moroccan agricultural territory and improved by the superposition of another map developed by USGS which provides data on the proportion of agricultural land for each pixel, reducing there after intra pixel variation. Agricultural zones of this map were extracted to serve as mask for NDVI images. Therefore, only values of NDVI of agricultural zones are saved for possible use in establishing relationship between NDVI and cereal yields.

1.6. AGRICULTURAL STATISTICS

Area and yield data of the three main cereal crops[15], soft wheat, durum wheat and barley, were graciously provided by "la Direction de la Stratégie et des Statistiques[16]" (DSS). They are available for 40 provinces of the country for the period of 1978-2011. Production at a province level is obtained by multiplying the yield value with the area estimated by DSS.

Area estimation for cereal crops in Morocco is made every year by DSS between February 10th and March 30th, using a sampling method of 3,000 unit areas representing 19 million hectares. Starting since 2008, DSS has renewed the sampling procedure to integrate modern techniques of satellite remote sensing and GIS which improved precision of estimators. A GIS application has been specifically developed for this purpose with capability of automated steps of the sampling procedure.

Within the sampled areas, sub-sampled plots are harvested and their yields directly measured. Production of a sampled area is the product of measured yield on sub-sampled plots and area represented by the sample. Data on production and area is then aggregated by province.

Monitoring of vegetation, area and yield estimations are carried out by DSS along the cereal crop cycle in three phases:

- **Phase 1:** A survey on the evolution of harvest, is done in February, to evaluate crop growth stages and vegetative stand of crops ;

[14] The objective of Africover project is to establish a numerized data base geo-referenced for global vegetation cover and geographic referential for all Africa, including: Geodesic referential, toponymic, roads, hydrographic. The polyvalent data base Africover for environmental resources is produced at a scale of 1:200.000 (1:100.000 for small countries and specific zones). www.africover.org/.

[15] These cereals are sown in the fall (autumn) and are sometimes called autumnal cereals as compared to spring cereals like corn or sorghum.

[16] Previously called « Direction de la Programmation et des Affaires Économiques » (DPAE).

- **Phase 2:** A survey on land cover, done between February and June, to estimate cereal areas ;
- **Phase 3:** A survey on expected production, done in April (1 to 2 months before harvest) to estimate production of the three main cereals: soft wheat, durum wheat and barley.

2. METHODS OF ANALYSES

2.1. EXPLORATORY TREATMENT OF RAINFALL DATA

In operational agrometeorology, the first modelling steps consist in computing basic statistics of agro-climatic variables (rainfall, temperature, yield, etc.). Simple statistics like averages, minima and maxima, or deviations, are calculated from daily or 10-days raw data of a series of crop cycles or meteorological stations. For temperature, daily average is obtained as the mean of minimum and maximum values. Monthly average temperatures are obtained as the mean of daily averages over a period of the month. The mean of 12 monthly averages represents year average temperatures. The mean temperature of a series of year's averages represents long term average. Difference between maximum and minimum of each average temperature represents thermal amplitude.

For rainfall, daily total is the sum of hourly rainfall records over a day. Likewise, 10-days, monthly or yearly averages are cumulated rainfall over each respective period. The sum of daily or 10-days rainfall data is used for better graphic visualization and interpretation, since punctual daily or 10-days[17] data graph representations for a number of years or stations are overlapping and hence difficult to interpret. An example of 10-days rainfall graphics of a series of years is presented in Figure 2.

[17] Only 10-days data on rainfall at the province level and satellite imagery were available and therefore used in all computations. 10-days rainfall data has generally proved to be sufficient for crop yield forecasting.

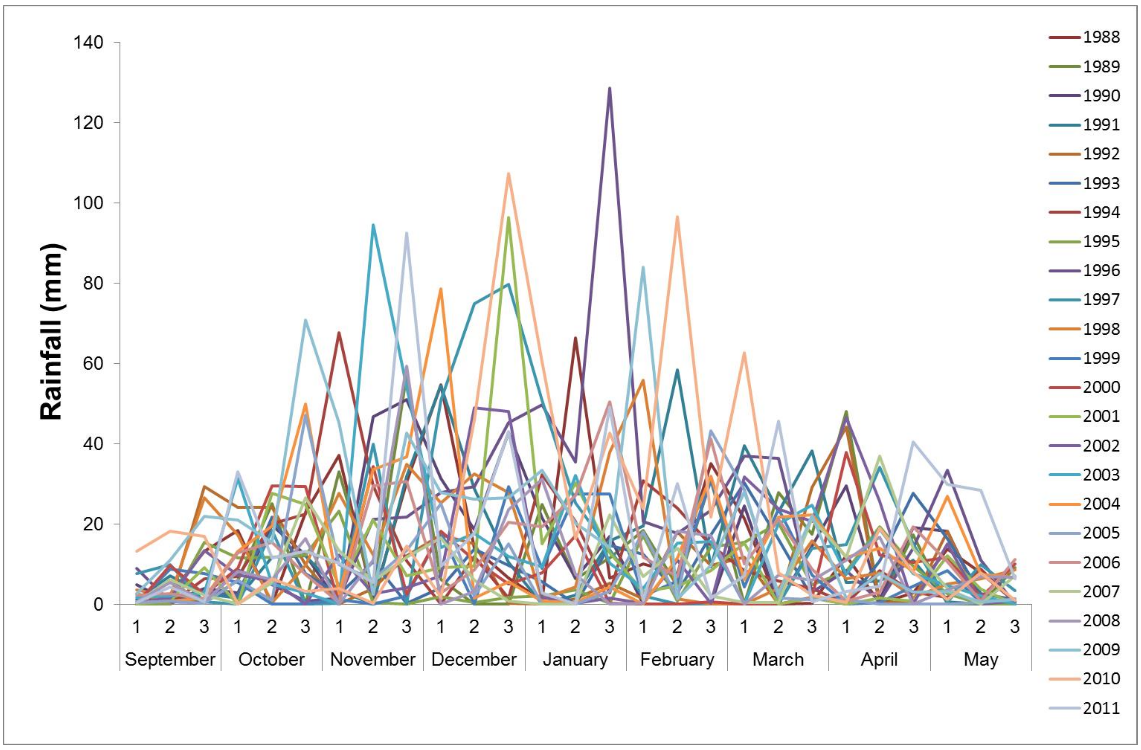


Figure 2: Country average dekadal (10-days) rainfall, of a series of crop seasons from 1988 till 2011.

The first rainfall data treatment consists simply in analyzing a graphic representation of average climatic data in the form of climograms, which indicate, for each dekad or month of the cropping cycle, the heights of average precipitations (or medians).

The next rainfall data treatment consists in cumulating rainfall over the cropping cycle for 10-days data points; reproducing clear graphs easy to interpret and even model statistically. Cumulus of rainfall has many advantages, it allows:

- Representation in a same curve, of the annual amount of rainfall as well as its distribution along the cropping season ;
- Modelling the obtained curve of rainfall by using linear, logarithmic or sigmoid equations;
- Identify and determine periods of droughts; they will appear as flat horizontal segment in the cumulative rainfall curve ;
- Comparison of different crop cycles and regions, with regard to amount and distribution of rainfall.

2.2. FREQUENCY ANALYSIS OF RAINFALL

Frequency analysis is justified for variables displaying Gaussian distribution (Nicholson, 1986), which is the case for 10-days or monthly rainfall in semi-arid regions. Frequency analysis method (or probability analysis) of rainfall has been used by Gibbs and Maher (1967) to study drought in Australia. In this analysis, values in series of rainfall data are arranged in ascending order, then limits of deciles of the distribution are calculated from a frequency curve or a table. The 1st decile represents the rainfall value that is not exceeded by one tenth of the values of the data series. Two tenths of the rainfall values are less than the 2nd decile; three tenths are less than the 3rd decile and so forth. The 5th decile or median is the rainfall value which could be received once in two seasons, dividing the data series into two groups of equal number.

Frequency distribution is one way of showing the general form of intra-annual rainfall distribution. A given season can be compared with median rainfall, which could be considered as reference value. For example, rainfall values smaller than the 1st decile indicate situations of severe drought, and those greater than the 9th decile indicate situations of high moisture. A major disadvantage of this method is that the deciles are calculated for a given dekad or a month of the season independently from other dekads or months.

2.3. OMBROTHERMIC INDEX OF BAGNOULS AND GAUSSEN

The Ombrothermic[18] index developed by Bagnouls and Gaussen (1953) is a climatic index which is used to identify dry and humid months during the season. It is simply calculated as the ratio of monthly rainfall (mm) over average monthly temperature (°C). This index was developed by these authors, for the purpose of comparing different stations over the world where periods of drought occur. Whenever the ratio is less or equal to 2, the month is considered as dry for plants, considering that evaporative[19] demand of the air is greater than rainfall supply. On the reverse, periods of the season where the index is greater than 2, are considered as wet. Dry and wet months can be identified graphically from an Ombrothermic diagram where variations of temperatures and precipitations are plotted in standardized grading: precipitation grade is “mm” and temperature grade is “°C”. Using this diagram, climates of different stations all over the world can be compared (Gaussen, 1956; Bagnouls and Gaussen, 1957). This diagram is however best adapted to the Mediterranean climate where variations of rainfall and temperature result in periods of drought and moisture. The Ombrothermic diagram was used in this document for the period of 1999-2009, since the 10-days data of both rainfall and temperature were available for only this same time period.

[18] Ombrothermic diagram includes both rainfall (Ombros in Greek) and temperature.

[19] Capacity of the atmospheric air to extract water vapor from the soil-plant system.

2.4. LENGTH OF THE GROWING PERIOD

The concept of Length of Growing Period[20] (LGP) was developed by FAO (1978) for the purpose of identifying periods of the year where moisture and temperature conditions are adequate for crop growth and development. It was later used by FAO for classifying agro-ecological zones to evaluate potential and resources of global agriculture (FAO, 1996; IIASA/FAO, 2012). It is a renewed version of Bagnouls and Gaussen (1953) ombrothermic diagram, taking into account water holding capacity of the soil and evaporative capacity of the atmospheric air.

In Morocco, the same concept was used (Jlibene and Chafai, 2002; Jlibene and Balaghi, 2009) to optimize cultural practices and placement of the crop cycle within the season, in order to minimize risks of shortage of water (drought) or excess and improve agricultural productivity in.

LGP is determined by producing classes of rainfall on the basis of potential evapotranspiration (ET0, i.e. atmospheric demand), under the following assumptions:

- An amount of rainfall above one tenth and half of ET0 is sufficient for land preparation for sowings ;
- Conditions of rainfall between half and 100% of ET0 would be favorable to plant growth and development ;
- Conditions of rainfall greater than ET0 correspond to moist periods ;
- The soil can hold a moisture equivalent to 100 mm of rainfall, which may extend the growing period longer depending on ET0.

Based on these assumptions, different periods of intervention can be determined, mainly: land preparation for sowings, date of sowings, growth period, moist period, start and end of each period.

Using this concept in Morocco, it was possible to make recommendations in terms of optimal crop cycle for cereals in the north-west region of Morocco (Jlibene and Chafai, 2002). A long series of data, from the meteorological station of Arbaoua, pertaining to the "Office Régional de Mise en Valeur Agricole du Loukkos", and consisted of 10-days rainfall and temperature.

[20] The concept of Length of the Growing Period (LGP), as defined by FAO (1978), is the period (in days) of the year where amount of precipitations is above half of potential evapotranspiration. A time period necessary to evaporate 100 mm of soil water is sometimes added, assuming that the soil water reserve is 100 mm.

2.5. ANALYSIS OF BREAKING POINT IN CHRONOLOGICAL SERIES OF RAINFALL

Long term series of monthly rainfall data were available for 15 meteorological stations at the Global Historical Climatology Network of the National Climatic Data Center of the United States of America (www.ncdc.noaa.gov). Global climatic data, including data from Morocco, are compiled and entertained by this institution. The long term climatic series for Morocco cover as much as 53 years period, variable depending on stations.

A homogeneity test was performed to identify break points in the long term series of rainfall cumulated between September and May (Balaghi, 2006). Three different tests were used: Mann and Pettitt test (Pettitt, 1979), Buishand test (Buishand, 1982) and Lee and Heghinian test (Lee and Heghinian, 1977).

2.6. PRODUCTIVITY OF RAIN WATER

Productivity of Rain Water (PRW) expressed by crops is defined as the quantity of grain produced per unit of rain water of a cultivated land area (Grams*Liter^{-1}*m^{-2}). It is equal to grain yield weight per hectare or meter squared (grams/m^{2}) divided by the quantity of rainfall (in liters or millimeters) received during crop cycle (October till April). PRW refers to productivity of green water[21] in agriculture which concerns non-irrigated agricultural lands representing 87% of total land in Morocco (MAPM, 2011). PRW differs depending on cultivation method, species, regions and seasons. It is higher for crops grown under optimal conditions of fertilization, phytosanitary protection, soil tillage, preceding crop, full or complementary[22] irrigation, etc. PRW is also higher for species and cultivars that have been genetically improved.

In arid and semi-arid environments, in particular, wheat genetic improvement consisted in developing cultivar resistant or tolerant to drought, efficient in using the limited water resources available. When the actual evapotranspirated part of rainfall by the crop during the cycle is considered, RWP is called Rain Water Use Efficiency (RWUE). Potential RWUE of improved wheat cultivars for agro-ecological zone « Bour Defavorable[23] » (unfavorable rainfed lands), has been estimated at 2.2 Grams/liter, which represents a saving of water equivalent to 0.77 mm per year and per hectare in comparison with previous cultivar Nasma (Jlibene, 2011). After three decades of genetic improvement, water savings amount to 25 mm per hectare through the use of improved new cultivars, as compared to Nasma.

[21] The concept of « green water », introduced by Falkenmark (1995), is the part of rain water that is evapo-transpired from the soil by non-irrigated crops. It is either consumed by plants (transpired) or evaporated by the planted soils. The concept of « green water » is used as opposed to « blue water », which is water of surface runoffs and underground tables used for agriculture and non-agriculture needs.

[22] Irrigation that is generally supplied as complementary to rainfall during dry periods of the crop cycle, to meet the crop needs.

[23] The word « bour » means rainfed agriculture, which concerns about 7.9 million hectares in Morocco.

RWP differs according to regions due to soil type's variation, topography and mainly changes in temperature. Hence, deep flat soils, with cool temperatures, use water more efficiently. RWP differs also depending on years due to internal variation of rainfall and temperature, being more important in uniformly distributed rainfall within the cropping season. It is also greater in environments where temperatures across the season are relatively cool, because of reduced evaporation losses. Soil can be classified with respect to RWP into three main categories of water holding capacity (Roux, 1938):

1. Sandy soils, rich in sand and gravel fine or gross, poor in loam and clay, low in hygroscopic capacity, have a limited stock of water ;
2. Clay soils, with high proportion of colloidal and fine elements, high in hygroscopic capacity, have large stock of water, but not all readily available to plants ;
3. Soil of intermediate texture, with a balanced physical composition and intermediate hygroscopic capacity, have high stock of water most of it made available for plant consumption.

These three categories of soil can be further divided with regard to soil depth, permeability of underground subsoil, and the existence of near and durable underground water table.

RWP was computed for autumn cereals at the country level, and agro-ecological zones, based on provincial agricultural statistics from DSS and rainfall statistics from DMN, for the period of 1987-2011.

2.7. PROCESSING OF SATELLITE IMAGES

Cereal yields forecasting on the basis of NDVI has been improved by two main preliminary actions on raw NDVI data:

1. First, radiometric, atmospheric, and geometric corrections have been automatically performed by the center producing NDVI images ;
2. Second, non-agricultural zones were removed from the geo-referenced map of NDVI. The layer delimiting agricultural lands is called "agricultural mask". This is a work of agro-climatologists. The objective is to produce a new NDVI map which is free of NDVI from non-agricultural origin.

The « agricultural mask» has been extracted from numerical maps of land cover, by eliminating areas of the maps that do not correspond to agricultural land, like forests, pastures, cities, lakes, rocky areas, etc. Agricultural masks available for Morocco at the moment have low spatial resolution of 1x1 Km.

For this size, corresponding to 100 hectares, pixels identified as originating from agricultural land, may not be entirely covered by agriculture. Therefore, another precision is added, consisting of a new layer, i.e. the proportion of agricultural land in each pixel, a variable called "Area Fraction Image" (AFI). This map is available in higher resolution than existing agricultural masks.

By using pixels that are predominantly covered by agriculture, the relationships between NDVI and yields of the three cereal crops (soft wheat, durum wheat and barley), have been improved; despite the fact that a pixel's NDVI is a reflectance from more than one crop. Three main reasons for these improved relations: (1) cereals occupy most agricultural lands (5 of the 8.7 million hectares); (2) the three species react almost simultaneously to variation of rainfall; and (3) spontaneous vegetation (or weeds) responds to rainfall in a similar way. However, the agricultural mask can further be improved, if the area specifically covered by cereals could be identified. This work is under investigation by INRA, DSS, and DMN, as part of the project « *Crop Monitoring as an E-agriculture tool in Developing Countries* » (E-AGRI, http://www.e-agri.info/), financed by the European Union in its 7th *Framework Programme for Research and Technological Development*.

Images of NDVI corresponding to corrected agricultural mask are then subdivided into polygons to fit the administrative boundaries of the country, the provinces or the agro-ecological zones, using respective specific GIS layers. Spatial resolution used depend on the importance of the area for which yield is predicted. Average NDVIs of all pixels within administrative boundaries are then calculated to generate yield predictors for these geographic and administrative unit areas.

2.8. CEREAL YIELD FORECASTING APPROACH

The cereal yield forecasting approach for Morocco has been developed by INRA, in collaboration with the University of Liège, VITO and JRC, using a combined approach which relied on several methods of yield forecasting, mainly:

- Analogy analysis, using rainfall or NDVI ;
- Linear[24] regression, simple or multiple, using rainfall and NDVI data ;
- Models of simulation of growth and development of crops. The simulation model WOFOST[25], which quantifies growth and production of annual crops, was used in the forecasting of cereal yields.

Unlike agrometeorological modelling which is considered as basic research and oriented toward scientific publications, operational forecasting of harvests has economic, social and political implications on the society, leaving little room for error. In high level decision making, an error of

[24] A very interesting lecture on linear regression models is given by Kutner *et al*. (2005).

[25] WOFOST (WOrld FOod STudies) is a simulation model for the quantitative analysis of the growth and production of annual field crops. It is a simulation model from "Wageningen family" (van Diepen *et al*. 1989; Supit *et al*. 1994; Hijmans *et al*. 1994; Van Kraalingen *et al*. 1991).

forecasting can ruin the reputation and even the carrier of whoever is making this error. Estimating the error of forecasting is hence necessary for quality systems of crop harvests forecasting. For example, JRC considers an error of forecasting of 3% as low giving high precision, and as acceptable as long as it is less than 6% (Genovese and Bettio, 2004). The European crop forecasting system "Crop Growth Monitoring System" (CGMS) predicts yields of main crops in Europe with an error of 3% to 5%; higher for durum wheat (8.6%). In absolute terms, this error is equivalent to 2 to 4 Q/ha for wheat yields at the level of European countries (Genovese, 2001). The CGMS system is an output of the European project « Monitoring Agricultural ResourceS » (MARS) carried out by the Joint Research Centre of the European Commission (JRC) of General Agriculture and Rural Development of the European Commission. The CGMS system provides, in an operational way, crop harvest forecasts over Europe, in due time, at the regional and country levels. It monitors crops development along the season, based on meteorological conditions, soil characteristics and crops parameters. The heart of CGMS system is based on the deterministic crop growth model called WOFOST. The CGMS system has three levels (Figure 3):

1. **Level 1**: Monitoring meteorological data and interpolating them over a square grid ;
2. **Level 2**: Simulation of growth for major crops ;
3. **Level 3**: Yield forecasting of crop harvests.

An organizational scheme of the CGMS model is presented in Figure 3.

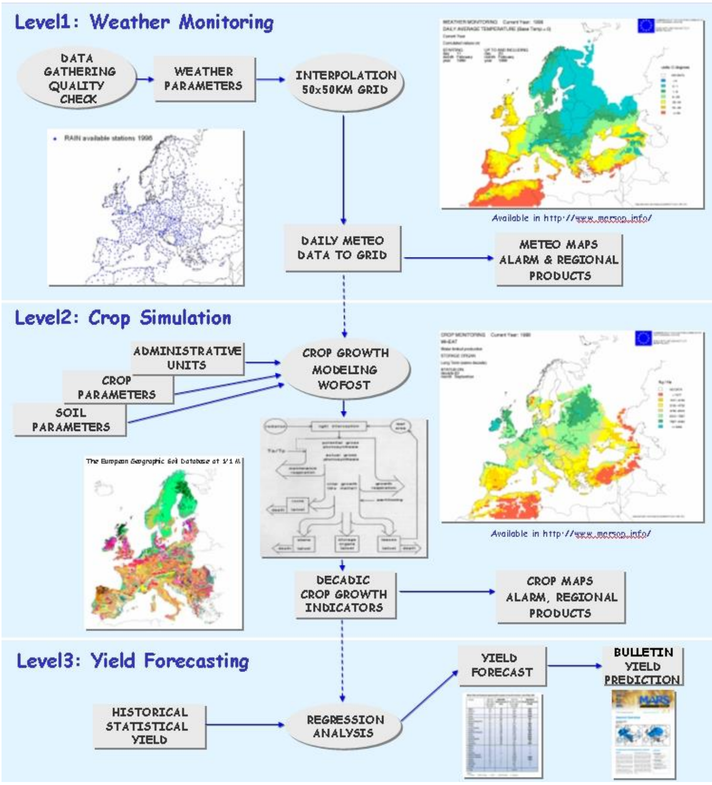


Figure 3 : Crop Growth Monitoring System (CGMS) for crop harvests forecasting.
http://mars.jrc.ec.europa.eu/mars/About-us/AGRI4CAST/Crop-yield-forecast/The-Crop-Growth-Monitoring-System-CGMS

The combined approach offers a wide range of options for crop yield forecasting, as different independent methods can be used simultaneously. It is used when none of the empirical or simulation approaches available can predict crop yields with a satisfactory accuracy. This is the case in operational forecasting where factors that affect crops development are complex and difficult to measure and model. Combined approach is based on the use of expertise in agronomy which offers flexibility to adapt to variations in database and limiting environmental factors (rainfall, temperature, soils, pests and diseases, etc.). The combined approach is an alternative to simulation approaches which cannot estimate forecasting[26] error. Also, simulation approaches are not entirely adapted to procedures of calibration and validation because they generally produce no replicated estimates and hence no variability of the estimates to use in usual statistical tests of comparison with observed samples (Sinclair and Seligman, 2000; Van Oijen, 2002).

2.8.1. TECHNOLOGICAL TREND

One of the major problems in operational agrometeorology, in general, and crop yield forecasting in particular, is the confounding effect of environmental factors with technology (fertilization, irrigation, variety, phytosanitary treatment, etc.) and economic ones, which have a tendency to influence yields over a long period of time (Gommes *et al*., 2010). A hypothetical example is illustrated in Figure 4:

- Technological trend (curve F1) has a direct influence on yields over long term (curve F3) ;
- Economic policies (such as price) also influence the trend in yields (curve F2), since they can encourage or discourage the use of inputs ;
- Extreme weather factors, such as floods, hail, etc., can instantly influence crop yields, as well (curve F4).

In general, technological trend is difficult to quantify as agricultural statistics in Morocco are aggregated by province, region or dry vs. irrigated areas, therefore encompassing a multitude of various inextricable agronomic situations. Based on agricultural statistics, it is generally difficult to distinguish between the effect of the technological trend of price effects, inputs and extreme factors. By product, the technological trend is considered to crop yield trend from a long period of time.

[26] A major disadvantage of deterministic simulation models is that they produce predictions with no error associated with the estimates. A solution can be found using a holistic approach, where running a simulation model over climatic variables and parameters associated with a probabilistic distribution as to obtain all probable estimates and their statistical distribution (Allard *et al*., 2009). It is an indirect way of measuring prediction error in deterministic models.

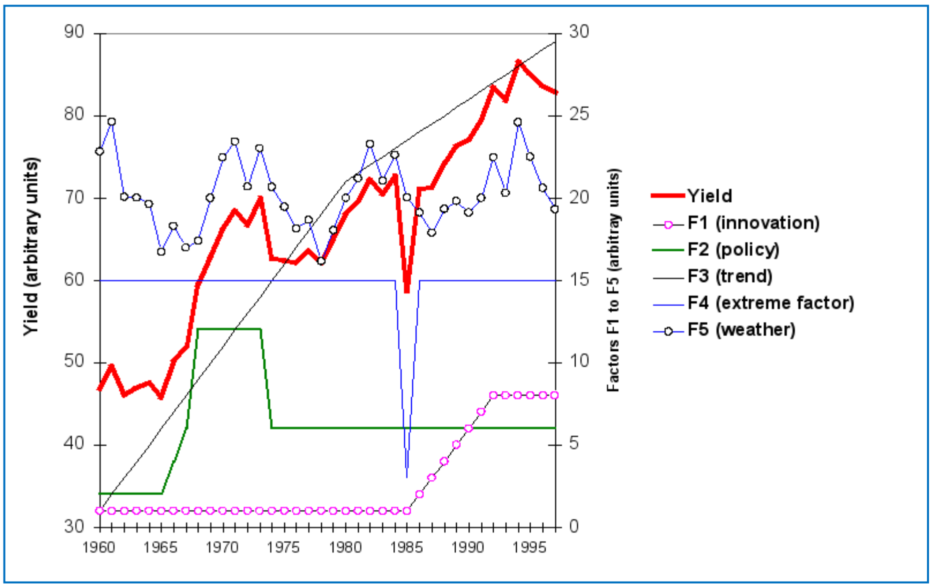


Figure 4: Hypothetical example showing how crop yields (red curve) can be influenced by weather, technology innovation, policy, extreme factors and general trend (Source: Gommes *et al*., 2010).

2.8.2. SIMILARITY ANALYSIS

Similarity analysis[27] is an effective, fast, and easy means for forecasting cereal yields. It consists in identifying, among past cropping seasons, those that are agro-climatically similar to the one concerned with crop yield forecasting. It is a statistical analysis that assumes that a cropping season of similar agro-climatic conditions to past ones would result in similar crop yields, all other factors assumed to be equal. This approach can be used only if a cropping season with similar climatic conditions can be found in the past seasons. Consequently, a long chronological series of weather data is necessary to encompass large agro-climatic variation, and to include the particular situation under study. Obviously, specific copping seasons, like extremely moist or extremely cold ones, have little chance of being encountered within historical seasons, and will be forecasted with higher error. While this approach refers to real past agro-climatic situations, crop yields forecasted on the basis of similarity analysis have to be adjusted for technological trend (cultivar, sowing, fertilization, machinery, irrigation, crop protection, harvest etc.) achieved so far during the time difference among the similar cropping seasons. For this type of analysis, it is also possible to associate a forecasting error, considering that similar seasons, if any, are a sample of all similar seasons.

[27] The concept of similarity analysis is used by meteorologists to quantitative forecast precipitation. It assumes that the evolution of atmosphere is not random, but is governed by physical laws. Therefore, future evolution of precipitation for example can be predicted, based on the precipitation pattern early in the season, using deterministic, probabilistic or similarity models. Refer to Bontron (2004) for further readings on this subject.

Similarity analysis can accommodate different kinds of analyses: visual graphics, simple statistical techniques, Euclidian distance, principal components, or *cluster analysis*. One or more agro-climatic factors, such as rainfall, or temperature, or indicators of vegetation such as NDVI or DMP[28], can be easily used for analysis, using simple computing facilities like spread sheet or usual statistical procedures. Similarity analysis has been used at INRA, to forecast cereal yields as early as the month of February, using rainfall or NDVI. As a matter of facts, while climatic conditions of the months of March and April are determinant for final cereal yields, premises of a bad of good cereal harvests are perceivable as early as end of February. The method, simple as it is, consists of computing for each dekad (10 days), the absolute difference between respective values of the agro-climatic variable used (rainfall or NDVI) of the cropping cycle of interest and those of historical cycles, integrated over the cropping season. When the rainfall variable is used, the cropping cycle extends from the first dekad of September to the 3rd dekad of April. For NDVI, means of dekadal NDVI, over the period of first dekad of February to last dekad of April, are computed. A table of absolute differences is then obtained, with dekads in columns and previous cropping seasons in rows. From this table of absolute differences, averages across seasons by dekad (column average), between February and April, are computed. Cropping cycles similar to the season of interest, are those that deviate little from average values across seasons of absolute differences. Several cropping seasons can be identified as similar to the season of interest, with however differences among dekads within the cropping cycle. Yields of similar seasons are averaged to estimate yield of the cropping season of interest. Yield of each cropping season can also be weighed according to the relative distance from that of the season of interest. Due to inter-dekads variation, a confidence interval of the weighed mean can be calculated. Similarity analysis relies on the principle of likely neighborhood, with no distinct cutting point. Choice of how far a cropping seasons is similar is hence subject to the forecaster's appreciation, depending on his/her experience and knowledge of past agro-climatic situations.

2.8.3. LINEAR REGRESSION ANALYSIS

Linear regression analysis using the ordinary least squares method is a way to identify relationships between crop yields and agronomic, environmental or economic variables used as predictors. Agronomic predictors include inputs (water supplied, fertilizers, herbicides, pesticides, sowing and harvest times) and methods of their application. Major climatic factors include rainfall, and temperature, while NDVI and water balance are among environmental indicators, and price of harvested crop, production cost are among major economic indicators. Indicators other than those representing direct agronomic and climatic inputs can advantageously be used to improve yield

[28] Dry Matter Productivity (DMP, http://www.geoland2.eu/) is an indicator of plant biomass growth rate derived from remote sensing images of SPOT-VEGETATION and meteorological data, on a 10-dayss basis and a 1km spatial resolution. It is expressed in kilogram per hectare and per day. Preliminary results of using this index in Morocco in E-AGRI project, indicate a promising potential use in cereal yields forecasting.

forecasting. For example, NDVI, which is an indirect measure of biomass dynamics, integrates conditions of rainfall, temperature, soil water balance, agronomic practices, and any other factor or condition affecting biomass production. However, contribution of any of these factors to NDVI is hard to quantify. Predictors can be a quantitative variable like temperature, rainfall or NDVI, as well as qualitative like presence or absence of drought, phenomena of alternance of some fruit trees, and can be used separately or in combination. In Morocco, relevant predictors worth considering in cereal yield forecasting include: rainfall, temperature and vegetation indices (NDVI and NDVI derived). They can be computed for the entire cropping cycle or for parts of the cycle, and used in simple linear regression models with yield or in combination in multiple regressions (Balaghi *et al*., 2008). In a multiple regression model, variables must be carefully chosen to avoid collinearity[29] between variables, using statistical procedures of variables selection like « *Stepwise* », « *Forward* » or « *Backward* » (Kutner *et al*., 2005).

[29] Collinearity problems have been often encountered in agrometeorology because climatic or environmental variables are never completely independent from each other. These variables can be considered as measures of a same but different local, regional or global climate.

III. ANALYSES OF MOROCCAN CLIMATE

Exploration of climatic indicators, correlated to cereal yields to be used as predictors, focused on characteristics of rainfall, temperature and derivatives. First, long term yearly averages were used. Rainfall average over the country appeared to be highly influenced by North Atlantic Oscillation. This influence has been cited in the literature for winter precipitations and verified also for total season precipitations, as well as winter ones using historical rainfall data at the country level. Season rainfall is variable from year to year, but relatively homogeneous on the long run, until 1980 where a change point in rainfall series has been statistically identified in many meteorological stations, resulting in a clear rainfall decrease. Due to this change, forecasting the behavior of crops in relation with the climate should be done using recent series, starting from 1980. Detailed analyses of the within cropping season variation of rainfall and temperature have been undertaken, using climatic data of series after this change point (i.e. 1980). Rainfall increases with increased latitude, and increased elevation in agricultural zones. Temperature, on the opposite, decreases with increased latitude and elevation. Low temperatures are encountered in mountains, high temperatures in Saharan regions of Morocco, and cool temperatures are encountered in coastal areas. Average temperature of the country varies little from year to year. Intra cropping season variation of temperature is also low from year to year, with more stable temperatures during the spring season than the winter. Rainfall, however, varies enormously from one cropping season to another. In general, rainfall of the cropping season does not follow a Gaussian distribution. Unlike normal distributions, means and medians of annual rainfall do not correspond, with medians being on the dry season side. Annual distribution of rainfall is, for example, of Gamma type in the Meknes region where average rainfall is close to median, of Log-Logistic type in the provinces south of Meknes (Khemisset, Settat and Safi). Despite this high year to year variation, distribution of intra-season rainfall is relatively stable, with a rate of accumulation of dekadal rainfall fitting a simple linear regression, and where the slope of the regression is generally an indicator of the whole season rainfall. Ombrothermic index and Length of the Growing Period (LGP) has been studied, using Ombrothermic index (ratio of rainfall over temperature) and FAO method (ratio of real evapotranspiration over rainfall) both based on rainfall and temperature. The Ombrothermic index shows, a growing period of six months long on average, situated between the months of October and March, but variable from 2 months in Saharan regions to 8 months in the mountains. The FAO method provided an estimate of LGP in addition to periods of cultural interventions, taking into account the water capacity holding of soils. However, due to climate change, LGP and its position in the cycle may be modified.

1. INFLUENCE OF NORTH ATLANTIC OSCILLATION

The climate in Morocco is under the influence of extra-tropical circulation modes (Ward *et al*., 1999; Glueck and Stockton, 2001; Herrera *et al*., 2001; Knippertz *et al*., 2003). Geographically, there are three relatively homogeneous regions (in addition to Moroccan Sahara) with regard to precipitations (Knippertz *et al*., 2003):

1. Atlantic region which includes northern and western parts of Morocco ;
2. Mediterranean region which includes north-east of Morocco, north-west of Algeria on the Mediterranean coast ;
3. Southern region, which includes all Moroccan or Algerian regions, south of the Atlas Mountains.

Differences in precipitation pattern between the three regions are probably due to orography, as they are separated by the Mountain chains (High Atlas, Middle Atlas, Anti-Atlas, and Rif). In addition to the North Atlantic Oscillation (NAO), rainfall during the winter season in the Atlantic region is influenced by the southward shift of medium latitude disturbances, by local depressions, and by advection from the west bringing wet air. Winter precipitation in the Mediterranean region is resulting from the western Mediterranean depressions and moist air advection from the northwest.

The region south of the Atlas Mountains has a more complex winter rainfall, resulting from the transport of moisture from the Atlantic along the southern flank of the Atlas Mountains via a stream south, enhanced cyclone activity at the Canary Islands and the occurrence of cyclones in the southwest of the Iberian Peninsula (Driouech, 2010).

The North Atlantic Oscillation (NAO) has a great influence on precipitation in Morocco, as shown in Figure 5 by the strong negative correlation between the NAO index and rainfall. The average index of the NAO, during the months of September to February, explain three-quarters (R^2 = 74%) of the variation of the national average rainfall (cumulated from September till May) (Figure 5).

El Niño (ENSO) austral oscillation exerts also some influence on precipitations in Morocco. The warm phase (positive) of the ENSO phenomenon is associated with a reduction in precipitations, particularly during the spring season (Nicholson and Kim, 1997; Ward *et al.*, 1999).

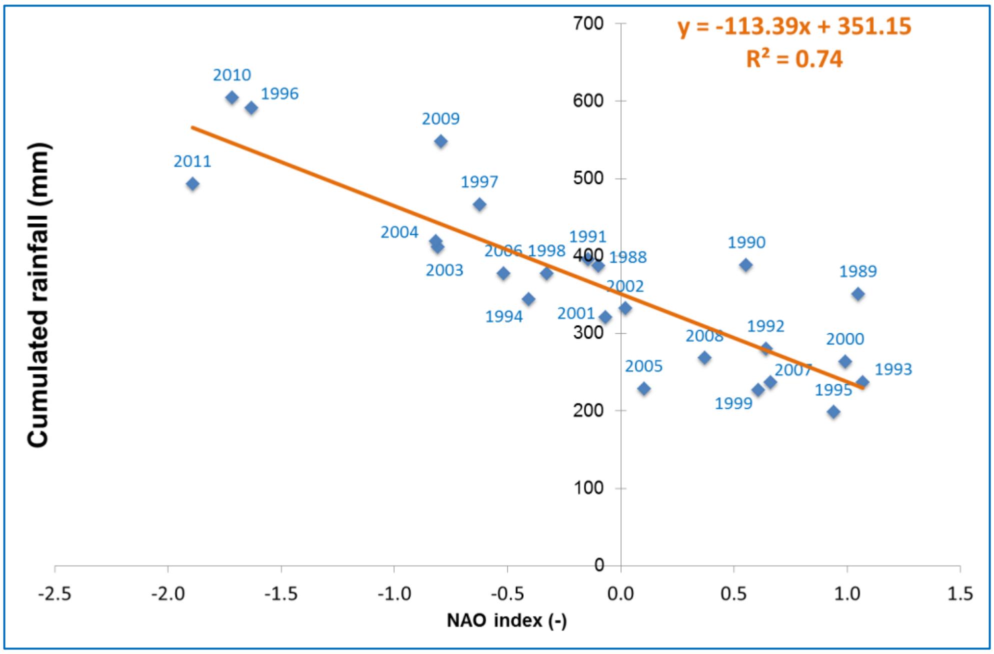


Figure 5: Correlation between the North Atlantic Oscillation (NAO) index, averaged from September to February and cumulated precipitation from September to May in Morocco (data of 1979 to 2011)

2. CLIMATE CHANGE

A change point analysis performed on 15 Moroccan meteorological stations, detected a break in the time series of rainfall around 1978 and 1981, for five of the 15 meteorological stations (Balaghi, 2006) (Table 2). For some stations (Tangier, Kenitra and Ouarzazate) change points was detected at earlier dates. Annual rainfall decreased drastically after 1980, by 151 mm in Meknes and Oujda, and by 82 mm in Fes, corresponding to a reduction of the annual rainfall of more than 25%. The change point analysis also showed that the climate remained steady, from the 1980 onward, from a statistical point of view. Of course, three very wet seasons of 2008-2009, 2009-2010 and 2010-2011 were exceptional. These results are also consistent with the work of Hurrell and Van Loon (1997) in their analysis of anomalies caused by North Atlantic Oscillation on the southern part of Europe and the Mediterranean. Both authors have detected particularly dry periods between 1981 and 1994 as compared to the period of 1951-1980. The rainfall change was also observed, during the 1970s in the West and Central Africa, but more significantly in the northwest of this region (Paturel *et al.*, 1998). Morocco seems to have been very sensitive to global warming since the drastic reduction of rainfall that occurred in Morocco, has coincided with the rapid increase in air temperature across the globe (Brohan *et al.,* 2006). Since 1979, the rate of warming has been twice as fast on land than on the ocean and in the last century, the Arctic has warmed by almost twice the global average rate (IPCC, 2007). In addition to the decline in rainfall, the climate warmed significantly in Morocco, during the period 1961-2008, from 0.2 to 0.4 °C per dekad (Driouech, 2010).

Table 2: Change point analysis in chronological series of cumulated rainfall between September and May, at the provincial level (Source: Balaghi, 2006).

Province	Series	Rainfall	Change point Test		
		Average (mm)	Mann and Pettitt	Buishand	Lee and Heghinian
Tangier	1932-2004	770	1948 (0,0262)	(0,0001)	1948 (0.3214)
Tetouan	1938-2004	671	ns	ns	1971 (0.1669)
Kenitra	1951-2004	571	1972 (0,0375)	(0,1000)	1972 (0.1697)
Meknes	1932-2004	535	1980 (0.0009)	(0.0001)	1980 (0.2618)
Rabat	1931-2004	510	ns	ns	2002 (0.1435)
Fes	1915-2004	483	1978 (0.0846)	(0.1000)	1978 (0.0970)
Casablanca	1903-2004	399	ns	ns	1978 (0.0271)
El Jadida	1932-2004	371	ns	ns	2002 (0.0555)
Safi	1901-2004	353	ns	ns	2003 (0.0403)
Settat	1910-2004	353	1942 (0.0861)	(0.0500)	1980 (0.0781)
Essaouira	1894-2004	305	ns	(0.1000)	1898 (0.1362)
Oujda	1932-2004	297	1981 (0.0045)	(0.0001)	1981 (0.2376)
Agadir	1922-2004	232	ns	ns	Ns
Marrakech	1919-2004	229	ns	ns	1919 (0.2433)
Ouarzazate	1932-2004	91	1950 (0.0842)	(0.1000)	1950 (0.1564)

Ns: non-significant test.

This rainfall change in Morocco has also been observed by Knippertz *et al.* (2003), and Chaponniere and Smakhtin (2006), Driouech (2010) and Sebbar *et al*. (2011). The decline was mainly severe in areas of the Middle Atlas Mountains and arid areas of the Oriental zone. Knippertz *et al.* (2003) explained this change by disturbances of the North Atlantic Oscillation, but no explanation of the underlying causes was given.

Rainfall reduction that occurred around 1980 in Morocco had a direct impact on agricultural research strategy at INRA. The institute indeed launched in 1981 an ambitious research programme for arid and semi-arid environments, named « Aridoculture[30] Research Programme», in collaboration with the Mid-America International Agricultural Consortium composed of five American universities of the Middle West (MIAC), and with financial support from the Agency of International Development of the United States (USAID) and the government of Morocco. The objective of the Aridoculture Research Programme was to increase and stabilize the production of cereals, food legumes and forages in arid and semi-arid environments of Morocco (250 to 450 mm/season), while developing profitable production systems to improve the rain use efficiency. In terms of agrometeorology in particular, this change point in rainfall led INRA revise its climate analysis methodologies toward a research programme on cereal yield forecasting in the objective of

[30] The term « aridoculture » is not recent, dating back at least to the 1950s, having been quoted by Varaldi-Conia in 1953. It originates from the word "dry farming" imported from the United States of America. Already at the beginning of last century, Augustine (1910) launched an advocacy in favor of this type of agriculture in North Africa.

country's food security. A new research opportunity in the field of agrometeorology has led its way to agricultural research during the recurrent droughts between 1980 and 2008, during which agricultural production became more than ever dependent on rainfall conditions.

A major conclusion of all this work is that the analysis of the climate in Morocco could now be carried out, on the homogeneous series of rainfall after the change point which occurred around the year of 1980. Revealed break also meant that it became hazardous to forecast future climate behavior based on past experience prior to 1980, including the use of frequency analysis. The recommended series for analyzing Moroccan climate must take account this change point, and therefore include data series posterior to 1980.

3. TEMPERATURE

3.1. SPATIAL VARIATION OF TEMPERATURE

The long term average of **mean temperature** in Morocco (average over 1950 to 2000) varies geographically from 22 to 24 °C in summer and 12 to 14 °C in winter, a variation range from 1 to 2.25 (Figure 6A) . The lowest temperatures are encountered in the mountains and the highest in the desert. The daily cumulated average temperatures between September and May is maximum in the Sahara site Laâyoune, (7,860 °C) and minimum in the Mountain site Ifrane, (5,110 °C). The variation in average temperatures between stations remains low, ranging from 11% at the beginning of the season to 9% at the end of the season.

The long term average of **minimum temperature** (1950-2000) of the coldest month varies from -15.0 to -13.6 °C (range of variation of 1 to 2) and decreases from the Atlantic coast to the mountains (Figure 6B). In general, the highest minimum temperatures occur in desert areas. Some varieties of cereals, of winter type, fail to flower and produce seed if they do not accumulate enough cold early in their cycle, and remain in a vegetative state. This kind of event has happened several times in Morocco, when imported barley grain from Europe and distributed to farmers for animal feed was planted. It is therefore necessary to be aware of the cooling requirements of introduced varieties from cool regions like those in the northern hemisphere, before growing them.

The long-term average of **maximum temperature** of the hottest month, which is usually July (1950-2000), varies from 22 to 46 °C, a wide range. In general, the highest temperatures occur in the desert areas and the lowest maximum temperatures occur in the mountains, but also on the sea coast (Figure 6C). The average daily temperatures accumulated between September and May is highest in the *Saharan* site Laayoune, (7,860 °C x days) and lowest in Mountain site Ifrane (5,110 °C x days). The variation in average maximum temperatures between stations remains low, ranging from 11% at the beginning of the season to 9% at the end of the season. Biologically, high temperatures can have negative effects on grain, at flowering, photosynthetic process and mobilization of carbohydrates to grain. At the metabolic level, proteins, especially enzymes responsible for the synthesis, denature at high temperatures and lose their primary functions.

Temperature range or amplitude, as a difference between maximum and minimum temperatures, varies on average from 5.7 to 17.5 °C (a range of 1 to 3) with the highest amplitude obtained in the Mountains and surroundings (Figure 6D). The lowest amplitude is encountered on the coastal areas. Geographical distribution of crops species depends largely on this amplitude. For example, tropical crops like Banana tree thrive on the coast where temperature amplitudes are lowest.

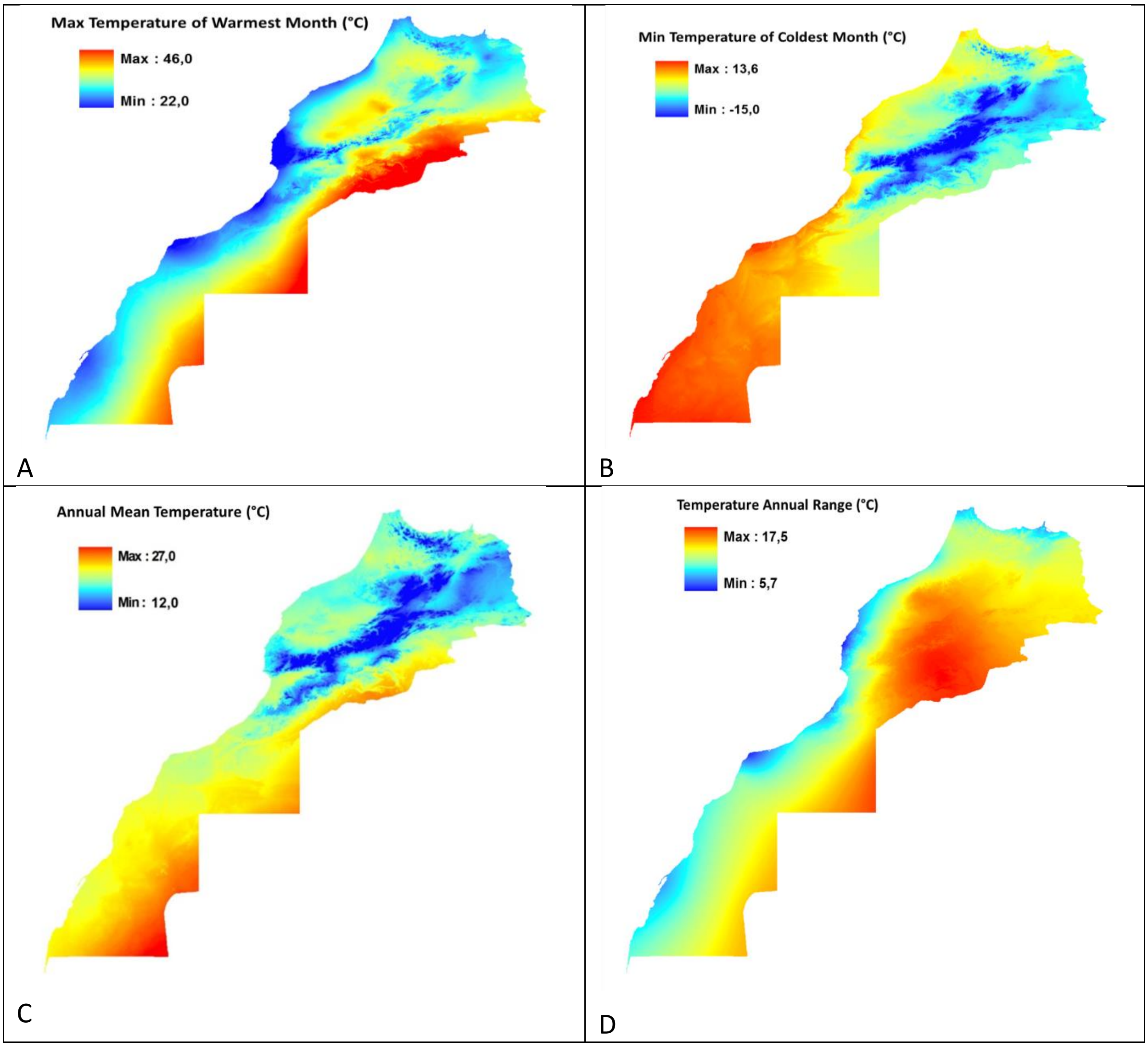


Figure 6: Maximum temperature of the warmest month (A), minimal temperature of the coldest month (B), annual mean temperature (C) and temperature annual range (D) in Morocco (these maps were created from data taken from www.worldclim.org at the spatial resolution of 1 km, Series from 1950 to 2000, Hijmans *et al*., 2005)

Temperature affects plant development as a whole; it is particularly a major determinant of plant phenology. Effects of cumulated temperature on the development of phenological stages of crops have been largely documented in the scientific literature, mainly on wheat which requires a specific sum of temperatures. In Morocco, soft wheat reaches flowering stage at approximately a cumulated sum of daily temperatures of 1,750 °C x days an physiological maturity at 2,750 °C x days, variable according to water and mineral conditions of the crops. Obviously, variation from station to station in phenological stages development is associated with variation of cumulated temperatures. For wheat, length of the biological cycle increases with reduced temperatures, from south to north, and from the plains to the Mountains. Range of variation in wheat flowering and maturity between extreme cereal regions (south vs. Mountain) can be as high as three months. Wheat harvest starts mid-May in the Southern provinces of Rhamna and Abda and ends three months later in the Atlas Mountain regions.

3.2. INTER-ANNUAL VARIATION OF TEMPERATURE

Similar to rainfall, inter-annual variation of temperature, at the country level, can be apprehended using cumulated daily temperatures[31]. Cumulated daily temperatures between September and May (in °C), averaged over 35 synoptic stations used to compute country average, is relatively stable among years, with a low variation of 10.47%. Range of variation amounts to 475 °C x days at the end of May, ranging from a minimum of 4,300 °C x days during the 2008-2009 cropping season to a maximum of 4,775 °C x days during the 2002-2003 cropping season (Figure 7).

Differences between cropping seasons in cumulated temperature are expressed between September and mid-February. After mid-February rate of increase in temperature is similar for all seasons, as indicated by paralleled curves in Figure 7. Spring temperatures seem to be stable across seasons, as opposed to autumnal and winter temperatures.

While variation of cumulated temperature until the end of May is low, it is maximal at the 3rd dekad of February (CV=4.9%), and minimal (CV=2.9%) at the 3rd dekad of May, indicating that most of the temperature variation occurs during the winter. However, data series used was limited to the period of 1999-2009. The 2008-2009 cropping season had an exceptionally high and regularly distributed rainfall, and cool temperatures.

[31] The concept of sum of temperatures (or degree x days) is used to express the plant requirements for an accumulated quantity of heat. It is influenced by genetic variability of cultivated plants, extreme heat spells, need for low temperatures, water constraint and photoperiodism. This concept is used in numerous models of agrometeorological simulations of crops and pests development.

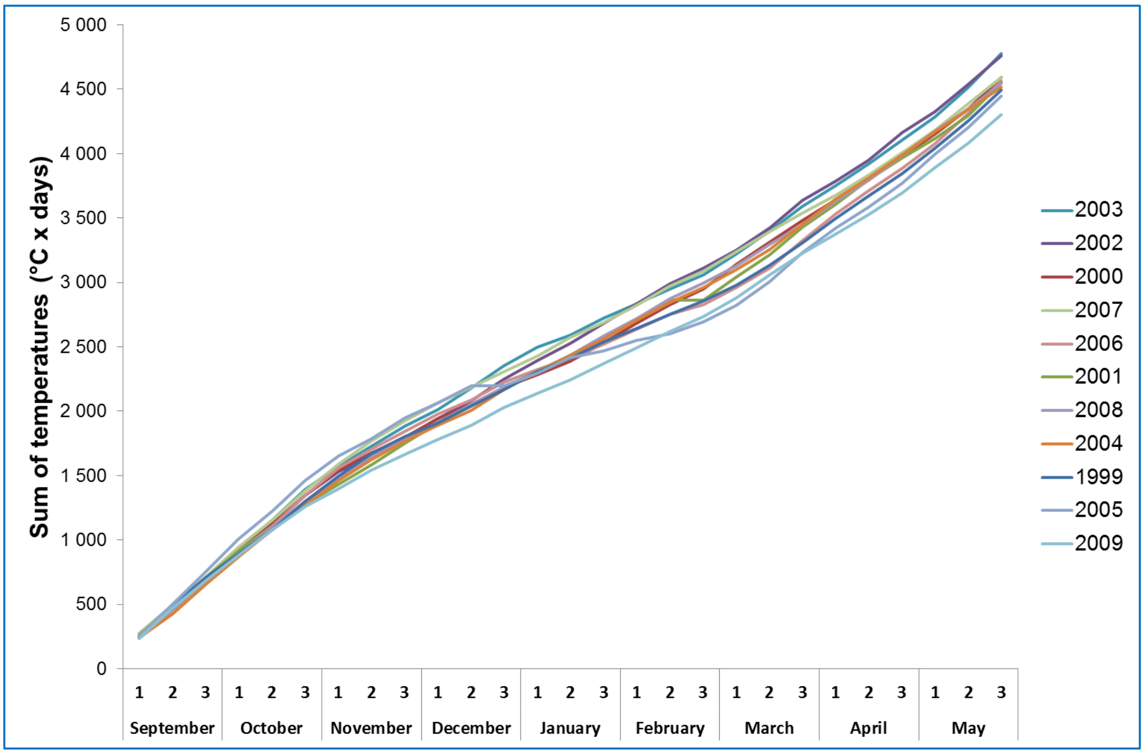


Figure 7 : Sum of daily average temperatures, in growing degree days, along cereal cropping season, at the country level. Growing cycles from 1999 to 2009 (year of harvest) are sorted out in descending order of cumulated temperature.

Unlike, year to year variation of cumulated temperature at the country level, it is higher at the level of meteorological stations. For Meknes station, for example, the variation increases starting from September, to a maximum in February, and decreases there after (Figure 8). Coefficient of variation fluctuates between a minimum of 7.5% at the start of the season (September) to a maximum of 42.5% in the winter (February). This increase in temperature variation between September and February explains increased divergence among curves of cumulated temperatures shown in Figure 7.

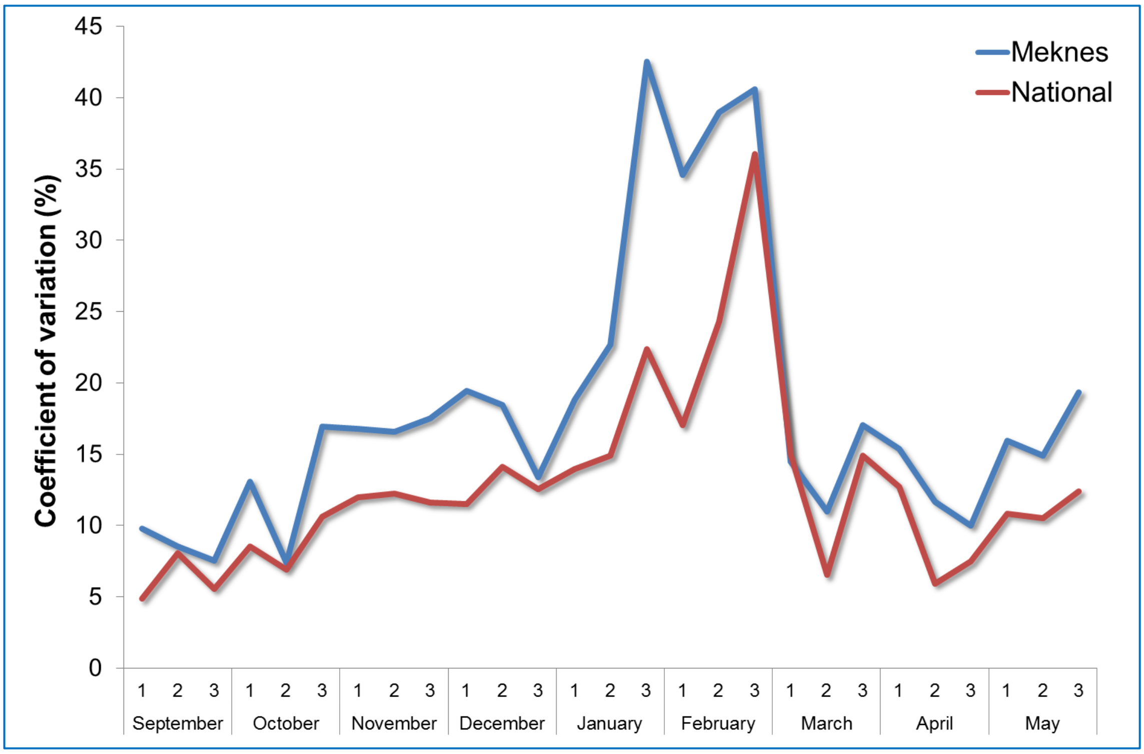


Figure 8 : Evolution of coefficient of variation of average inter-annual dekadal temperatures at the country and Meknes levels (data of 1999 to 2009).

3.3. SEASONAL VARIATION OF TEMPERATURE

Temperature in Morocco is high in summer (July, August and September), diminishes progressively to attain a minimum in winter (between December and January) and increases in spring (starting from February). Along the cropping season, dekadal maximum temperature decreases on average from 32.3 °C at the first dekad of September to 18.5 °C at the last dekad of December (data series of 1999 to 2009), a drop of 13.8 °C (Figure 9); minimal dekadal temperature also decreases on average from 17.2 °C at the first dekad of September to 3.8 °C for the last dekad of January, a drop of 13.4 °C, similar to maximum temperature.

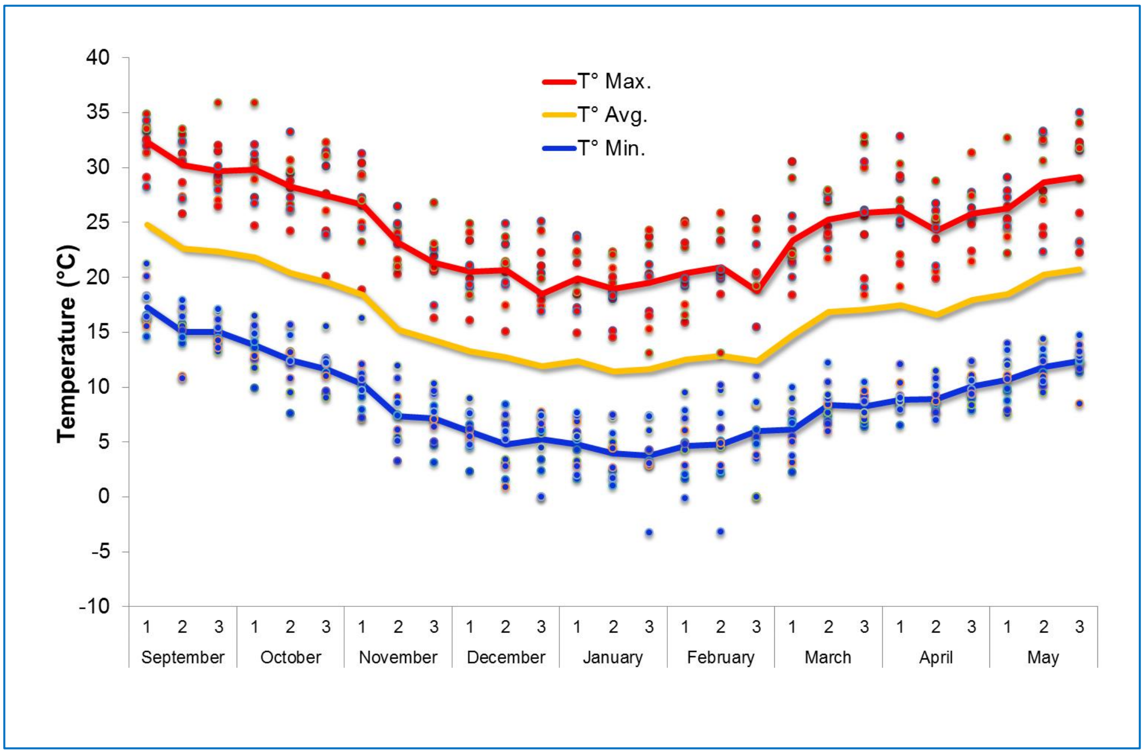


Figure 9 : Average maximal (red curve), mean (yellow curve) and minimal dekadal temperature (blue curve), along the cereal growing season. Red dots correspond to dekadal values of maximal temperature and blue dots to minimal temperature, from 1999 until 2009.

4. RAINFALL

4.1. SPATIAL VARIATION OF RAINFALL

The first rainfall map of Morocco was elaborated by the German geographer Theobald Fischer early 1900. It contains some errors due to lack of meteorological observations and to meager technical resources at that time. Many rainfall maps have been developed since then, with varied degree of accuracy (Augustin, 1921; Jury and Dedebant, 1924; Roux *et al*., 1949). All these maps reveals high spatial heterogeneity of total annual rainfall in Morocco like in Figure 10, varying from 13 mm in the Sahara to above 1000 mm at Tangier. This heterogeneity had already been illustrated by the first global work on rainfall in Morocco done by Augustin Bernard (1921). This author made a classification of vegetation in Morocco, on the basis of total rainfall received during the cropping season, into four classes: (1) regions of spontaneous vegetation where crops can be grown under favorable rainfall conditions (> 400 mm), (2) intermediate regions where crops can also be grown under conditions of deep soils and well distributed rainfall (300 < Rainfall < 400 mm), Steppic regions where annual rainfall lies between 200 and 300 mm, and Saharan regions of less than 200 mm annual rainfall.

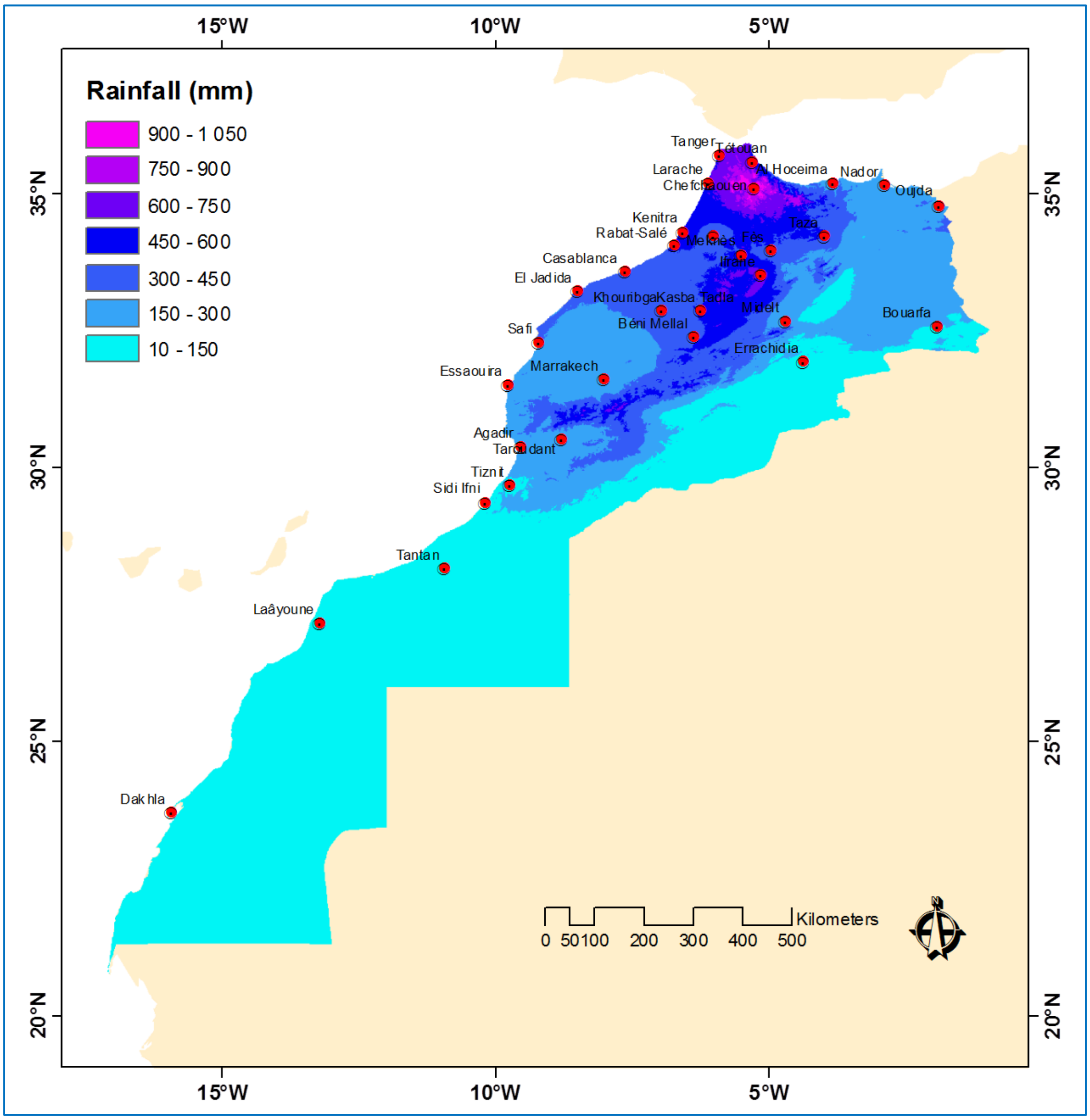


Figure 10 : Country average rainfall cumulated between September and April. The map created from data of www.worldclim.org (Hijmans *et al*., 2005). Red dots refer to main cities of Morocco.

Annual rainfall data were first interpolated to cover all points of the map by Hijmans *et al*. (2005). The map presented in Figure 10, shows a spatial distribution of annual rainfall heavily concentrated over the Middle Atlas and north-west. The map illustrates once more, increased rainfall gradient with latitude and elevation. In the same Figure 10, rainfall seems to be overestimated in the High Plateaus of Eastern Morocco, between Oujda and Bouarfa. In this region, as in any other steep region of the world not satisfactorily disserted with climatic stations, interpolation errors of rainfall are high (Hijmans *et al*., 2005).

4.2. INTERANNUAL VARIATION OF RAINFALL

Long term rainfall average in Morocco is around 364 mm, varying from a minimum of 198 mm recorded in 1994-1995 to a maximum of 610 mm recorded in 2009-2010 season. Rainfall data of 35 synoptic stations and 24 years (1988 to 2011), were used to arithmetically compute long term average of cumulated rainfall over the cropping season, between September and May. Inter-annual variation of rainfall at the country level is extremely high, in a ratio of 1 to 3; that is 300% variation (Figure 11).

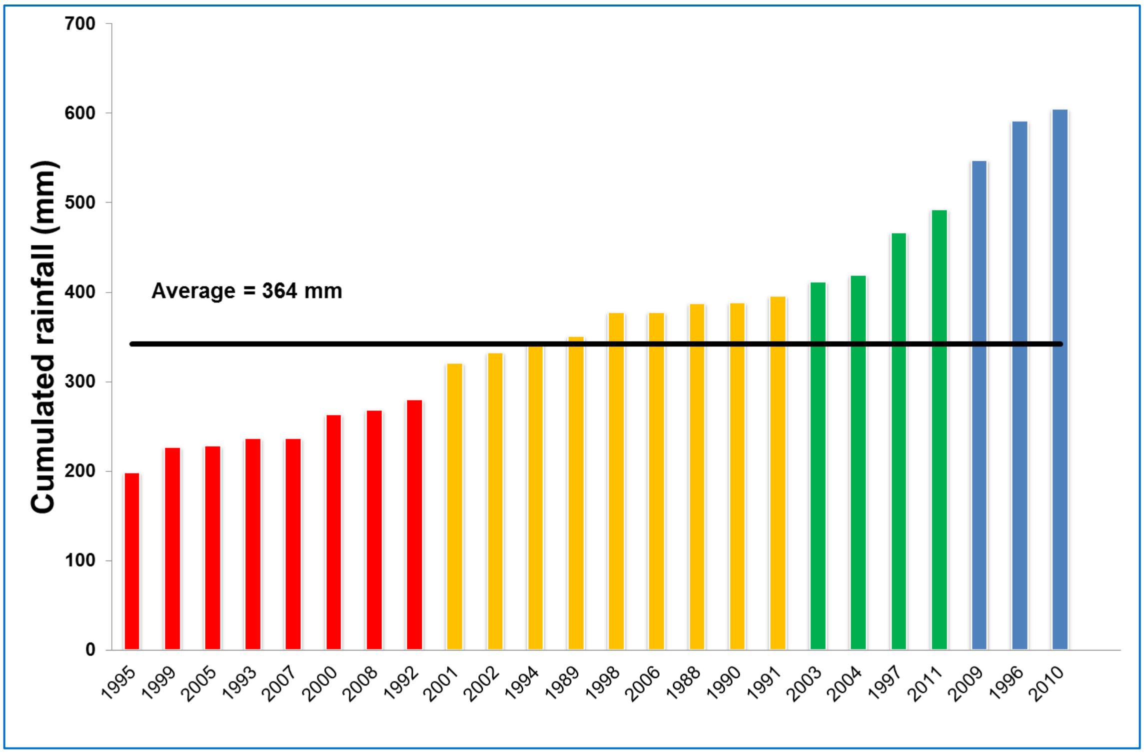


Figure 11 : Inter-annual variation of cumulated rainfall between September and May, at the country level, for 1988 to2011.
The cropping season starts on the first day of September and ends the last day of May of next year. The cropping seasons are arranged in ascending order of cumulated rainfall, and are grouped into four classes of rainfall (200 to 300 mm, 300 to 400 mm, 400 to 500 and > 500 mm).

Cropping seasons can be grouped into four classes of rainfall with the following frequencies:

1. 200 to 300 mm: 8 seasons (1992, 1993, 1995, 1999, 2000, 2005, 2007 and 2008) ;
2. 300 to 400 mm: 9 seasons (1988, 1989, 1990, 1991, 1994, 1998, 2001, 2002 and 2006) ;
3. 400 to 500 mm: 4 seasons (1997, 2003, 2004 and 2011) ;
4. Above 500 mm: 3 seasons (1996, 2009 and 2010).

Annual rainfall cumulated over the cropping seasons of the 24 seasons are plotted in Figure 11, in ascending order of rainfall, with a different color assigned to each class of rainfall.

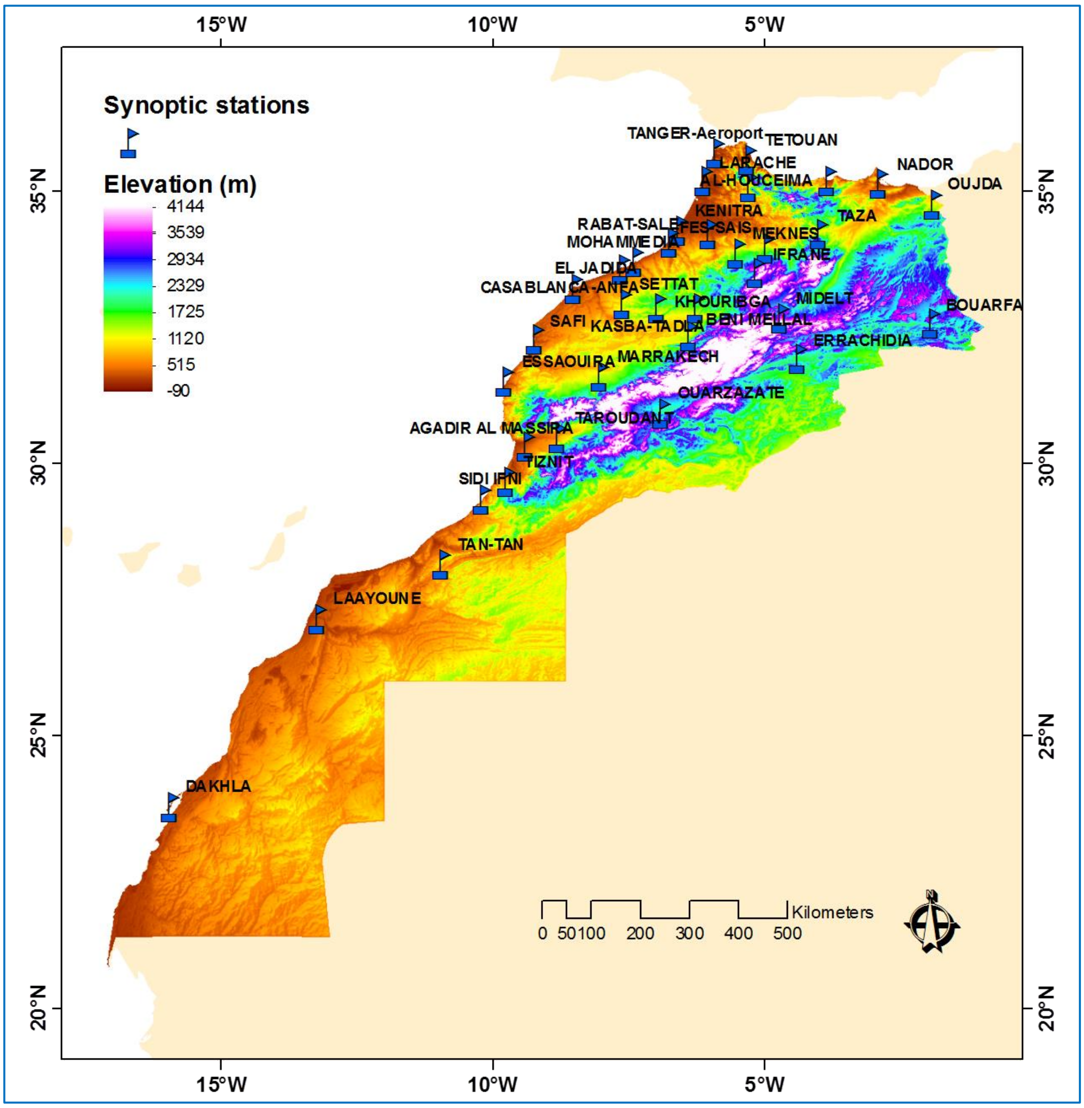


Figure 12 : Geographic localization of the 35 synoptic weather stations used to generate weather data of Morocco, on a background map of elevation provided from radar data of « *Shuttle Radar Topography Mission* » (http://www2.jpl.nasa.gov/srtm/).

However, for agricultural purposes, the arithmetic mean of the 35 synoptic stations may yield a biased estimate of the average rainfall, because used stations are not all localized in agricultural areas of Morocco; some of them are localized in mountainous, pastoral or Saharan regions (Figure 12), not representing climatic conditions prevailing in cereal areas of Morocco. In addition, these stations are not uniformly distributed across the country; most of them being scattered along the coastal areas. A better coverage would definitely improve the understanding of Moroccan climate. To reduce the bias, DMN has adapted the AURELHY[32] method (Analysis Using RELief for Hydro-

[32] The AURELHY method utilizes terrain to improve the cartography of precipitations. The method is based on 3 points: (1) automatic recognition of the statistic link existing between precipitation and surrounding relief; (2) optimal utilization of this statistical relationship to points where no measured values are available; and (3) generation of a regional map of precipitations, integrating effects of relief.

meteorology) of interpolation and mapping of precipitation data provided by synoptic stations to cover inter stations[33] spaces. Initially developed by Meteo-France (Bénichou and Le Breton, 1987), DMN has adapted it for Moroccan conditions, to produce a map of rainfall, on a dekadal data basis for the whole territory. This method is being integrated into the National Crop Growth Monitoring System to predict cereal harvests, named « CGMS-MAROC » (see chapter VII). It is then possible to extract rainfall data for agricultural zones, using the agricultural mask described in section II1.5.

4.3. SEASONAL VARIATION OF RAINFALL

Most of the rainfall in Morocco is received between the months of September and May, the months of June, July and August being generally dry (Figure 13). Rainfall distribution within the season is random, with a great disparity between the south and the north, or between the west and the east of the country. Rainfall increases proportionally from arid to humid regions, with more accentuated increases in the winter than in any other time period during the season.

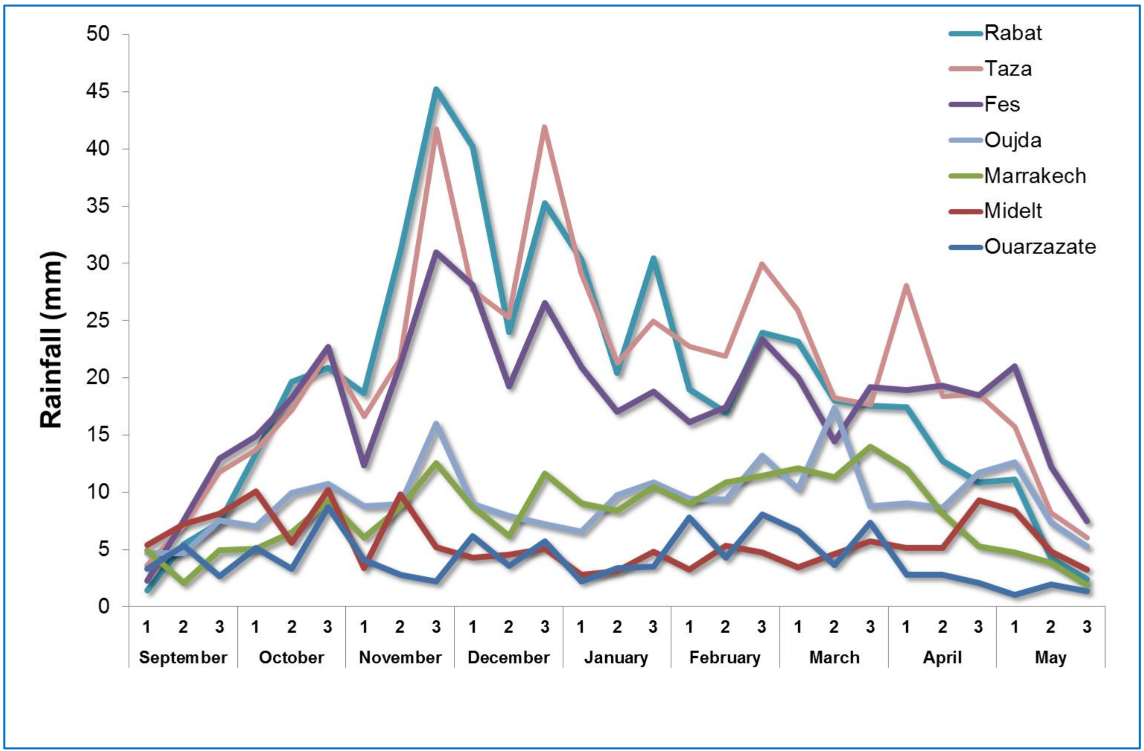


Figure 13 : Examples of dekadal rainfall distribution along the cropping cycle, for specified contrasting synoptic weathers stations (averages of 1988 to 2010).

[33] It is a priori possible to interpolate data of rainfall provided by climatic stations using NDVI images, due to the high correlation between rainfall and NDVI, which is the principle of « *Satellite enhanced data interpolation* » (SEDI) method developed by FAO and integrated in WinDisp (version 4) software. http://www.fao.org/giews/french/windisp/hist.htm.

4.3.1. FREQUENCY ANALYSIS OF DEKADAL RAINFALL

Seasonal variation of rainfall can be statistically modelled, using frequency analysis of its dekadal values[34]. Frequency analysis is a statistical approach[35] which allows modelling or caching most of rainfall distribution pattern, irrelevant of the crop under consideration. It determines probabilities or chances of a rainfall value (dekadal or monthly) to occur based on a long time series of rainfall data. It is therefore a pure statistical analysis method which nonetheless helps making decision in agriculture (Jlibene and Balaghi, 2009).

Frequency analysis of dekadal rainfall, for recent series of cropping seasons after the climate change (i.e. 1980), shows that within season distribution of rainfall is one-mode, concentrated in winter, with a peak during the months of November, December or January (Figure 14). It also shows that rainfall is rather concentrated in the fall, indicating the importance of the success of planting operations for improved water efficiency, and ultimately improved crop yields. Rainfall received in the fall helps reconstituting water reserves in the soil after the usually hot summer season.

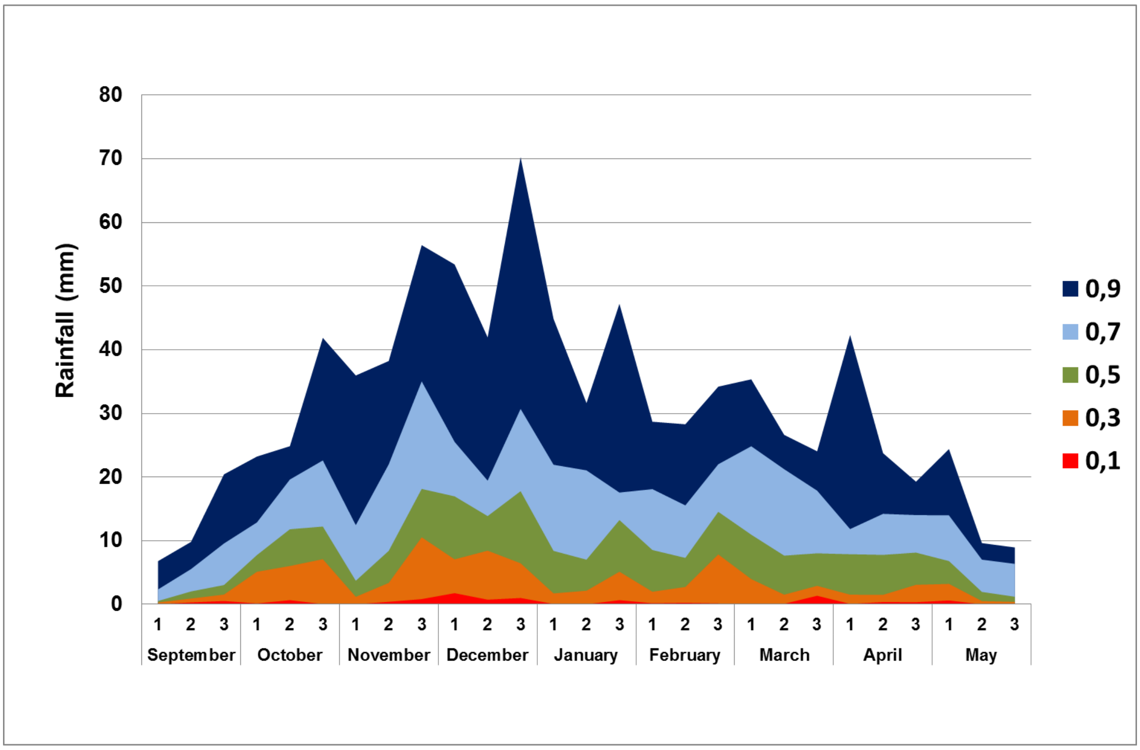


Figure 14 : Distribution of dekadal rainfall, at the country level, for 5 frequency levels (0.1; 0.3; 0.5; 0.7 and 0.9). Data series from 1988 to 2011.

[34] Worth keeping in mind that the frequencies associated with a rainfall value of a given dekad, are independent from frequencies of other dekad's rainfall.

[35] In frequency analysis, observations are considered as a random sample representative of the climate under study, assuming that time series is stationary (Péguy, 1983).

When using rainfall time series before the change point, the distribution of rainfall appears to be a two-mode (Balaghi, 2000). Less important peaks were observed for the months of October and March. During the summer, rainfall is infrequent and falls in the form of storms, especially near the Atlas Mountains. The usefulness of heavy rains is proportional to the soil water holding capacity. High rainfalls are more beneficial to crops in deep soil of heavy to intermediate texture, than light soils or soils that poorly drain (Roux, 1938). In these last types of soils, agricultural production is better only if rainfall is low but uniformly distributed within the cropping season. During dry seasons, plants use water more easily in soils with low water holding capacity than in soils with high capacity. Usually rainfall received during the fall allows development of a good plant stand in both types of soils. However, under water stress, plant keep growing on residual water in soils with high water holding capacity, until depletion and death of plant before seed set. In soils with low water holding capacity, plants sense drought early due to low water reserves and thus tend to mature earlier.

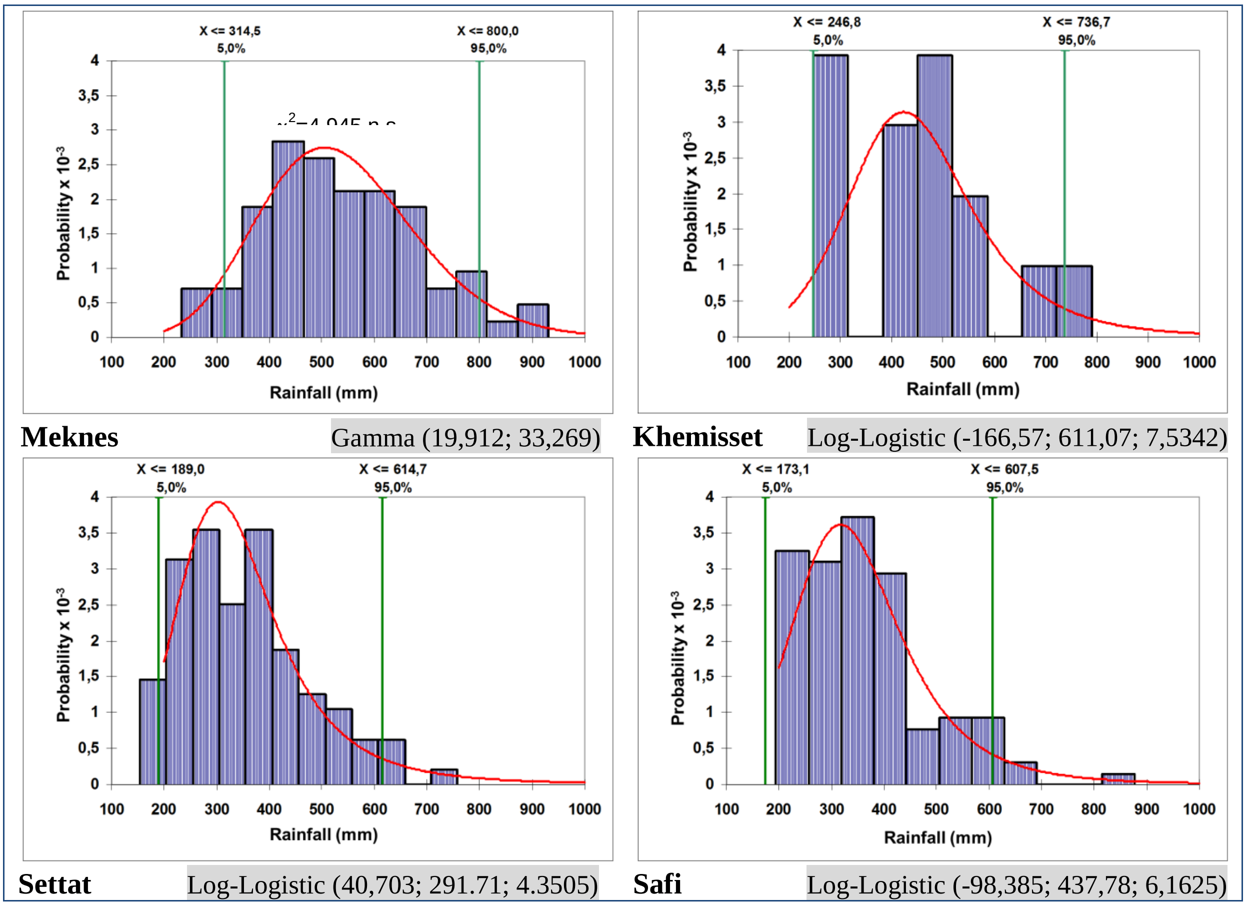


Figure 15 : Annual rainfall distribution (cumulated from September to June) at Meknes (1932-2004), Khemisset (1986-2004), Settat (1910-2004) and Safi (1901-2004). The red curve represents adjusted theoretical distribution curve to observed one (Balaghi *et al.*, 2005).

Rainfall is distributed asymmetrically with respect to the median, with low rainfall seasons outnumbering wet years, and therefore departing from statistical Normal (Gaussian) distribution. Examples of distribution of annual rainfall of the stations Meknes, Khemisset, Settat and Safi are given in Figure 15 (Balaghi *et al.*, 2005). Annual rainfall during the growing season (September to June), follows a theoretical non-Gaussian distribution, according to the χ^2 test of Snedecor and Cochran (1989). The distribution is of Gamma type for Meknes (1932 to 2004 data series) and Log-Logistics for Khemisset (1986 to 2000 data series), Settat (1910 to 2004 data series) and Safi (1901 to 2004 data series). The annual rainfall is distributed more evenly in Meknes than in the other three provinces, with years of low rainfall being more frequent further south.

4.3.2. LINEAR APPROXIMATION OF DEKADAL RAINFALL

Graphical representation of cumulated dekadal rainfall, from September to May, indicates that such curve can be approximated by simple linear regression. Indeed, the dekadal rainfall accumulated during the growing season (from September to May) rose almost linearly (Figure 16), with high and significant coefficients of determination (R^2) greater than 91%.

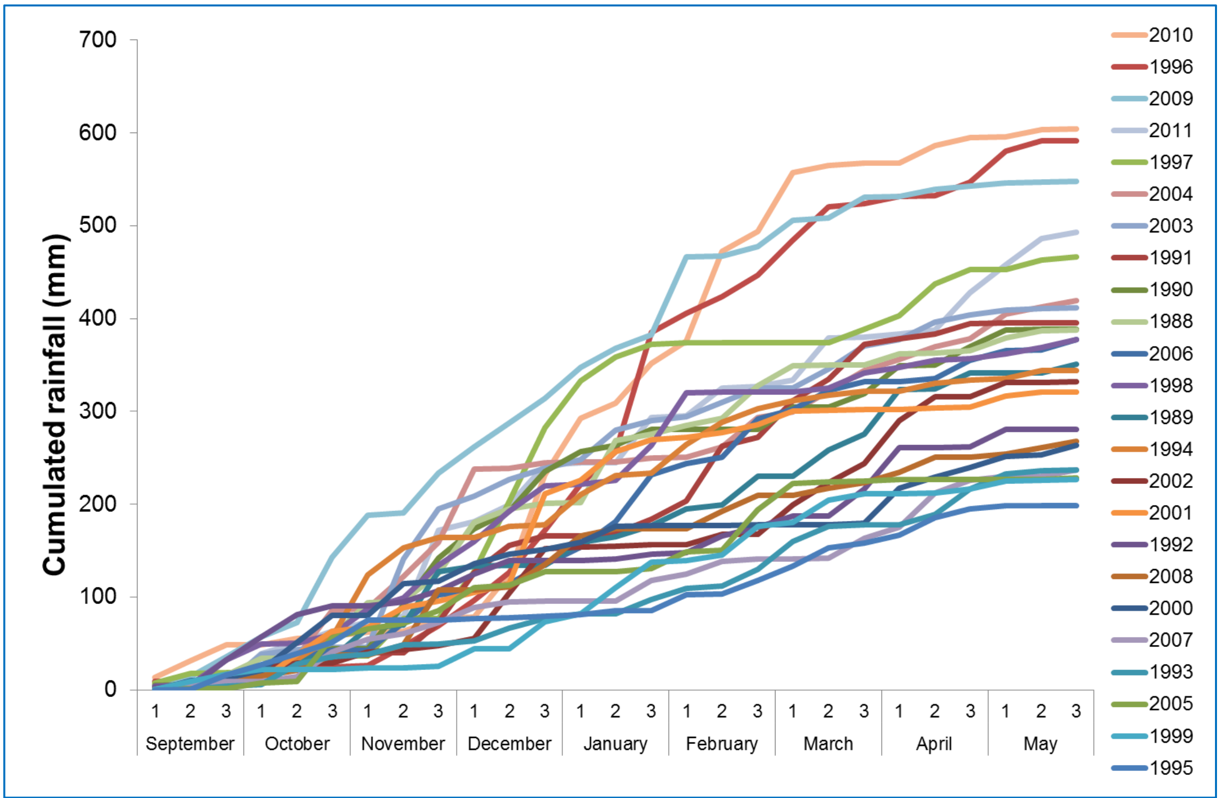


Figure 16 : Dekadal cumulated rainfall from September till May, at the country level. ***Cropping cycles of 1988 to 2011 are arranged in ascending order of cumulated rainfall.***

Given the quasi-linearity of the cumulative dekadal rainfall, it is possible to fit a linear regression model. The R^2 of these models are very high, exceeding 90% (Table 3). For example, the 1988-1989 growing season recorded a rainfall that regularly accumulates at a rate of 14.94 mm/dekad, with very high R^2 equal to 99%. Relatively lower R^2, which may fall below 95%, indicates the occurence of drought. The increase rate of cumulated dekadal rainfall starting from September is measured by the slope of the linear regression function over dekads. It varies from 7.64 mm/dekad in the case of the historic droughty season 1994-1995 to 28.63 mm/dekad 2009-2010 in the case of the rainiest season in the post 1980 series of data; 1980 was the year of breaking point in chronological series and announcement of climate change in Morocco.

Table 3: Linear regression models applied to cumulated dekadal rainfall over the growing season (from September to May) at the country level.
Growing seasons (Years of harvest) are classified in ascending order of rainfall.

Season	Rainfall (mm)	Intercept (mm)	Slope (mm/dekad)	R^2
1995	198.2	-4.89	7.64	0.96
1999	226.9	-34.77	10.50	0.95
2005	228.4	-12.22	10.30	0.95
1993	236.9	-31.75	9.73	0.97
2007	237.1	-18.29	9.29	0.98
2000	263.6	13.36	9.50	0.93
2008	268.1	-16.59	11.48	0.97
1992	280.3	7.73	10.28	0.96
2001	320.6	-13.33	14.61	0.91
2002	332.2	-47.55	14.20	0.96
1994	344.4	-2.77	14.91	0.94
1989	350.9	-36.57	14.94	0.99
1998	377.3	-5.67	16.07	0.95
2006	377.5	-45.51	16.80	0.98
1988	387.7	-17.09	17.04	0.96
1990	388.5	-20.02	16.75	0.95
1991	395.5	-60.24	18.36	0.97
2003	411.3	-12.26	17.80	0.95
2004	419.2	-10.44	16.84	0.95
1997	466.4	-37.47	21.02	0.91
2011	492.9	-34.67	19.85	0.98
2009	547.9	6.93	23.61	0.95
1996	591.3	-109.58	28.13	0.94
2010	604.8	-88.54	28.63	0.93

The rate of dekadal rainfall accumulation determines the total rainfall in the growing season, with a coefficient of determination close to unity (R^2 = 97%).

The rate of dekadal rainfall increase is on average de (Figure 17):

- **9.82 mm/dekad** for the growing seasons with total rainfall between 200 and 300 mm (years of harvest: 1992, 1993, 1995, 1999, 2000, 2005, 2007 and 2008) ;
- **15.97 mm/dekad** for the growing seasons with total rainfall between 300 and 400 mm (years of harvest: 1988, 1989, 1990, 1991, 1994, 1998, 2001, 2002 and 2006) ;
- **18.88 mm/dekad** for the growing seasons with total rainfall between 400 and 500 mm (years of harvest: 1997, 2003, 2004 and 2011) ;
- **26.79 mm/dekad** for the growing seasons with total rainfall above 500 mm (years of harvest: 1996, 2009 and 2010).

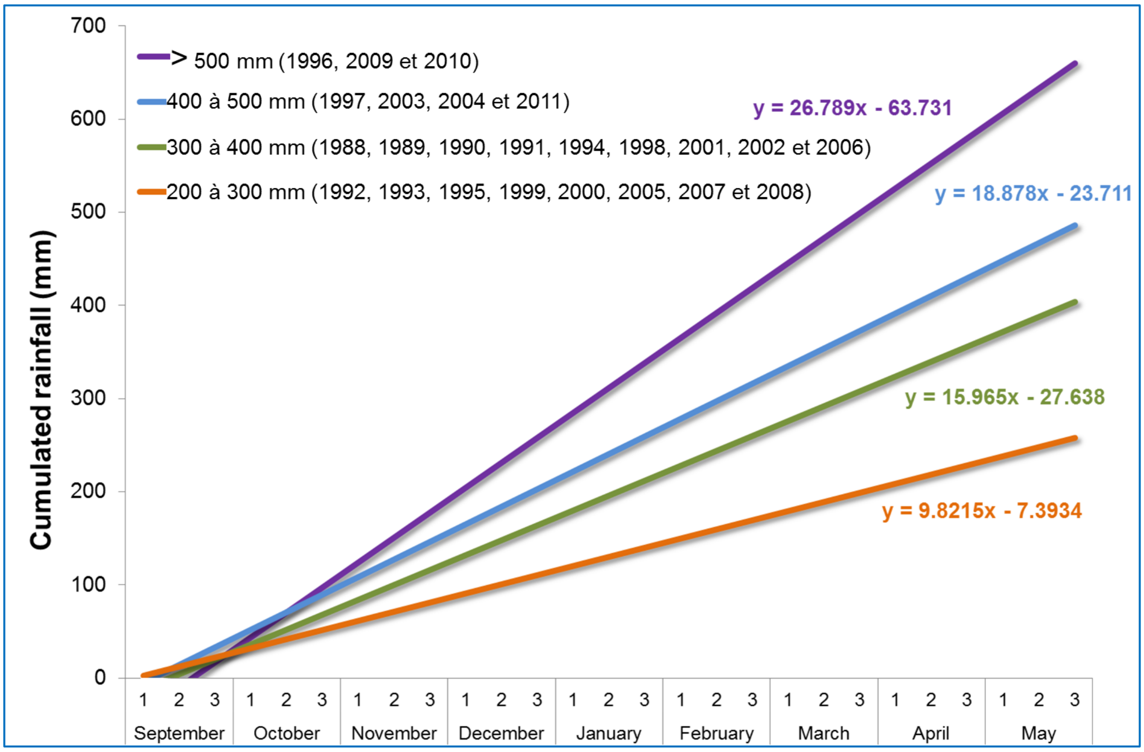


Figure 17 : Average increment rate of rainfall per dekad (x-axis, in mm/dekad), for 4 classes of cumulated rainfall (200 to 300, 300 to 400, 400 to 500 and > 500 mm). Data are country averages of 1988 – 2011 series.

4.4. SEASONAL VARIATION OF RAINFALL

Similar to inter-annual variation, intra-annual rainfall distribution can also be modelled, based on total rainfall or the latitude of the station, as total rainfall is proportional to the latitude. Monthly rainfall from 1988 till 2005 is shown in Figure 18, sorted out in increasing order. This figure was produced based on spatial interpolation of monthly rainfall using a Geographic Information System (GIS). In spatial terms, annual rainfall increases with latitude, from south to north. Four classes of rainfall can be distinguished rainfall: an arid class with less than 250 mm, a semi-arid class with rainfall between 250 and 350 mm, a sub-humid class with rainfall between 350 and 450 mm, and a wet class with rainfall over 450 mm (Jlibene, 2011).

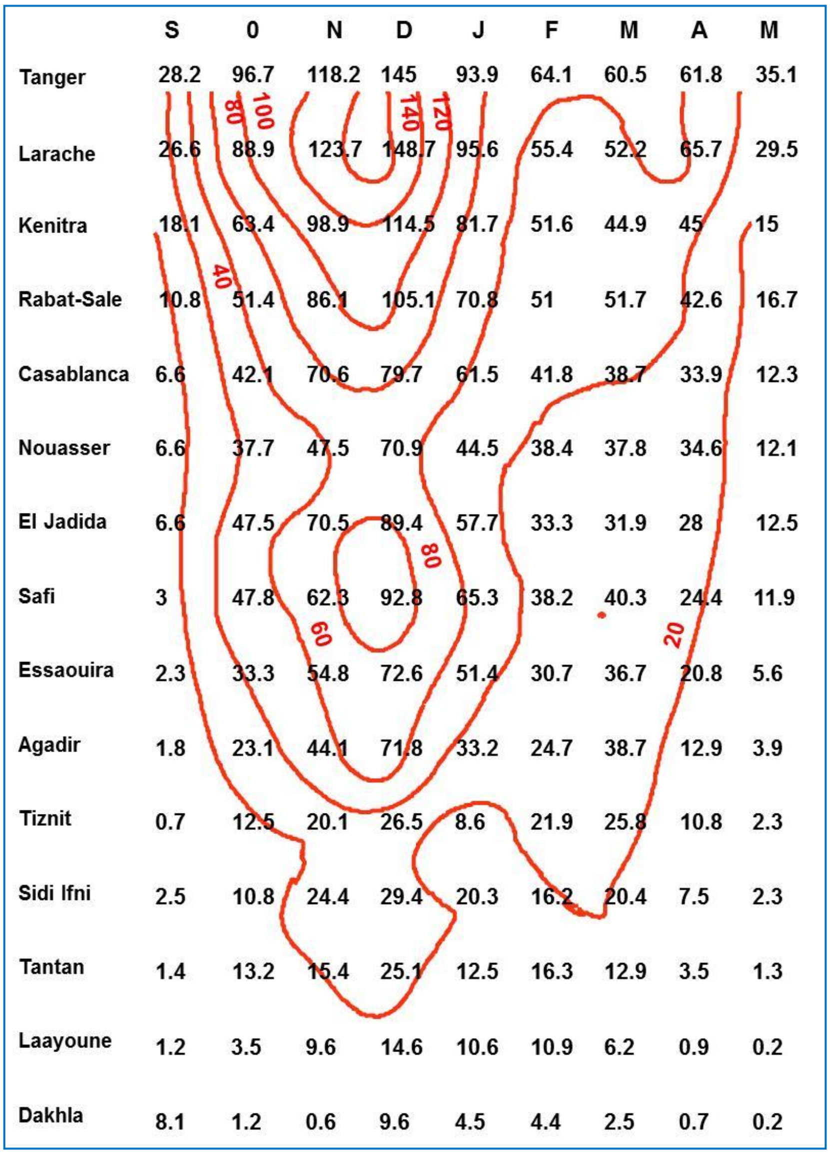
Total season rainfall is generally concentrated within the period of September to May, for all seasons, regardless of the amount of total rainfall. However, with increased volumes, rainfall becomes more concentrated in winter season showing higher peaks that seem to disappear during dry seasons (Figure 18).

	S	O	N	D	J	F	M	A	M	Total
1996	9,9	14,3	44,5	101,7	212,8	60,7	76,3	22,6	44,4	587,2
1997	17,8	18,2	40	206,3	89,4	2,1	14,2	64	13,5	465,4
2004	2,9	82,8	73,1	85,7	5,6	43,6	50,3	33,9	41,3	419,2
2003	6,8	39,4	148,7	43,7	51,8	35	44,9	33,9	7,1	411,3
1991	10,8	25,1	35,1	93,2	17,8	87,2	100,6	21,9	0,7	392,4
1988	15,8	41,3	68,8	75,2	74,1	52,9	21,9	15,3	22,4	387,7
1990	9,2	34,8	94,8	91,8	45,4	1,1	39,4	49,3	19	384,9
1998	31,8	27,3	74,6	85,9	43,9	58,5	19,8	15,9	19,7	377,4
1989	2,4	31,2	93,9	6,3	42,8	53,8	45,4	66	9,1	350,9
1994	6,3	49,1	108,1	13,9	55,4	69,7	18,5	11,5	10,8	343,3
2002	15,4	13,4	19,2	104,4	3,7	11,5	76,3	72,3	16	332,2
2001	10,3	52,8	32,5	115,2	58,4	16,3	17	2,3	15,9	320,6
1992	32,4	59,1	15,8	32	6,5	29,2	40,9	45,8	17,7	279,4
2000	12,3	68	37	34,2	25,1	0,7	1,9	60,6	23,7	263,6
1993	3,5	31,5	13,5	26,8	20,1	32,2	48,6	37,8	19,8	233,9
2005	1,7	54,3	29,4	42,2	3,3	62,9	31,4	1,4	1,8	228,4
1999	16,8	5,4	3,4	47,5	64,1	38,9	35,4	5	10,3	226,9
1995	15,3	35,6	23,4	4	5,8	32,3	39,5	37,3	2,8	196,0

Figure 18 : Monthly rainfall distribution, as influenced by the overall volume of rainfall in Morocco (data of 1988 to 2005).

Cropping cycles are arranged from high to low rainfall. Areas of similar rainfall are represented by a range of blue colors, from clear (low rainfall) to dark blue (high rainfall).

Intra-annual rainfall distribution also differs, depending on latitude which is correlated to total amount of rainfall cumulated during the growing season. Figure 19 shows intra-annual rainfall distribution for meteorological stations located along the Atlantic coast. In general, rainfall distribution appears to be similar in all latitudes, but peaks of rainfall during winter flatten with decreased latitude, from north to south of the country.



	S	0	N	D	J	F	M	A	M
Tanger	28.2	96.7	118.2	145	93.9	64.1	60.5	61.8	35.1
Larache	26.6	88.9	123.7	148.7	95.6	55.4	52.2	65.7	29.5
Kenitra	18.1	63.4	98.9	114.5	81.7	51.6	44.9	45	15
Rabat-Sale	10.8	51.4	86.1	105.1	70.8	51	51.7	42.6	16.7
Casablanca	6.6	42.1	70.6	79.7	61.5	41.8	38.7	33.9	12.3
Nouasser	6.6	37.7	47.5	70.9	44.5	38.4	37.8	34.6	12.1
El Jadida	6.6	47.5	70.5	89.4	57.7	33.3	31.9	28	12.5
Safi	3	47.8	62.3	92.8	65.3	38.2	40.3	24.4	11.9
Essaouira	2.3	33.3	54.8	72.6	51.4	30.7	36.7	20.8	5.6
Agadir	1.8	23.1	44.1	71.8	33.2	24.7	38.7	12.9	3.9
Tiznit	0.7	12.5	20.1	26.5	8.6	21.9	25.8	10.8	2.3
Sidi Ifni	2.5	10.8	24.4	29.4	20.3	16.2	20.4	7.5	2.3
Tantan	1.4	13.2	15.4	25.1	12.5	16.3	12.9	3.5	1.3
Laayoune	1.2	3.5	9.6	14.6	10.6	10.9	6.2	0.9	0.2
Dakhla	8.1	1.2	0.6	9.6	4.5	4.4	2.5	0.7	0.2

Figure 19 : Monthly rainfall distribution for 15 contrasting synoptic weather stations scattered along the Atlantic coast (data from 1988 till 2005). Stations are arranged in ascending order of latitude. Red lines represent points of equal monthly rainfall, of 20 mm, 40 mm, 60 mm and 80 mm.

5. GROWING SEASON FROM OMBROTHERMIC DIAGRAM

The Ombrothermic diagram of Bagnouls and Gaussen (1953) assumes that crop growth is possible as long as monthly rainfalls are greater than two times the monthly temperatures. Used to estimate the length of the growing period, this diagram shows that the country average growing season for cereal crops extends from October to March (Figure 20). During these months, monthly rainfall values are greater than two time average monthly temperatures. This diagram integrates the two most important factors for growth and development of crops: rainfall and temperature.

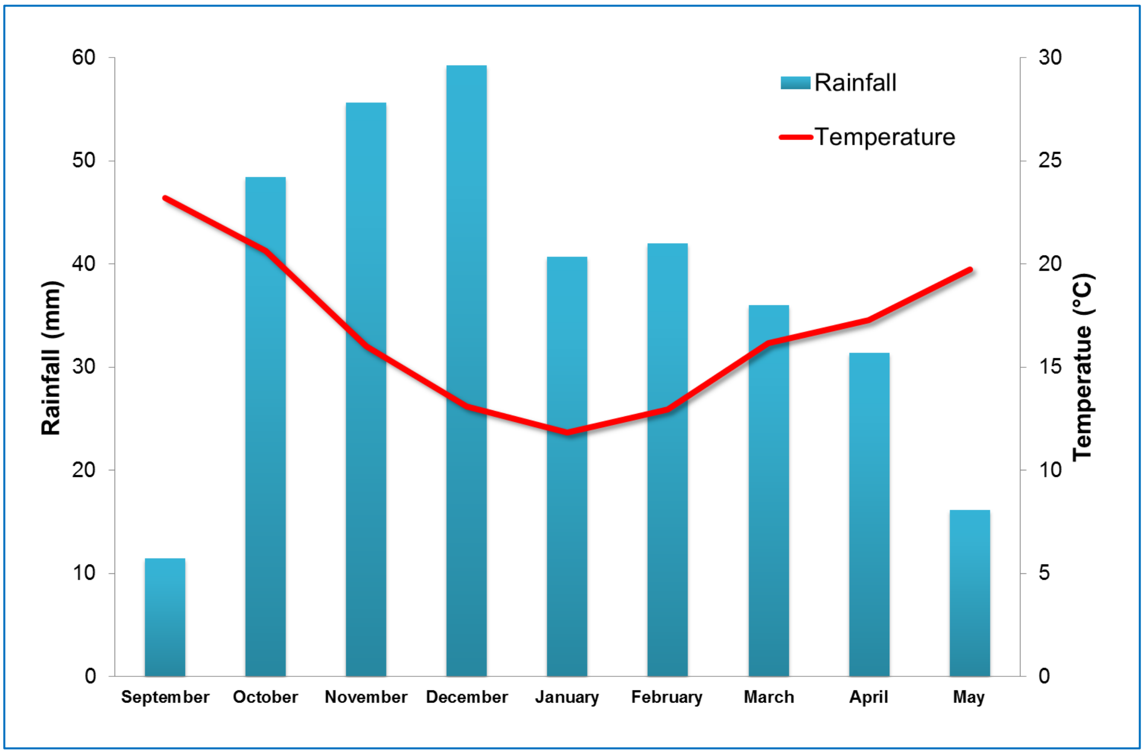


Figure 20 : Ombrothermic diagram, at the country level. ***(Average rainfall and temperature, from a series of 1999 to 2009).***

Length of the growing season of crops varies greatly with latitude (Figure 21). It increases with latitude from south to north, in the Atlantic regions of the country, situated between the Atlas Mountains and the Atlantic Ocean. The increase in Ombrothermic index with latitude is exponential, changing from less than 1 at the Saharan site Dakhla to more than 6 at the northern site Chefchaouen. This result was expected since there are simultaneous increase in rainfall and decrease in temperature with higher elevation, increasing the ratio of rainfall to temperature more than proportional.

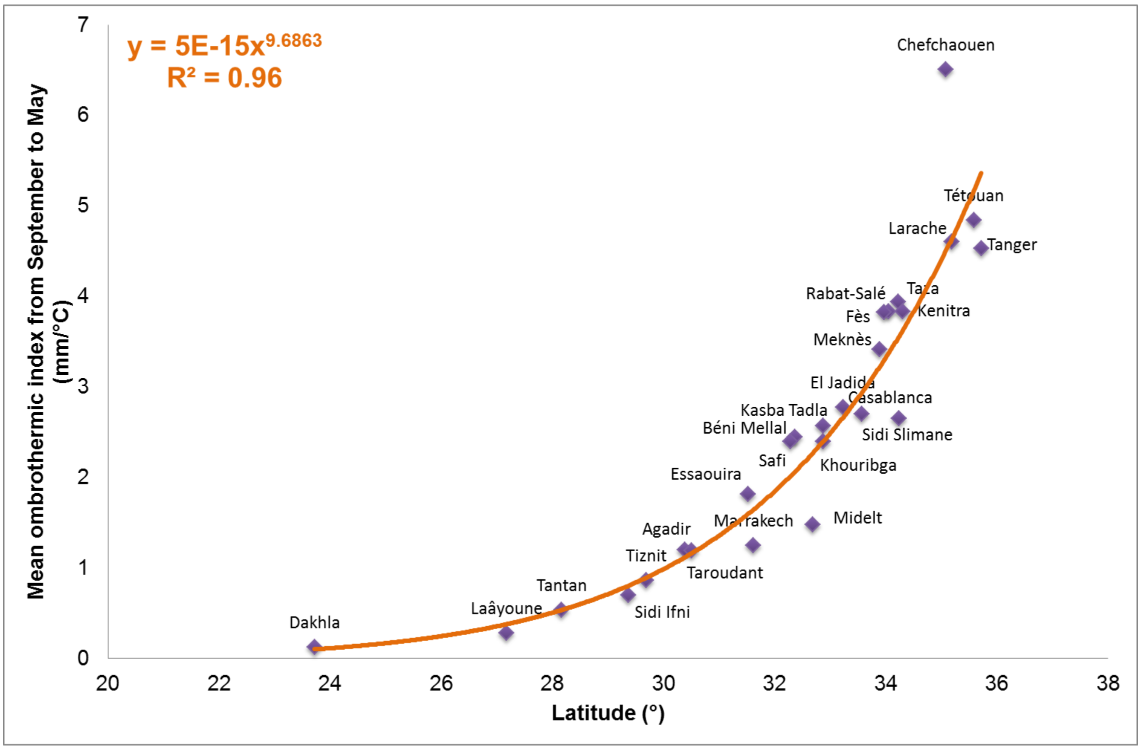


Figure 21: Average Ombrothermic index (from September to May) as influenced by latitude. Monthly data series of 1999-2009 for 25 different synoptic stations were used.

The growing season of crops becomes shorter and shorter with lower elevation south, until inexistent in Saharan provinces (Table 4). In other parts of the country, the growing season starts with the first rains of October (Table 4). For most cereal regions, the length is limited only by the end of the season, which could be in March for Khouribga in the center, April for Chefchaouen in the north, and May for Ifrane in the Atlas Mountains. In general, the growing season ends in April in regions above 33° 30' latitude.

Ombrothermic index can be spatially presented, to map the end of growing season dates throughout the country. This map presented in Figure 22 shows the season end, which varies across latitude and elevation, between March and May. The season ends in March throughout the area between Agadir and Bouarfa, south of the 32° 30' parallel excluding areas of medium and high elevation. It ends in April in the coastal area north of Safi, the central plains and plateaus of the country in addition to Anti Atlas area. The season continues through May, in high elevation area of Rif, Middle and High Atlas Mountains, and some high elevation area in eastern plateaus.

Table 4 : Ombrothermic Index, as a ratio between precipitation (P) and temperature (T), by synoptic station. Unit of P/T is in mm/°C.

Indices lower than 2 indicate dry months not suitable for growth (in orange) and indices greater than 2 indicate humid month suitable for growth (in green). Stations are arranged in descending order of index. (Monthly rainfall and temperature series of 1999 to 2009).

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Latitude (North)	Longitude (West)	Elevation (meter)
Ifrane	1.3	6.8	15.7	33.1	26.3	20.3	10.5	9.1	4.1	33 ° 30'	5 ° 10'	1663
Chefchaouen	1.2	5.3	7.8	14.3	8.0	9.6	5.5	5.6	1.3	35 ° 05'	5 ° 18'	300
Tetouan	1.8	5.2	6.4	7.9	5.5	6.7	4.6	4.0	1.5	35 ° 35'	5 ° 20'	5
Larache	1.0	4.9	6.5	9.4	6.5	3.8	4.4	3.5	1.5	35 ° 11'	6 ° 08'	47
Tangier	1.4	5.0	5.8	8.1	6.4	4.7	4.4	3.5	1.6	35 ° 43'	5 ° 54'	15
Taza	0.8	3.1	4.7	7.2	6.3	5.7	3.0	3.3	1.3	34 ° 13'	4 ° 00'	509
Kenitra	0.7	3.3	6.4	7.1	6.1	4.3	3.3	2.3	1.1	34 ° 18'	6 ° 36'	5
Rabat-Salé	0.5	3.4	6.6	6.9	5.7	4.6	3.3	2.3	1.2	34 ° 03'	6 ° 46'	75
Fes	0.8	3.6	4.6	6.5	6.5	4.8	2.7	3.5	1.4	33 ° 58'	4 ° 59'	571
Meknes	0.5	2.8	4.0	6.9	5.4	4.6	2.7	2.7	1.2	33 ° 53'	5 ° 32'	548
El Jadida	0.3	2.7	4.1	6.3	3.7	3.3	2.4	1.5	0.7	33 ° 14'	8 ° 31'	27
Casablanca	0.4	2.6	4.5	4.3	4.5	3.2	2.3	2.0	0.6	33 ° 34'	7 ° 40'	56
Nador	0.6	3.2	4.3	3.1	2.6	3.7	2.9	2.5	1.0	35 ° 09'	2 ° 55'	7
Sidi Slimane	0.3	2.3	4.1	5.2	4.4	2.5	2.3	1.9	1.0	34 ° 14'	6 ° 03'	52
Al Hoceima	0.5	3.8	4.6	2.8	3.0	3.0	2.2	2.2	1.0	35 ° 11'	3 ° 51'	12
Kasba Tadla	0.2	1.6	3.5	4.2	4.6	3.8	2.4	1.8	1.1	32 ° 52'	6 ° 16'	507
Béni Mellal	0.2	1.8	3.6	4.3	3.7	3.3	2.5	1.8	0.9	32 ° 22'	6 ° 24'	468
Safi	0.1	2.1	3.6	5.1	3.0	3.7	2.2	1.3	0.5	32 ° 17'	9 ° 14'	43
Khouribga	0.2	1.3	3.3	5.2	4.0	3.6	2.0	1.2	0.7	32 ° 52'	6 ° 58'	770
Oujda	0.4	1.8	3.2	2.9	3.2	2.7	2.1	1.6	1.1	34 ° 47'	1 ° 56'	465
Essaouira	0.2	1.6	2.2	3.5	2.5	3.1	1.9	1.1	0.3	31 ° 31'	9 ° 47'	7
Midelt	0.8	2.1	1.7	2.7	1.2	1.9	1.0	1.0	0.9	32 ° 41'	4 ° 44'	1508
Marrakech	0.2	1.1	1.7	1.9	1.8	1.7	1.4	1.0	0.5	31 ° 37'	8 ° 02'	464
Agadir	0.1	0.9	1.8	2.6	1.2	2.1	1.5	0.6	0.1	30 ° 23'	9 ° 34'	23
Taroudant	0.1	0.8	1.8	2.7	0.9	2.2	1.3	0.7	0.1	30 ° 30'	8 ° 49’	264
Bouarfa	0.7	2.0	1.5	1.4	1.4	1.4	1.0	0.8	0.4	32 ° 34’	1 ° 57'	1142
Tiznit	0.1	0.6	1.2	1.6	1.0	1.5	1.1	0.6	0.1	29 ° 41'	9 ° 44'	260
Errachidia	0.4	1.6	1.1	0.6	1.2	1.2	0.6	0.5	0.4	31 ° 56'	4 ° 24'	1037
Sidi Ifni	0.1	0.7	1.4	1.1	0.8	1.1	0.8	0.3	0.1	29 ° 22'	10 ° 11'	50
Tantan	0.0	0.8	0.5	0.8	0.9	1.1	0.6	0.1	0.0	28 ° 10'	10 ° 56'	45
Laâyoune	0.0	0.1	0.2	0.6	0.6	0.8	0.1	0.1	0.0	27 ° 10'	13 ° 13'	64
Dakhla	0.4	0.2	0.0	0.1	0.2	0.1	0.0	0.1	0.0	23 ° 43'	15 ° 56'	11

While the end of the growing season is in general influenced by latitude and elevation, a particular spot in the map between Safi west and Beni Mellal east, and between El Jadida north and Marrakech south (in blue, Figure 22), seems to be an exception. This spot includes arid zones of Rehamna[36] and Chemaia (bordering the provinces of Marrakech, Safi and Chichaoua), corresponding to the plateau of phosphates in Morocco. The same spot has been reported in maps of rainfall as early as 1921 (Augustine, 1921) or agro-climatic maps developed for Morocco (Goebel *et al.,* 2007; Sebbar *et al.*, 2011).

The Ombrothermic index does not take into account the capacity of soils to hold water, which could further extend length of the growing season due to soil moisture. Soils with high water holding capacity maintain humidity for root system to use for a time longer than that expressed in the Ombrothermic map in Figure 22.

The length of plant growing season determined by the Ombrothermic index, matches that of most annual fall sown crop cycles, particularly cycles of autumn cereals. Crop cycle may be referred to as cropping cycle or cropping season in the rest of the text. According to Augustin (1921) the growing season can be divided into three periods of 4 months each: (1) period of seed preparation, from 1st of September to December 31; (2) period of plant development, from 1st of January to April 30th ; (3) period of harvest, from 1st of May to August 31th. Cereals are sown in the fall season, around the month of November, complete their vegetative growth and development in the winter season, and the reproductive growth in spring season. The rainy season starts in October, but cereal sowings are rarely done in this month. They usually start in November for practical reasons mainly:

- Ease of tilling soils for seed bed preparation and weed control; the first rains of the month of October loosen soils, and induce emergence of weeds ;
- Optimization of crop growth and development, as November sowings seem to be optimal for cereal yields expression.

Temperatures during October are still relatively high, which tend to accelerate development on the expense of biomass accumulation, reducing the crop cycle and therefore yields. In dry areas like the Abda region, farmers plant their cereal crops before the first rains, to take advantage of early rains.

Physiological maturity of cereals, which marks the end of seed growth and the beginning of desiccation, is reached at the end of the rainy season. Cereal harvests are usually done at grain moistures ranging from 12 to 14%. The range of final harvest maturity date extends over more than three months depending on region, ranging from May in the southern regions (e.g. Haouz, Rehamna and Abda) to August in Mountain regions. Farmers are not sufficiently equipped to

[36] Readers are referred to the publication of De Martonne *et al*. (1924), which describes the morphology and the aridity of Rehamna.

harvest their crops earlier in the season at grain moistures above 14%. In majority, they await for the arrival of combine harvesters coming up from the south, where harvests begin earlier.

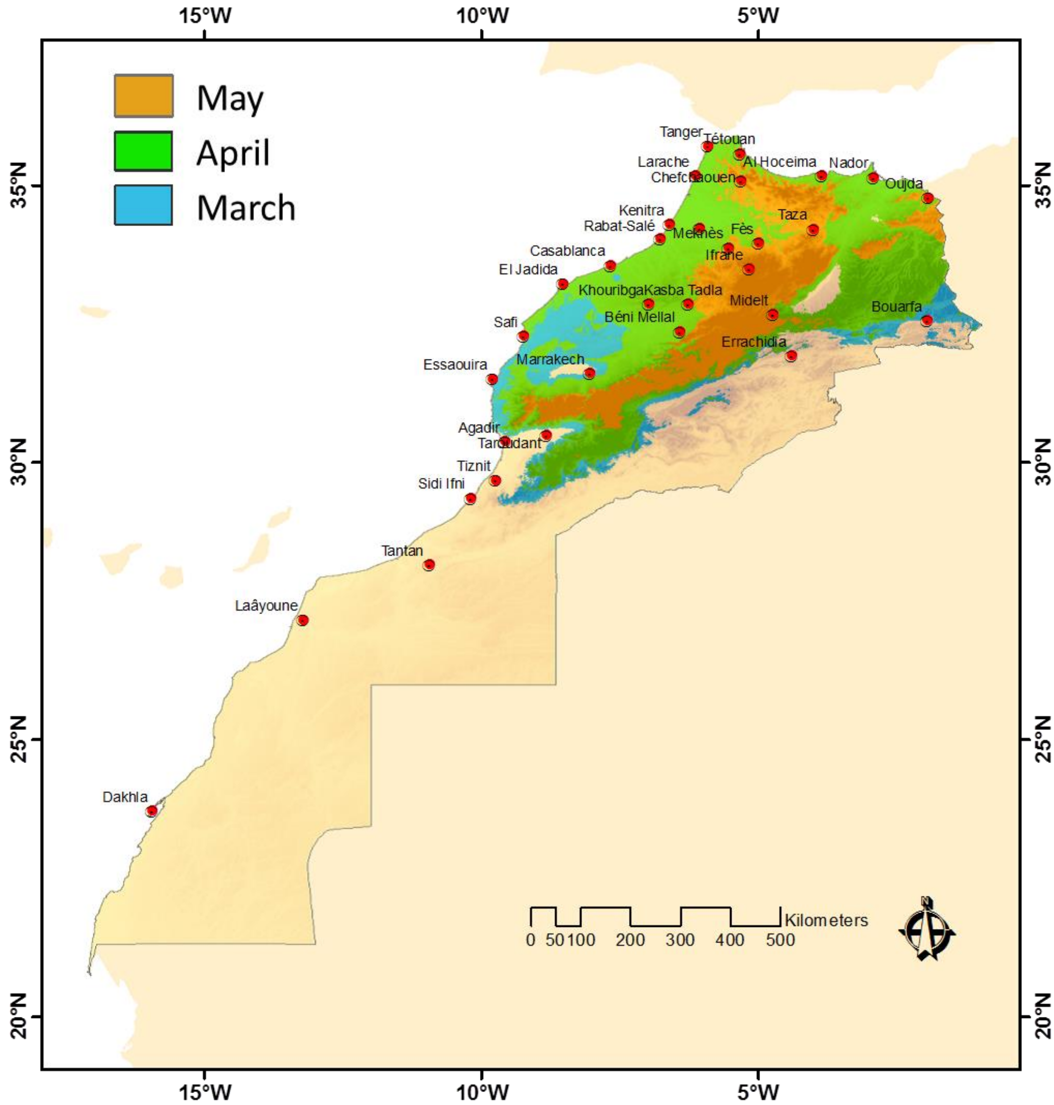


Figure 22 : Geographic areas where cereal growing seasons extend from September until March (areas in blue, green and brown colors), or until April (areas in green and brown colors) or until May (areas in brown color), according to Ombrothermic index of Bagnouls and Gaussen (1953). The map was generated from data of www.worldclim.org (Hijmans *et al*., 2005).

6. LENGTH OF THE GROWING PERIOD

The ratio of evapotranspiration to rainfall was used by FAO (1978) to identify lengths and time limits (start and end) of major phases within the growing cycle, mainly:

- Period of soil tillage for seed bed preparation ;
- Period of crop growth (growing cycle) ;
- Humid period which is part of the period of crop growth.

Based on identified limits of each period, dates of sowing and harvests can be identified.

This method was used in Morocco by Jlibene and Chafai (2002) to determine optimal cultural phases for wheat crop in the north-western part of the country (Figure 23).

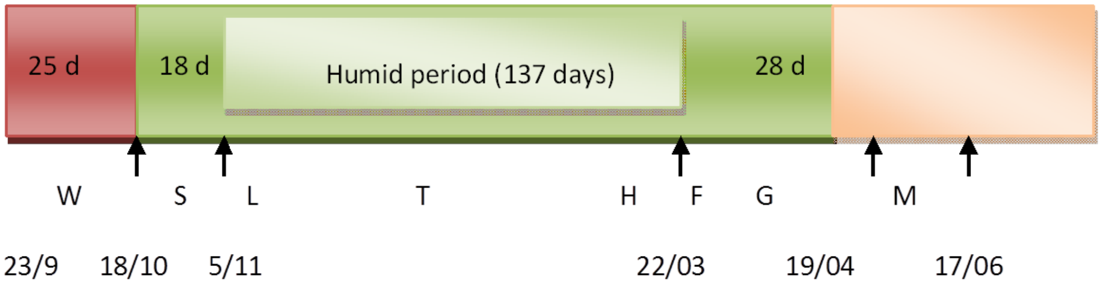


Figure 23 : Lengths and time limits of different periods within the cereal crop cycle: (1) soil preparation (W in purple), (2) period of growth (green) which includes sowing period (S), (3) humid period (light green), flowering (F) and grain filling (G); and (4) grain maturity and ripening (M in pink). The humid period includes times of emergence (L), tillering (T), and heading (H) of cereal crops in the north-western Morocco (Jlibene and Chafai, 2002). Weather data are a series of 70 years from Arbaoua Meteorological station (Data source: ORMVAL).

It turns out, according to this study, that for the Loukkos region in particular and North-West Morocco in general (Figure 23):

- The period of land preparation starts September 23th and is limited by the start of the growing period, October 18th ;
- The growing period starts October 18 and ends April 19th ;
- The humid period included in the growing period starts November 5th and ends Mach 22th ;
- Evaporation of 100 mm of soil residual moisture would take 60 days to deplete.

Applied to wheat cultivation in this region, the weather conditions allow:

- A long growing period of 183 days, 155 days for vegetative growth, and 28 days for reproductive growth ;
- Sowings have 18 days to be completed, before the fields become wet and difficult to access (November 5th), preferably during the first week of November. Major vegetative stages take place during the humid period: emergence, tillering, elongation, and heading ;
- At the end of the humid period (March 22th), flowering should take place, and seeds have 28 days to complete their development ;
- Remobilization of carbohydrates from leaves and stems to seeds can be done outside the growing period using reserve water available in the soil.

IV. ANALYSYS OF CEREAL PRODUCTION

The three main cereal crops in Morocco include soft wheat, durum wheat and barley. They are grown for grain, and straw is used as animal feed. Grain of soft wheat is mostly used to baking bread and biscuit; grain of durum is used to make pasta and semolina (couscous) and the grain of barley is used as feed and a small proportion of it is used as food. They are grown in all provinces and all agro-ecological zones. However, the geographic distribution of each crop follows market demand for yield potential and grain quality, in addition to their inherent geographic adaptive ability. In high yield environments, soft wheat is more grown because of its high productivity. In intermediate environments where grain quality is better expressed, durum wheat is more frequent. In dry environments where durability of agriculture system requires diversification, barley is mostly grown as feed in association with sheep production.

Technological trend is a result of cereal yield improvement, which is positive for durum wheat and soft wheat, and negative for barley. The positive trend observed for both wheat crops is mostly due to genetic improvement. The negative technological trend for barley yields does not necessarily result from negative yield improvement, since significant genetic improvement was achieved, but mainly from the shift of barley areas to drier environments for the benefit of soft wheat. Technological trend, quantified at the country or the agro-ecological zone levels, is taken into consideration in agrometeorological cereal yield forecasting in this document.

1. END USES OF CEREALS

Harvested grains, of the three major cereal crops (soft wheat, durum wheat and barley), are designed for various specific end uses depending on the crop. The grains of barley are used primarily (97%) to feed animals, with a small share (7%) being used for human consumption in the form of flat bread or semolina (Table 5). Wheat grains are used exclusively in human diet, basically in the form of bread and pasta, and also biscuit and semolina. At the industrial level, soft wheat is used for the production of bread and biscuit, while durum wheat is used for the production of couscous and pasta. At the household level or artisanal small businesses, wheat is used to produce a multitude of products made from flour and wheat grain.

Soft wheat has become the largest contributor to food security of the country's due to the large consumption of leavened bread by Moroccans (133 kg/person x year), accounting for two-thirds of the total cereal human consumption, followed by durum wheat which contributes to 25%. As a consequence of the high demand on soft wheat for bread, cropped area increased on the expense of durum wheat, barley and fallow. Areas of durum wheat and fallow were reduced, while that of barley shifted to drier areas. The market demand for soft wheat continues to increase due to population growth, while the agricultural area is almost constant, which limits the alternatives for cereal grain security in Morocco to the sole option of improving land productivity.

Table 5 : Main uses of cereal grains in Morocco (Source: ONICL, 2012).

Cereal crop	End use	Consumption share	Main use	Secondary use
Soft Wheat	Human	67%	Bread and biscuit	Noodles, other local products
Durum wheat	Human	25%	Pasta and semolina	Bread, other local products
Barley	Animal	7%	Animal feed	Semolina, flat bread

2. GEOGRAPHICAL DISTRIBUTION OF CEREALS

Cereals have large capacity to adapt to geographical, climatic, and cultural environmental conditions. They are grown all over the country, from the Sahara south to the Mediterranean border north, and from the Atlantic Ocean west to borders of Algeria east. Cereals occupy more than two-thirds of agricultural land (Figure 24). Although they are grown in 36 provinces, production is mainly concentrated in the coastal areas, followed by central and mountainous regions. Cereals are part of most crop rotations, in addition to continuous cereal cropping, and are grown on a wide range of soils, production systems and environments. The distribution of cereal areas by agro-ecological zones is as follows:

- *Favorable* zone: 39.3% of total cereal production on 31.1% area ;
- *Intermediate* zone: 18.3% of total cereal production on 16.8% area ;
- *Unfavorable South*: 18% of total cereal production on 25.5% area ;
- *Unfavorable East*: 8.5% of total cereal production on 9.8% area ;
- *Mountainous* zone: 12.6% of total cereal production on 10% area ;
- *Saharan* zone: 3.3% of total cereal production on 4.1% area.

Soft wheat production is mainly concentrated in the *Favorable* zone, i.e. humid and sub-humid agro-systems, which account for 53% of total production (Table 6). *Intermediate*, *Unfavorable South* and *Mountains* zones account for 40% of wheat production while 8% of the production comes from *Unfavorable East* and *Saharan* zones. For durum wheat, 41% of the production comes from the *Favorable* zone fallowed by the *Intermediate* zone (25%). The *Mountain* and *Unfavorable South* zones produce 27%, and *Unfavorable East* and *Saharan* zones produce about 8%. Barley production is spread across four major zones: *Unfavorable South* with 28% of the total production, followed by *Favorable* (22%), *Intermediate* (21%) and *Unfavorable East* (16%). Areas follow the same distribution as the production for the three cereals. In contrast, productivity is driven by the rainfall gradient and the rate of irrigation.

Table 6: Partitioning of cereal production, area and yield, by agro-ecological zones (Average of 1990 to 2011).

	Production (%)			Area (%)			Yield (Q/ha)		
Agro-ecological Zone	Soft wheat	Durum wheat	Barley	Soft wheat	Durum wheat	Barley	Soft wheat	Durum wheat	Barley
Favorable	53	41	22	46	39	17	15.9	13.7	11.7
Intermediate	13	25	21	13	23	18	12.7	13.7	10.4
Unfavorable East	5	4	16	7	5	15	10.0	8.7	9.3
Unfavorable South	11	15	28	18	19	36	8.4	9.6	6.9
Mountain	15	12	9	13	12	8	16.8	13.2	10.8
Saharan	3	3	5	3	2	6	12.9	20.2	6.7

Cereal productivity of soft wheat, durum wheat and barley, is strongly influenced by rainfall, varying in space and time: in space, the northern regions are more productive than those in the south, ranging in a magnitude of 1 to 3.5, and in time, the yield varies from about 1 to 5, 3.6 Q/ha recorded during the dry crop season of 1999-2000 to 18.5 Q/ha recorded during the wet season of 2008 - 2009 (official agricultural Statistics, 1979-2011).

Production of soft wheat is concentrated in the Atlantic plains of the country, from arid zones south to wet zones north. The provinces that contribute most to wheat production are: Beni Mellal (11.4%), Sidi Kacem (10.0%), Kenitra (8.9%), Khemisset (6.7%), El Kalaa Sraghna (6.0%) El Jadida (5.7%), Settat (5.5%), Taounate (5.3%), Meknes (4.9%) and Fez (4.4%) (data series from 1990 to 2010). These ten provinces contribute more than two thirds (69%) of the country's wheat production. Among these 10 provinces, eight provide 61% of the national production of durum wheat. Each one of the remaining provinces contributes less than 4% of the total soft wheat production.

The provinces that contribute most to the country's production of durum wheat are: Settat (12.4%), El Jadida (10.9%), Taounate (9.3%), Taza (7.1%), El Kalaa Sraghna (6.1%), Safi (6.1%), Beni Mellal (5.1%) and Sidi Kacem (4.4%) (data series from 1990 to 2010). These eight provinces provide 61% of the national production of durum wheat. Each of the remaining provinces contributes less than 4% of the total durum wheat production.

Barley production is concentrated in arid and semi-arid zones and in mountainous areas. The provinces that contribute the most to the national production of barley include: Settat (8.4%), El Jadida (7.2%), Safi (6.8%), Nador (6.6%), El Kalaa des Sraghna (6.1%), Essaouira (5.3%), Oujda (4.6%), Khouribga (4.5%), Taza (4.4%) and Marrakech (4.2%) (data series from 1990 to 2010). These ten provinces provide 58% of the country's production of barley. Each of the remaining provinces contributes less than 4% of the total barley production.

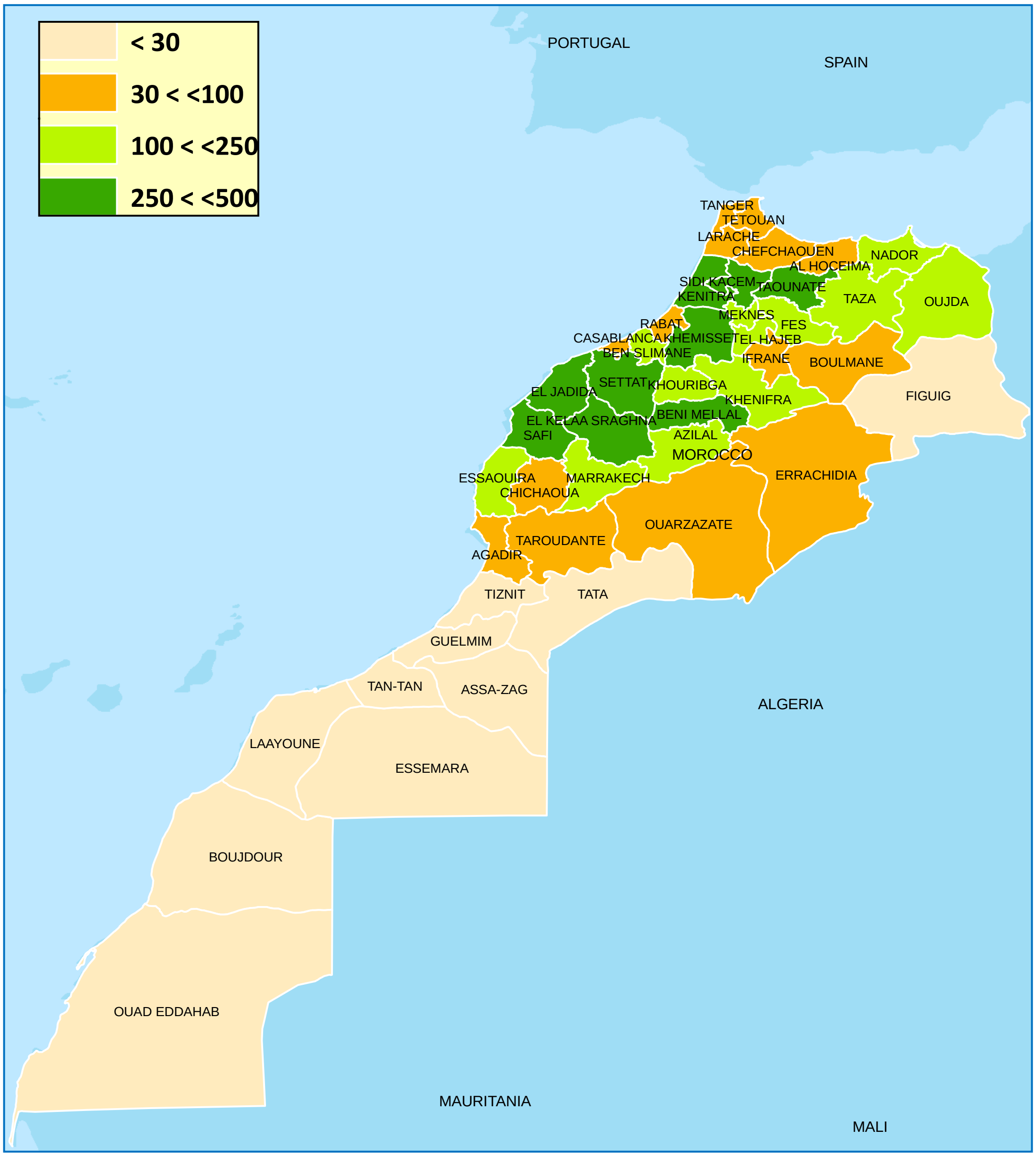


Figure 24 : Map of average production (in Mega tons) of autumn cereals (soft wheat, durum wheat and barley confounded) by province (data series from 1990 to 2010).

The final use of the grain produced by each of the three cereals influences their geographical distribution. Soft wheat is concentrated in favorable (wet) areas where high productivity is sought to meet the strong demand for this commodity. Durum wheat is concentrated in less humid areas, which are suitable for semolina pasta-making quality. Excessive moisture in the grain formation of durum wheat, causes "yellow berry" a phenomenon that transforms the grain starch from a state of hard glassy grain (suitable for the production of semolina) to a soft floury grain. Barley is concentrated in areas where sheep farming is dominant, mainly in *Intermediate*, *Unfavorable South*, and *Unfavorable East* agro-ecological zones.

Average yield at administrative province level can explain the overall yield average at the country level. Because of high correlations between province yields and country yield, some provinces can be indicators of the country's yield. Among the provinces most representative[37] of the country average cereal yield, Settat Province comes first with an R^2 of 95%, followed by El Jadida (R^2=92%), Casablanca (R^2=92%), and Khouribga (R^2=87%). For soft wheat, Settat comes first (R^2=93%), followed by Casablanca (R^2=89%), Benslimane (R^2=89%) and Taounate (R^2=84%). For durum wheat, Settat province comes first (R^2=92%), followed by Casablanca (R^2=89%), Benslimane (R^2=86%) and Rabat (R^2=85%). For barley, Khouribga province comes first (R^2=92%), followed by Azilal (R^2=90%), Safi (R^2=89%) and Settat (R^2=88%). Settat province which may represent the country yield for soft wheat and durum wheat, belongs to *Intermediate* zone, and Khouribga province, which may represent the country for barley yield, belongs to *Unfavorable South* zone. Preliminary cereal yield forecasts at the country level can thus be done based on the yield of one province, namely Settat for soft and durum wheat and all cereals confounded, and Khouribga for barley. Similar to yields, the country's production can also be forecasted based on these provinces productions.

3. TECHNOLOGICAL TREND

Technological trend, reflected in yield improvement, is undeniable for cereals in Morocco. During season of 1914-1915 which experienced heavy rains, Augustin (1921) noted that the yields of three main cereals, reached: 10-12 Q/ha for durum wheat and barley, and 8-10 Q/ha for soft wheat. In normal seasons, yields were around 7 Q/ha. At that time, the low yields of soft wheat compared to barley and durum wheat was due to inadequacy of imported cultivars from Europe to local conditions (Jlibene, 2009). The wheat was traditionally grown in the Saharan oases of the country. Since 1921, the level of productivity of cereals raised significantly. For example, during the extremely wet season of 2008-2009, country yields were 21.0 Q/ha for durum wheat, 21.6 Q/ha for soft wheat and 17.3 Q/ha for barley. A quick comparison between the two rainy seasons of 1914-1915 and 2008-2009, with regard to cereal yields, indicates that yields have doubled since early 1920's, at an annual average rate of 3%.

If we consider only the post climate change period (since 1980), agricultural statistics from 1979 to 2006 (Source: Direction of Strategy and Statistics) show that there has been an average annual yield increase at the country level of nearly 0.2 quintal per hectare (Q/ha.year) for wheat (0.19 and 0.18 for durum wheat and soft wheat, respectively), while for barley, technological trend was negative (Table 7). This improvement was greater for wheat than for barley, despite similar investment in agricultural research in Morocco. For barley, yields at the country level have not increased mainly due to the low utilization rate of improved cultivars and certified seed (less than 1%), and shift of part of the traditional barley areas to unfavorable areas for the benefit of soft wheat, following the large scale wheat promoting operation launched in 1985.

[37] Representativeness is measured by the correlation (R^2) between a Province yield and country yield, using a recent data base: series of 1999-2000 to 2010-2011.

The technological trend is not the same in all agro-ecological zones of Morocco. It is particularly high for *Favorable* and *Intermediate* agro-ecological zones. This trend is the result of research efforts deployed by INRA, especially in the fields of production system improvement in arid environments, and cereal breeding cultivars with high productivity and resistance to drought and weather associated diseases and pests.

Table 7: Yield trend over years (Quintal/ha.year), due to technology improvement of the three main cereals, by agro-ecological zone, and coefficients of determination (R^2) of the regression lines. (Data series of 1979 till 2006; Source: Balaghi and Jlibene, 2009).

Agro-ecological Zone	Soft wheat		Durum wheat		Barley	
	Trend	R^2	Trend	R^2	Trend	R^2
Favorable	**0.24**	**0.79**	0.19	0.71	-0.15	0.12
Intermediate	0.22	0.73	**0.26**	**0.85**	0.01	0.00
Unfavorable South	0.11	0.48	0.15	0.70	-0.01	0.00
Unfavorable East	0.06	0.20	0.08	0.37	-0.09	0.08
Mountain	0.17	0.60	0.13	0.70	-0.32	0.02
Saharan	0.05	0.08	0.13	0.20	-0.04	0.03
National	**0.19**	**0.87**	**0.18**	**0.86**	**-0.03**	**0.03**

Because of the high variability of cereal yields, which is due to the uncertainty of the climate especially since 1980, the technological trend cannot be distinctly observed in the curve representing yield evolution over years. When fitting a curve through the records of country's wheat yields observed during the crop seasons of 1961-1962, 1967-1968, 1985-1986, 1987-1988, 1990-1991 and 2005-2006, significant technological improvement made in favorable environments can be observed (Table 7). We also note that wheat yields can fall down to a very low yield level in seasons of extreme agricultural drought, around an average of 5 Q/ha at the national level. This lower limit of country yields, which has not been raised since 1961, continues to weigh on the country's food security. However, the fact that yields were kept at this lowest limit of 5 Q/ha despite the decline in rainfall during the 1990s and 2000s can be seen an indication of a relative technological improvement.

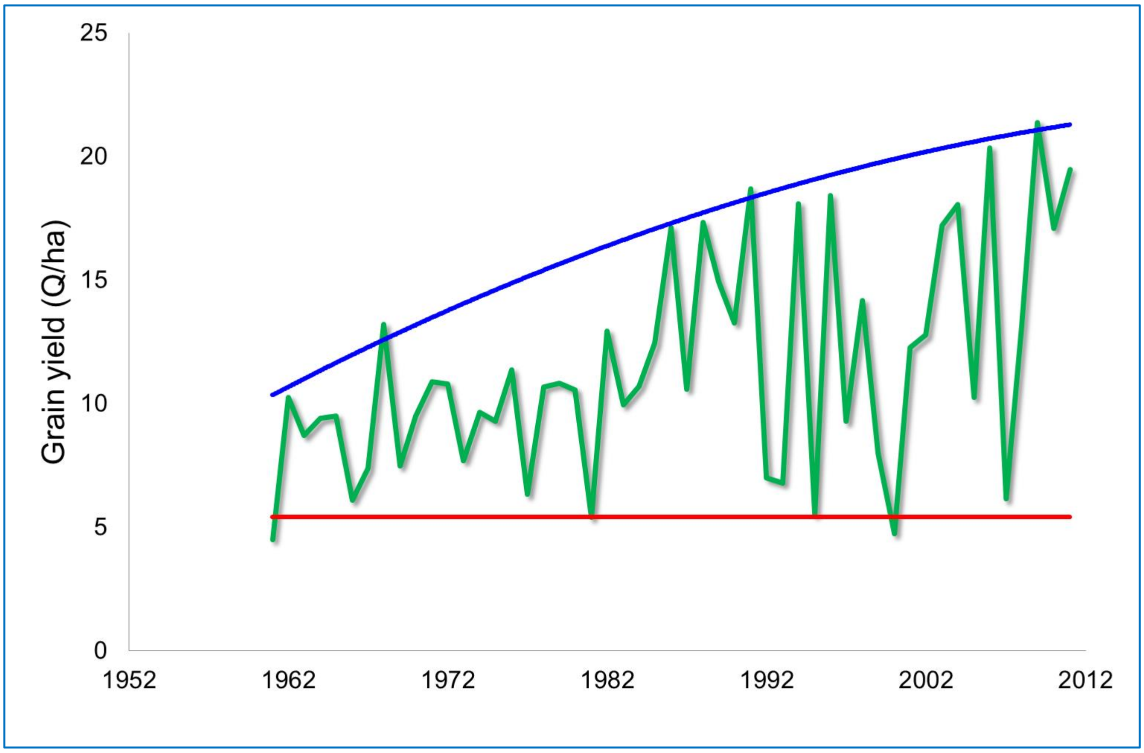


Figure 25 : Country soft wheat yield variation and trend in Morocco (in green) (Source of data: FAOSTAT and DSS).

The blue curve on top shows trend of record yields, for the last 50 years, obtained during 1961-62, 1967-68, 1985-86, 1987-88, 1990-91 and 2005-06 seasons. The red line below shows the lower level of yield obtained during seasons of extreme drought, which were: 1960-61, 1980-81, 1994-95, 1999-2000 and 2006-07.

The gap between yields obtained in experimental stations (Potential situation) and those obtained at the farmers' fields was analyzed through a modelling study done in 1994 at INRA's Regional Centre for provinces of Meknes, Annoceur and Douyet (Boughlala *et al.*, 1994). This study showed that the yield gap increases with improved production environments, from 20 Q/ha in adverse conditions to 50 Q/ha in extremely favorable environmental conditions in average (Figure 26). One might expect wet seasons to recover for dry seasons losses. This is not the case, since potential production during wet seasons is not unlocked, due to premeditated farmer's attitude in reducing inputs for minimizing climatic risk or due to the lack of farmer's knowledge concerning improved technologies (improved cultivars, certified seeds, fertilization, weed control, supplemental irrigation, etc.).

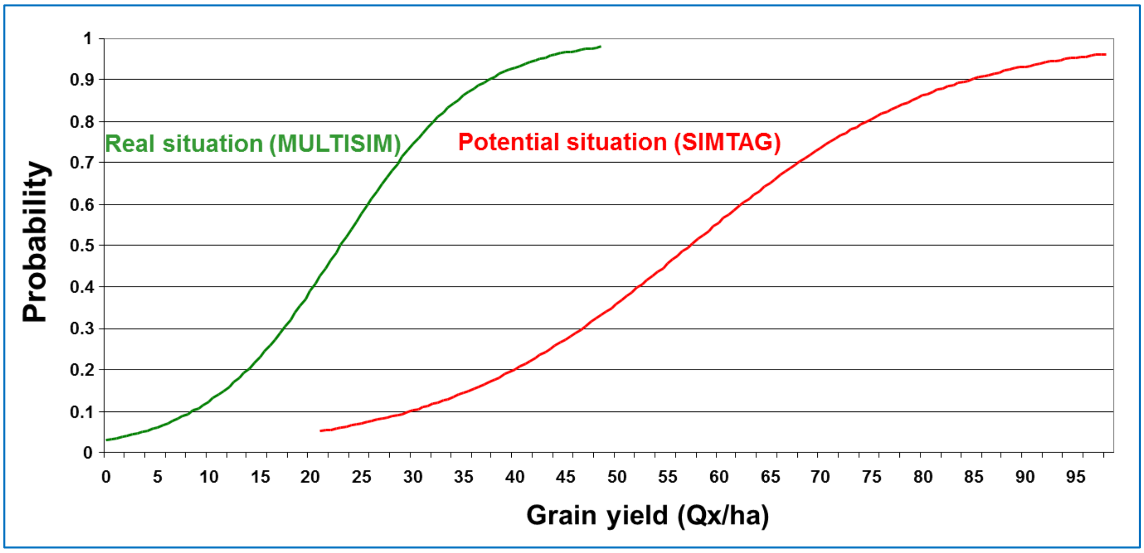


Figure 26 : Curves of cumulative probability of soft wheat yields at farm level (real situation) and at potential situations at Meknes (Source: Boughlala *et al*., 1994).

In experimental stations of INRA, the annual rate of yield increase since 1980 reached 0.5 Quintal/ha.year due to genetic improvement for wheat (Jlibene, 2011), against 0.19 Quintal/ha.year at farmer level (Table 7). This difference in productivity shows how much efforts remain to be done in terms of technology transfer. In the fields of some elite farmers that used improved wheat varieties, record yields greater than 80 Q/ha were recorded during wet seasons.

The productivity of rainwater (i.e. ratio of yield to rainfall) at national level was also improved by 67% between the 1960s and 1970s to the 1980s and 1990s, to the order of 2.5 kg per mm (Jlibene, 2011). The average technological trend at the country level was estimated more precisely at about 0.15 Quintal/ha.year (Figure 25) instead of 0.19 Quintal/ha.year, as previously reported in this document (Table 6). This average hides differences in improvement between contrasting seasons. The various seasons in Morocco can be classified into three contrasted classes of productivity corresponding to three classes of rainfall: wet (>400 mm), intermediate (300 to 400 mm) and dry (<300 mm). When analyzing separately each of these three classes, technological trend is found to be of more than 0.3 Quintal/ha during wet seasons, for both soft wheat (Figure 27) and durum wheat (Figure 28). During intermediate seasons, slow trend was observed for soft wheat and negative for durum wheat, while during dry seasons the trend was negative for all the two species. This seeming low productivity in intermediate and dry seasons can be explained by the severity of droughts experienced during the period of 1980 to 2008.

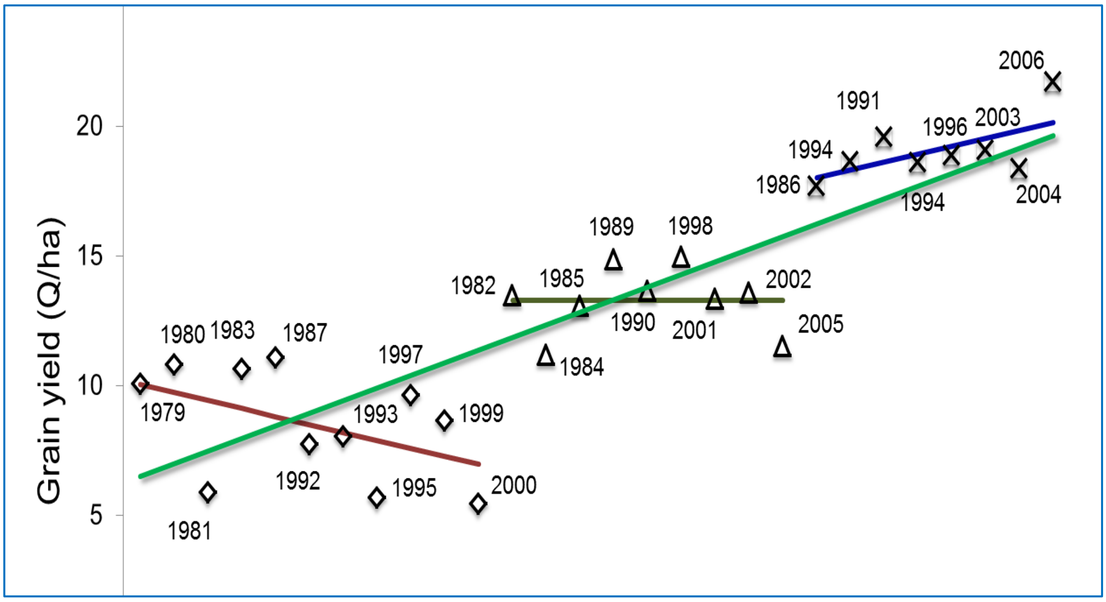


Figure 27 : Technology trend or improvement achieved in 28 years for soft wheat in Morocco.
Cropping seasons (series of 1979 to 2006) have been subdivided into three classes of yields, corresponding to three classes of rainfall (<300, 300 to 400 and >400 mm/season) : dry seasons (lozenge), Intermediate (triangle) and wet (cross). Technological trend is +0.15 Quintal/ha.year on average (green line), -0.3 Quintal/ha.year in dry seasons (brown line), nil in intermediate environments (dark green line) and +0.3 Quintal/ha.year in wet seasons (blue line). (Source: Balaghi and Jlibene, 2009).

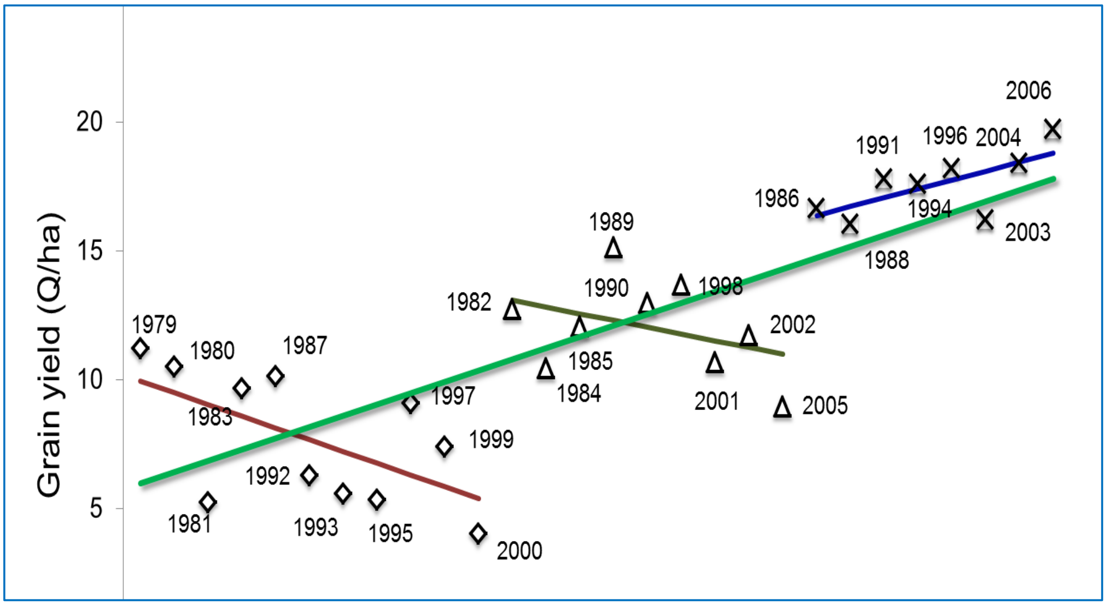


Figure 28 : Technological trend or improvement achieved in 28 years for durum wheat in Morocco.
Cropping seasons (series of 1979 to 2006) have been subdivided into three classes of yields, corresponding to three classes of rainfall (<300, 300 to 400 and >400 mm/season) : dry seasons (lozenge), intermediate (triangle) and wet (cross). Technological trend is +0.15 Quintal/ha.year on average (green line), -0.46 Quintal/ha.year in dry seasons (brown line), -0.26 Quintal/ha.year in intermediate seasons (dark green line) and +0.35 Quintal/ha.year in wet seasons (blue line). (Source: Balaghi and Jlibene, 2009).

4. CEREAL CROP DEVELOPMENT

All the three cereals are sown in the fall, within a time frame of two months, starting from last week of October to second week of December. In many parts of the cereal growing areas, sowing starts after the first significant rains which allow germination of weeds and soften soil for seed bed preparation.

The development of the aerial part of cereal undergoes several stages, of which the most important ones taken as benchmarks are:

- **Germination** takes place just after sowing, by seed imbibition, followed by swelling and issuance of the radicle, and then of coleoptile which protects the first leaf, and breaks through the ground. This stage requires moisture in the surface soil horizon and lasts about a week.
- **Emergence** is recognized by the appearance of the coleoptile, which wraps the first leaf for protection and pushes through soil up to the surface. It takes place ten days after sowing, but later if rains come late or if temperatures are lower than usual. The first leaf will be followed by a second and then a third one, which are supported by a stem, called main shoot. This stage lasts about a month.
- **Tillering** begins when a secondary stem (or tiller) appears at the axils of the primary stem, at the base of the eldest of the three formed leaves. The main shoot continues to issue leaves and tillers. Tillers in turn emit secondary tillers. Tillers continue to form (theoretically unlimited) at the basis of the oldest of the three leaves formed, but limited by temperature increase and water deficit. All tillers are grouped near ground level, constituting the basal tillering. Each leaf on the main shoot or a tiller is initiated from a node. At this point the nodes are grouped. Tillering ends when the nodes begin to separate and become discernible by touch at the base of tillers. The number of tillers determines the potential number of spikes. The issuance of tillers lasts about one month after emergence (three dekads).
- **Stem elongation** is the process of elongation of internodes, which begins with the judgment of the sheet formation and early spike initiation. During internodes elongation, parts of the spike are formed, in particular number of spikelets, number of flowers per spikelet and floral organs. Drafts of the spike are visible to the naked eye, since few inches of elongation. The spike is protected by rolled leaves, eight in number generally. Other intermediate stages can be identified as swelling that indicates the rise of the spike, or heading that indicates the appearance of the spike outside the sheath. This phase, which lasts more than one month, corresponds to maximum biomass accumulation. It is sensitive to water stress. The potential number of grains is determined at this stage.
- **Flowering** is the stage between the vegetative phase of the reproductive phase of the crop. It takes place about a week after heading, visually recognized when stamens come

out. Stamens, three in number per flower, are expelled outside the spike, once the pollen they contain is released to fertilize the stigma that will lead the genetic material of pollen towards the ovary, in order to the fertilize it. The exit of stamens indicates that fertilization took place, and also eventually fertilization.

- **Grain filling** begins immediately after fertilization, the egg develops into the seed whose development goes through benchmark stages: the milk stage and dough stage. During dough stage, stalk of the spike turns yellow, indicating physiological maturity. This phase determines the weight of the grain, and lasts one month and a half, approximately.

Final grain yield is the product of: (1) number of spikes per square meter, determined during tillering, (2) number of grains per spike, determined during elongation, and (3) grain weight, determined during grain filling.

V. AGROMETEOROLOGICAL ANALYZES

Climate and cereal production analyzes revealed a strong dependency of cereal yields on weather. In this chapter, the relationship between weather and cereal yields is studied in order to explore the agrometeorological indices that can be used to forecast yields. Evapotranspiration, which is a function of rainfall and temperature, is one of the variables that best explain cereal yields on fine scales, as it is directly related to the cereal production of biomass. On wider scales, rainfall used alone explains a substantial part of the inter-annual variability of cereal yields, when cumulated over the cropping season from September till May. At national level, this dependency is valid for cumulated rainfall below 378 mm, a threshold which is slightly above the long term rainfall average. Rainfall above this amount is not necessarily associated with higher yields, leading to introduction of the concept of water productivity (i.e. the ratio of yield per unit of rainfall). Improvement of water productivity over the seasons was correlated with improvement of technological trend achieved on wheat. Water productivity is significant in irrigated Saharan zones, followed by Intermediate and Unfavorable zones. In high rainfall areas or in rainy seasons, water productivity is relatively low, due to inefficiency of farmers in taking advantage of heavy rainfall. Drought events during the cropping season also impact cereal yields. NDVI taken as an environmental predictor index is positively correlated with both rainfall and cereal yields. It is positively and linearly correlated with rainfall below 550 mm/cropping season. NDVI is a powerful cereal yield predictor, when averaged from February till March, or from February till April.

1. RELATIONSHIP BETWEEN TRANSPIRATION AND GROWTH

In the mid-1950s, De Wit (van Keulen and van Laar, 1986) was among the first authors to recognize the direct relationship between transpiration[38] and plant productivity. This relationship was later used by FAO to develop models of crop response to evapotranspiration (Doorenbos and Kassam, 1979). Actual evapotranspiration[39] (ETa) of plants is one of the variables that best explain agricultural productivity, as it is directly related to the production of biomass. The relationship is linear, at various spatial scales (leaf, plant and region), and reconfirmed by many authors, in particular in Settat province of Morocco (Bazza and Tayaa, 1998).

Transpiration may be low, due to a shortage of water within the root zone (drought), or due to low amount of solar energy received (cold). One of the basic principles of agrometeorology is that plant growth (biomass accumulation) is governed by the incident energy which has to be released by plants through transpiration.

In Morocco, the relationship between evaporation and temperature has been demonstrated a long time ago (Loup, 1957). Temperature is the factor that most determines evaporation, either average

[38] Water evaporated from plant tissues. It depends on the energy received, the vapor pressure gradient and wind speed (Allen *et al*. 1998).

[39] Sum of plant transpiration and water evaporated from soils, in limiting water supply.

or maximum temperature. Temperature determines evapotranspiration as well, which combines both air evaporation and plant transpiration of water from the soil (Figure 29).

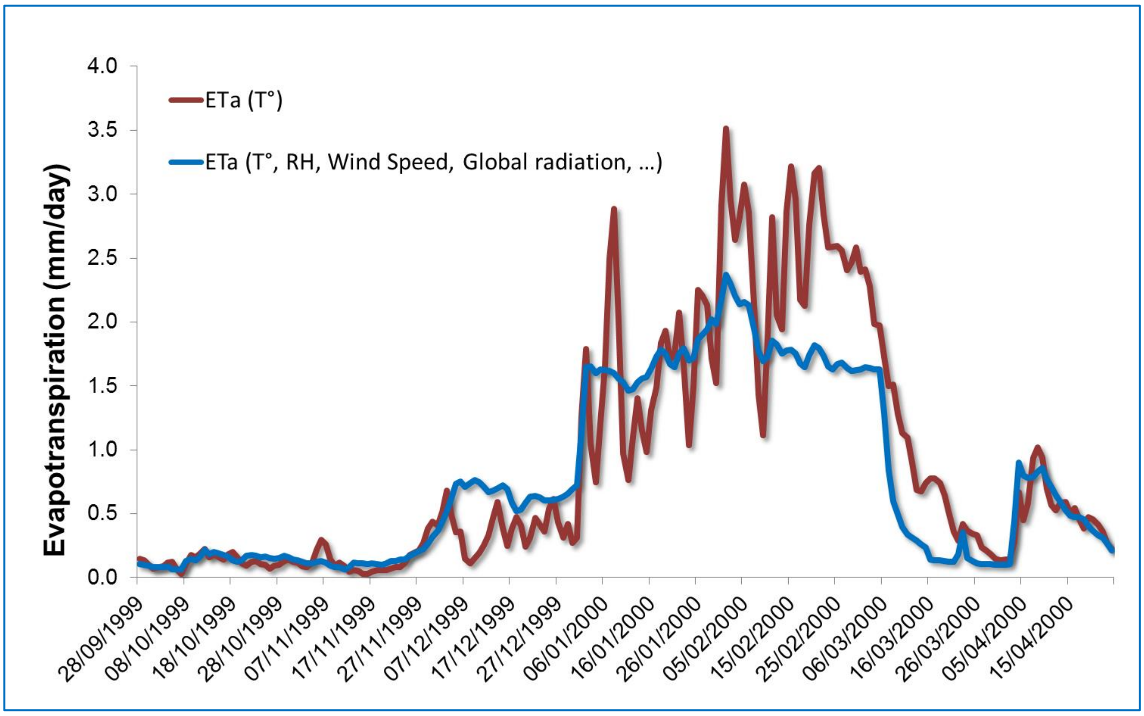


Figure 29: Evolution of daily actual evapotranspiration of soft wheat, simulated on the basis of temperature alone (Eta_T°) and of temperature in association with relative humidity (RH), wind speed and global radiation, at Meknes (Balaghi, 2000).

The approach was then updated by FAO, developing "AQUACROP" tool (http://www.fao.org/nr/water/aquacrop.html), which can simulate crop productivity by disaggregating field crop evapotranspiration (ETa), into soil evaporation and crop canopy transpiration (Hsiao *et al*., 2009; Raes *et al*., 2009; Steduto *et al*., 2009).

The relationship between transpiration and biomass is shown schematically in Figure 30 (Jlibene and Balaghi, 2009). The transpired water, which is essential for the metabolism, is transported from the soil to the atmosphere passing through plants. The amount of water transpired is proportional to the amount of water available in the soil. The latter results from the existing residual moisture within the soil, in addition to rainfall and irrigation, minus losses, due to runoff, drainage, soil evaporation and weeds transpiration. The soil acts as a buffer, keeping the humidity between two water supplies.

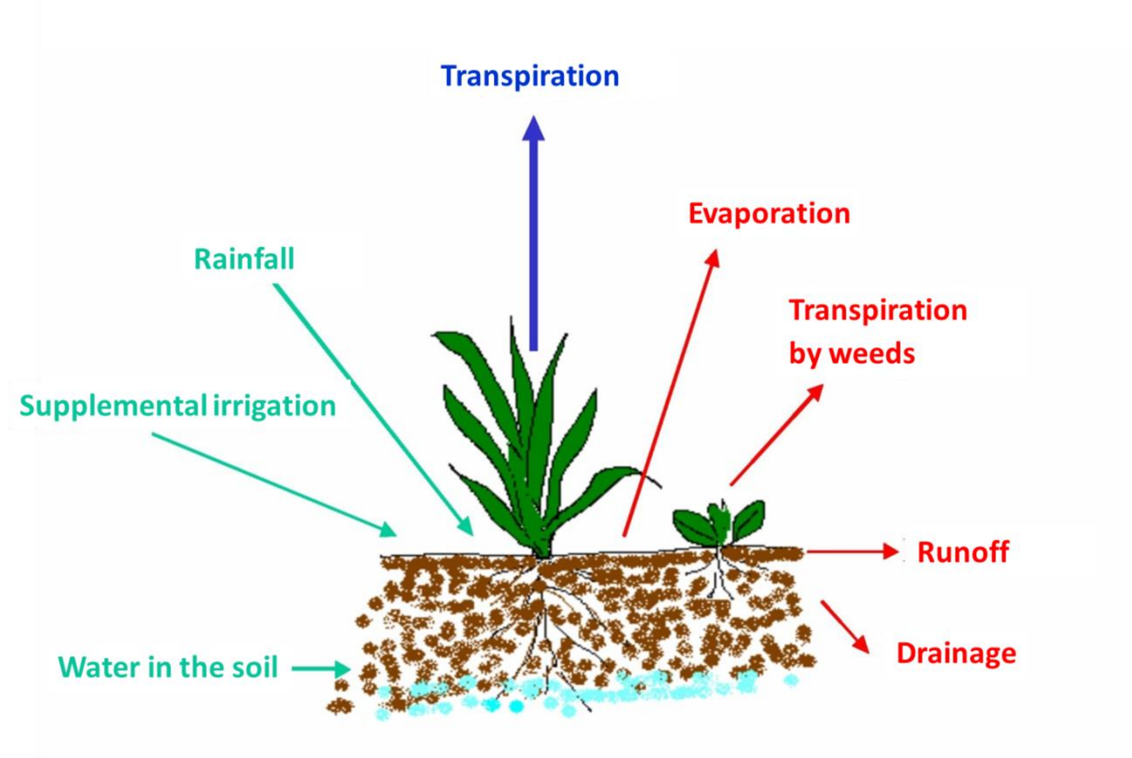


Figure 30: Schematic figure illustrating the relationship between transpiration and biomass production (Jlibene and Balaghi, 2009).

The direct action of these factors on biomass (Figure 30) has been experimentally demonstrated in a variety of agronomic studies. It has become a fact that rainfall, irrigation, weed control, mulching and soil moisture increase crop yields.

1.1. RELATIONSHIP BETWEEN RAINFALL AND CEREAL YIELDS

Rainfall is the factor that induces the major proportion[40] of cereal yields' variation in Morocco. The relationship between rainfall and cereal yields has, from long time and on several occasions, been demonstrated in Morocco (Papy, 1979; Douguedroit and Messaoudi, 1998; Douguedroit *et al.*, 1998). Cereals yields (and thus production) vary with rainfall, depending on the cropping season. In contrast, the area of the three cereals (soft wheat, durum wheat and barley) is relatively constant (5.3 million hectares), with low inter-annual variation (CV = 6%, between seasons of 1999-2000 and 2010-2011).

In general, cereal yields and cereal production evolve in the same direction as the rainfall. An

[40] The relative importance of other factors that could explain cereal yields' variation depends on the spatial scale considered. For instance, agro-technical factors and soil types are relevant to consider only at fine spatial scales, for explaining cereal yields. Unfortunately, in Morocco as in most developing countries, these data are often unavailable.

increase in rainfall, relative to previous season, is associated with an increase in yield and in production. Vice-versa, a decrease of rainfall is associated with a decrease in yields and in production (Figure 31). The coefficient of variation of rainfall is equal to 32%, while it is 37% for soft wheat, 41% for durum wheat and 47% for barley, over the period 1988-2011. There is a strong positive correlation (R^2> 65%) between cumulated rainfall over the cropping season and cereal yields. However, there are some exceptions to this rule. During both 1989-1990 and 1999-2000 cropping seasons, rainfall increased while yields decreased. In contrast, during the cropping season of 1997-1998, yields had increased despite a drop in rainfall compared to average. These exceptions demonstrate the importance of rainfall distribution within the cropping season.

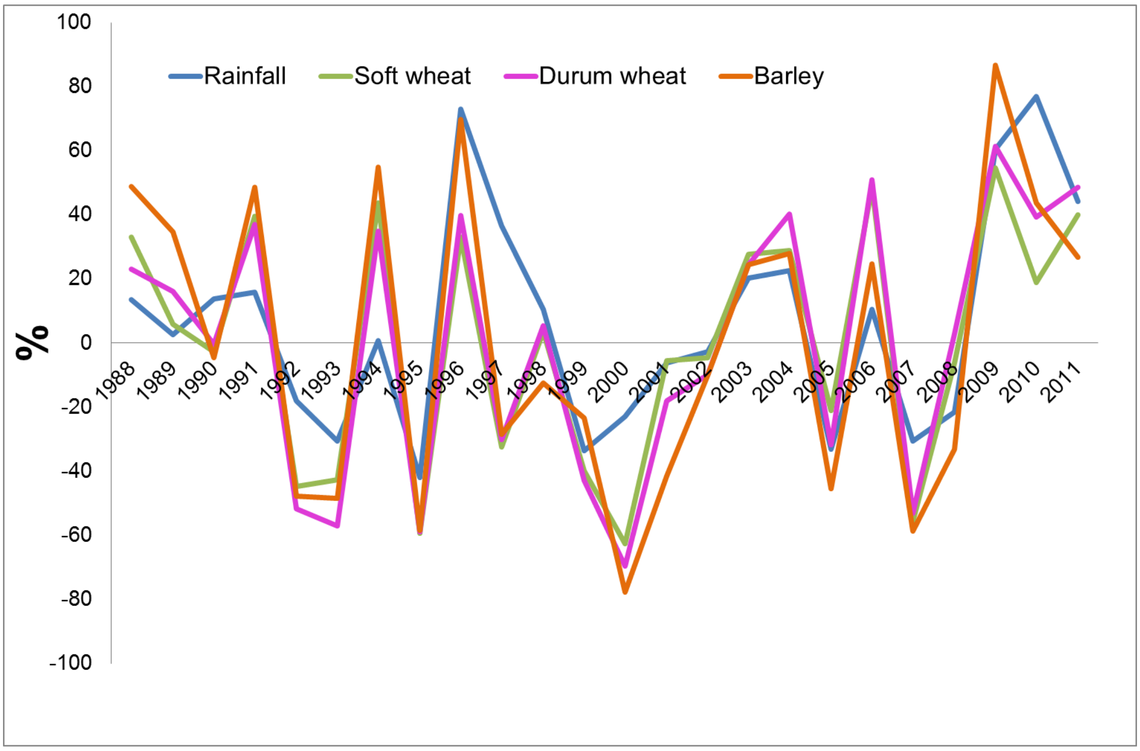


Figure 31: Deviation (%) from mean values of cumulated rainfall over September to May period, and main cereal yield (soft wheat, durum wheat and barley), at the country level (data from 1988 to 2011); indicating the co-variation of rainfall and cereal yields.

1.2. RELATIONSHIP BETWEEN RAINFALL AND CEREAL AREA

The total area of cereals has steadily increased since 1980, at an average rate of 39,600 hectares/season. This increase was mainly the result of increased soft wheat area, boosted by the large scale state promotion of this crop (in French, Opération de promotion du blé tendre), launched in 1985-1986 (Jlibene, 2011). This operation was designed to double the cultivated area of soft wheat, from 0.5 million hectares to 1.0 million hectares, using as incentives: the distribution of new improved varieties and fixed prices for harvested grain for producers, and fixed marketing margins for industrials (Ait El Mekki, 2006). The area of soft wheat which had stagnated at around half a million hectares for over thirty years, until the early 1980s, has been doubled in 1986, and multiplied by four, ten years later. The area stabilized then at around two million hectares, occupying more than a fifth (1.9 million hectares, from 1998 to 2011) of the agricultural area of the country (8.7 million hectares). Over the period 1998-2011, the area of soft wheat has increased at an average rate of 34,900 hectares/season, accounting for 88% of total cereal area increase. The area of durum wheat and barley declined at a rate of 11,600 and 13,800 hectares/season, respectively (Figure 32).

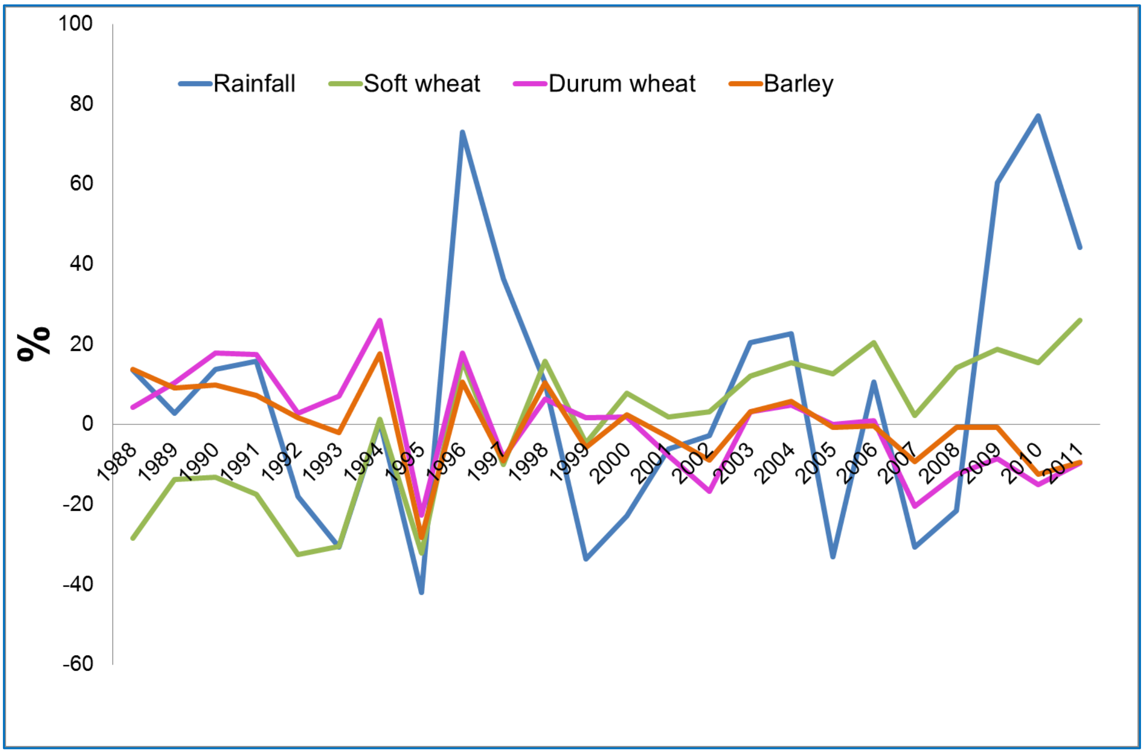


Figure 32: Deviation (%) from mean value of cumulated rainfall over September to May period, and of main cereal area (soft wheat, durum wheat and barley), at the country level (data from 1988 to 2011).

In Morocco, cereal area is also influenced by rainfall, especially rainfall of start of the season, from the first significant rains[41] till around November - early December (Figure 33). These first significant rains were estimated at a minimum amount of 25 mm, cumulated over a period of 10 days, in semi-arid regions of Morocco (Watts and El Mourid, 1988). The arrival date of these rains, which is highly inconsistent from one year to another, determines the sowing date for cereals in arid and semi-arid

[41] The first significant rains are defined as the amount of rainfall that allows germination and emergence.

environments (Benaouda and Bouaziz, 1992). The cropped area is larger when the rains come early and heavy in the season, as most farmers sow after these first rains. When rainfall is abundant at the beginning of the season, even arid areas of southern Morocco are sown, as for example in the region of Marrakech, Essaouira and Kelâa Sraghna.

Rainfall of the months of November till December best explains the cropped cereal area, especially in the case of barley, then for soft wheat and durum wheat. However, during the last cropping seasons, sowing tend to start from the first week of November, even in the absence of rain.

Rainfall of the months of November till December best explains the cropped area of cereal, especially in the case of barley, then for soft wheat and durum wheat. However, during the last cropping seasons, sowing tend to start from the first week of November, even in rain deficiency.

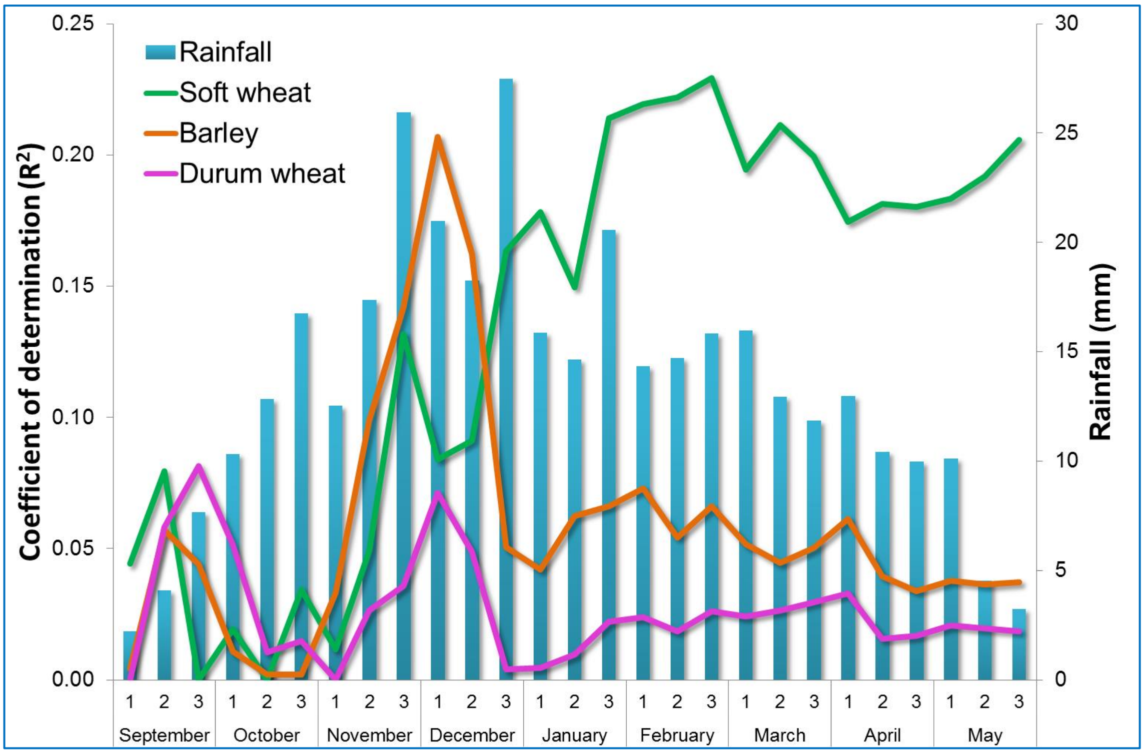


Figure 33: Coefficient of determination (R^2) of the relationship between main winter cereal area (soft wheat, durum wheat and barley) and cumulated rainfall during the cropping season (starting in October in average), at the country level (Data series from 1988 to 2011). Average dekadal rainfall is plotted in second axis (blue bars), for illustration.

1.3. RELATIONSHIP BETWEEN RAINFALL AND RAINWATER PRODUCTIVITY

1.3.1. AT NATIONAL SCALE

When cereal yield is regressed against cumulated rainfall during the cropping season, the slope of the regression line represents Rain Water Productivity[42] (RWP). At national level and for the three winter cereal combined, the average RWP translated in grams/liter rainwater (g/l), is in average 0.332 g/l, for the period 1988-2011. RWP varies depending on the cropping season, from a maximum of 0.506 g/l reached in 1993-1994 to a minimum of 0.149 g/l in 1999-2000. RWP is on average higher for soft wheat (0.404 g/l) than for durum wheat (0.370 g/l) or for barley (0.261 g/l).

Grain yield of three winter cereal (soft wheat, durum wheat and barley), increases with the cumulated rainfall from September to April, up to the limit of 378 mm slightly above long term average (Figure 34, Figure 35 and Figure 36). Beyond this limit, yields do not increase, indicating an undervaluation of wet seasons, which can be explained by the adaptation of cropping practices to slightly above average rainfall conditions in Morocco.

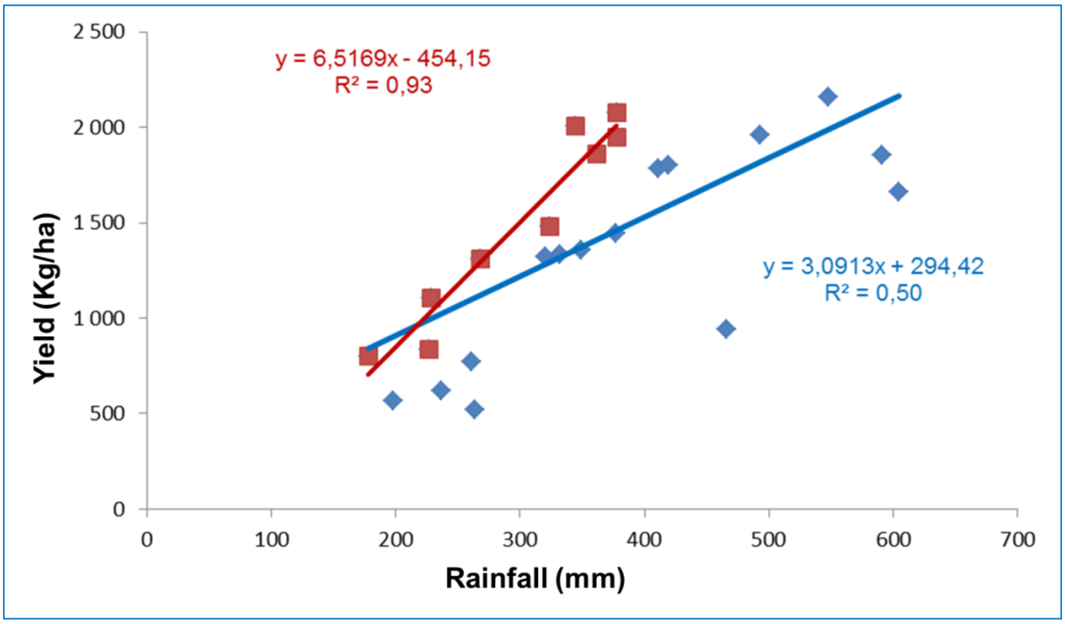


Figure 34: Relationship between soft wheat country yield (Kg/ha) and cumulated rainfall during the cropping season (mm) (data from 1988 to 2011).

Slope of the regression line (in blue) represents Rain Water Productivity of soft wheat in Morocco, which is 0.309 g/l. The slope of the regression line above (in red) denotes maximum Rain Water Productivity manageable in optimum conditions (0.652 g/l).

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[42] Rainwater Productivity (g/l) is defined as the ratio of yield (kg/ha) on the cumulated rainfall (mm) during the cropping season (September to April).

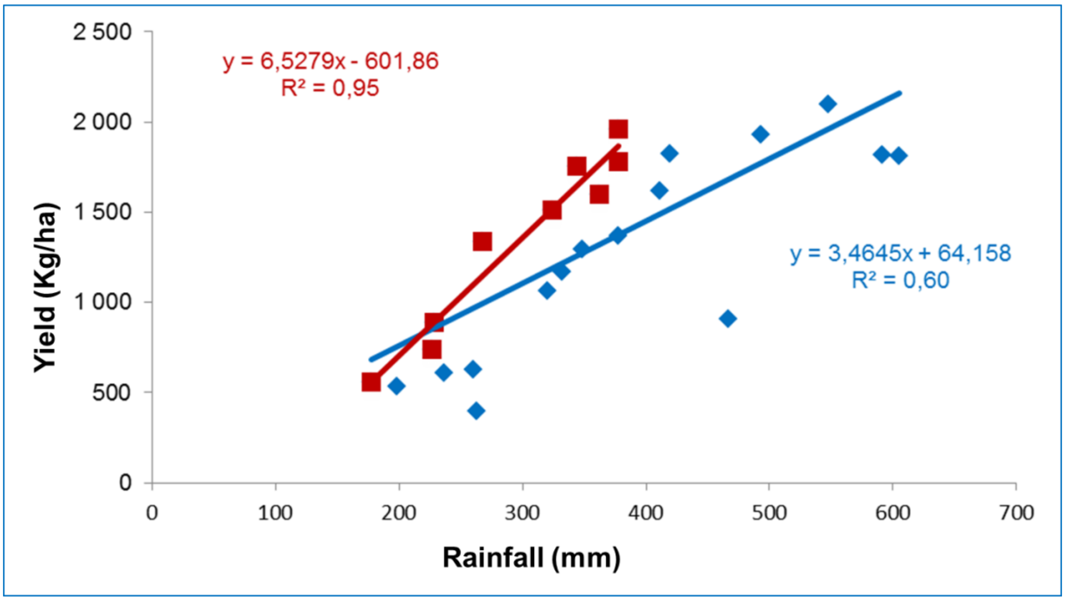

Figure 35 : Relationship between durum wheat country yield (Kg/ha) and rainfall during the cropping season (mm) (data from 1988 to 2011).

Slope of the regression line (in blue) represents Rain Water Productivity of soft wheat in Morocco, which is 0.347 g/l. The slope of the regression line above (in red) denotes maximum Rainwater Productivity manageable in optimum conditions (0.653 g/l).

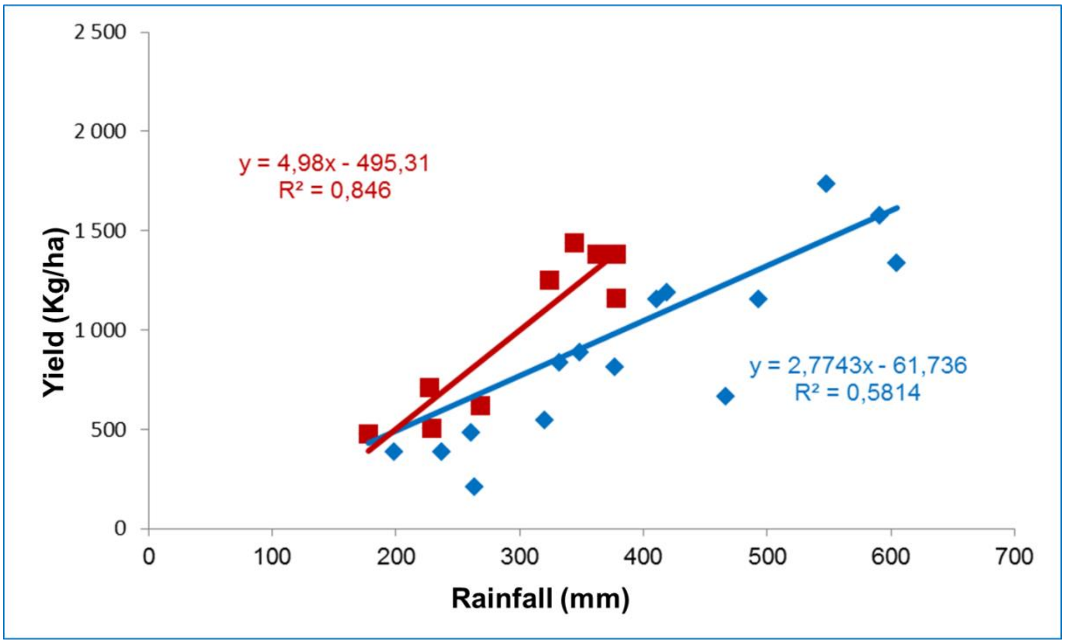

Figure 36: Relationship between barley country yield (Kg/ha) and rainfall during the cropping season (mm) (data from 1988 to 2011).

Slope of the regression line (in blue) represents Rain Water Productivity of soft wheat in Morocco, which is 0.277 g/l. The slope of the regression line above (in red) denotes maximum Rainwater Productivity manageable in optimum conditions (0.498 g/l).

The valuation of wet seasons requires more farmers' input investments, mainly concerning selected seeds, nitrogen and pesticides. Agriculture is also "*the art of managing uncertainty*" (Faurès *et al*., 2010), as it aims at minimizing production risks related to the variability and unpredictability of weather or of market. In unreliable environments, strategies for risk management are hardly compatible with the objective of maximizing crop yields, which involves larger investments and therefore higher risk-taking. The "*policy of dams*" launched in the early 1960s in Morocco, aimed at reducing climatic risk and in the same time ensuring water supply to cities (hydraulic potential of 21 billion m^3). Currently, irrigated lands account for 17% (1.46 million hectares) of agricultural lands, of which 76% are still under surface irrigation (MAPM, 2011).

On average, durum wheat (Figure 35) seems to better use rainwater with a RWP of 0.346 g/l, followed by soft wheat (0.309 g/l) (Figure 34) and barley (0.277 g/l) (Figure 36). The apparent advantage of durum wheat in RWP is probably related to the fact that durum wheat is mainly grown in semi-arid areas, unlike soft wheat which is relatively more cultivated in favorable (less valued) areas (Table 6).

Potential RWP, expressed by the slope of the regression line between the potential cereal yield and rainfall indicates that soft and durum wheat better value rainwater (0.652 g/l), unlike barley (0.498 g/l) (Table 8). Potential RWP is reached in optimal production conditions. It is almost double average RWP, highlighting shortfall of agriculture concerning the rainwater valuation, in particular, and management of natural hazards in general.

Theoretically, minimum rainfall required for grain production is 70 mm for soft wheat, 92 mm for durum wheat and 100 mm for barley (Figure 36). For the three species, this rainfall level is very low, indicating drought management improvement in Morocco. The difference between this minimum rainfall amount, for these three species is in favor of soft wheat, which is relatively a rustic species in Morocco, compared to durum wheat and barley.

Table 8 : Average and Potential Rain Water Productivity (RWP) of cereals, at national level. RWP is equal to the slope of the relationship between yield and rainfall.

Average RWP is computed using all yield data, while Potential RWP is computed using only the maximum yields observed for each level of rainfall.

Species	Rainwater Productivity (gram/liter)	
	Average	Potential
Soft wheat	0,309 ; R^2 = 49,6%	0,652 ; R^2 = 93,3%
Durum wheat	0,346 ; R^2 = 59,7%	0,653 ; R^2 = 94,6%
Barley	0,277 ; R^2 = 58,1%	0,498 ; R^2 = 84,6%

1.3.2. AT AGRO-ECOLOGICAL ZONE SCALE

For the three cereals together, RWP increases from *Favorable* agro-ecological zone (0.281 g/l), *Unfavorable South* (0.321 g/l), *Mountain* (0.333 g/l), *Unfavorable East* (0.334 g/l), *Intermediate* (0.340 g/l) to the *Saharan* zone (0.548 g/l) (Table 9). In *Saharan* zone, high RWP is due systematic irrigation. From these three species, soft wheat has the highest RWP in *Favorable*, *Mountain* and *Unfavorable East* zones. Durum wheat has the highest RWP in *Unfavorable South*, *Intermediate*, and more significantly, in *Saharan* zone. Barley has the lowest RWP in the six agro-ecological zones.

Table 9: Rain Water Productivity (gram/liter), for the three winter cereals, at the national and agro-ecological zones levels (average from 1988 to 2011).

		Rainwater Productivity (gram/liter)			
	Rainfall (mm)	Soft wheat	Durum wheat	Barley	Three cereals
Favorable	524.9	0.316	0.271	0.232	0.281
Unfavorable South	243.4	0.349	0.408	0.292	0.321
Mountain	436.4	0.409	0.314	0.253	0.333
Unfavorable East	273.3	0.349	0.297	0.333	0.334
Intermediate	350.3	0.360	0.393	0.293	0.340
Saharan	190.1	0.763	1.196	0.393	0.548
National	**346.6**	**0.404**	**0.370**	**0.261**	**0.332**

2. AGRICULTURAL DROUGHT

Cumulated rainfall during the cropping season can be an indicator of drought. Already in 1921 in Morocco, Augustin (Augustin, 1921) stated: "*It is the amount and distribution of rainfall that indicate which areas are suitable for cropping and for what crops*".

The number of dry seasons, with rainfall less than 400 mm, increased since climate change observed in the early 1980s in Morocco. Frequency of dry seasons has increased fivefold, from one dry season every 15 normal seasons, during the 1930s, 1940s, 1950s, 1960s and 1970s, to one dry season every three normal seasons, in the last three decades (Jlibene, 2011).

The accumulation of rainfall during the cropping season can be interrupted, thereby informing on drought. Interruptions can occur on one or many time periods, in the beginning, middle or end of the season. Examples of these interruptions are given in Figure 37.

- During season of 1994-1995, there has been no rain for almost three months (November, December and January), affecting grain and straw cereal production ;
- Season of 2004-2005 was almost identical to that of 1994-1995 (driest historical season), in terms of total rainfall, but not in terms of its distribution. During season of 2004-2005, dry spells during January and three consecutive months in March, April and May, were recorded ;

- During season of 1999-2000, 180 mm were recorded till January, then a drought settled for three consecutive months ;
- Season of 1996-1997 was rainy till mid-January, followed-on by two consecutive dry months ;
- During season of 2000-2001, 300 mm were recorded till late February, and then rains stopped during the following two consecutive months of March and April.

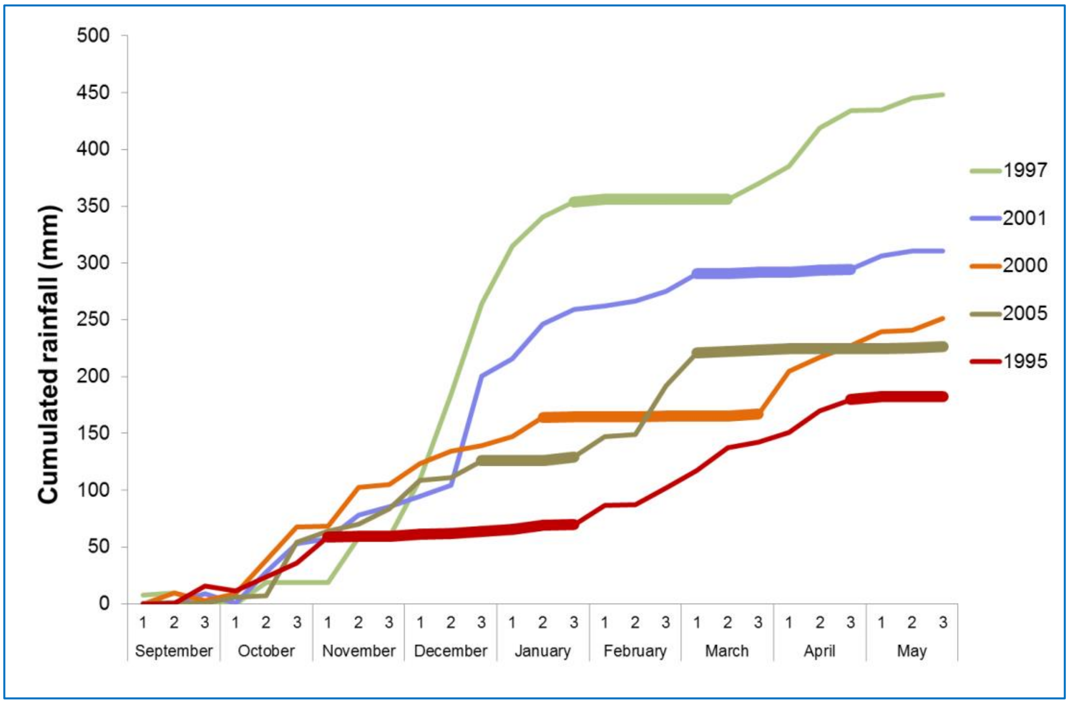

Figure 37 : Dekadal cumulated rainfall between September and May, of dry cropping seasons. Periods of drought are recognized as flat segments of the curves (in bold). Drought can occur at diverse periods of the crop cycle.

Figure 38 illustrates the similarity of rainfall distribution during the cropping season, covering many weather stations distributed all over the country. In this figure, the flat zones of cumulated rainfall curves indicate drought spells. Drought is hence generalized all over the country, whenever it occurs. For example, during the dry season of 1996-1997, there was almost no rainfall, in 23 provinces of the country taken as wide examples, during the first ten days of January and the last dekad of March (Jlibene, 2011). This situation systematically occurs whenever there is drought. Drought is thus due to low rainfall, inadequate intra-annual distribution of rainfall or the two reasons at once.

Drought can be explained by a deviation of rainfall compared to long term average, in terms of total amount or distribution. The idea behind this is that crops have adapted over the centuries to a usual rainfall distribution, and are thus affected when this normal distribution is disturbed.

Agricultural drought occurs when the amount of rainfall and soil water reserve are not sufficient to ensure crop water needs. In conclusion, drought is a water deficiency, sufficiently prolonged to cause a negative effect on crop. In this definition, there are two important concepts: sufficiently prolonged water deficit and the negative effect on crop. The effect on the crop depends on its sensitivity to water deficit, also known as vulnerability or tolerance.

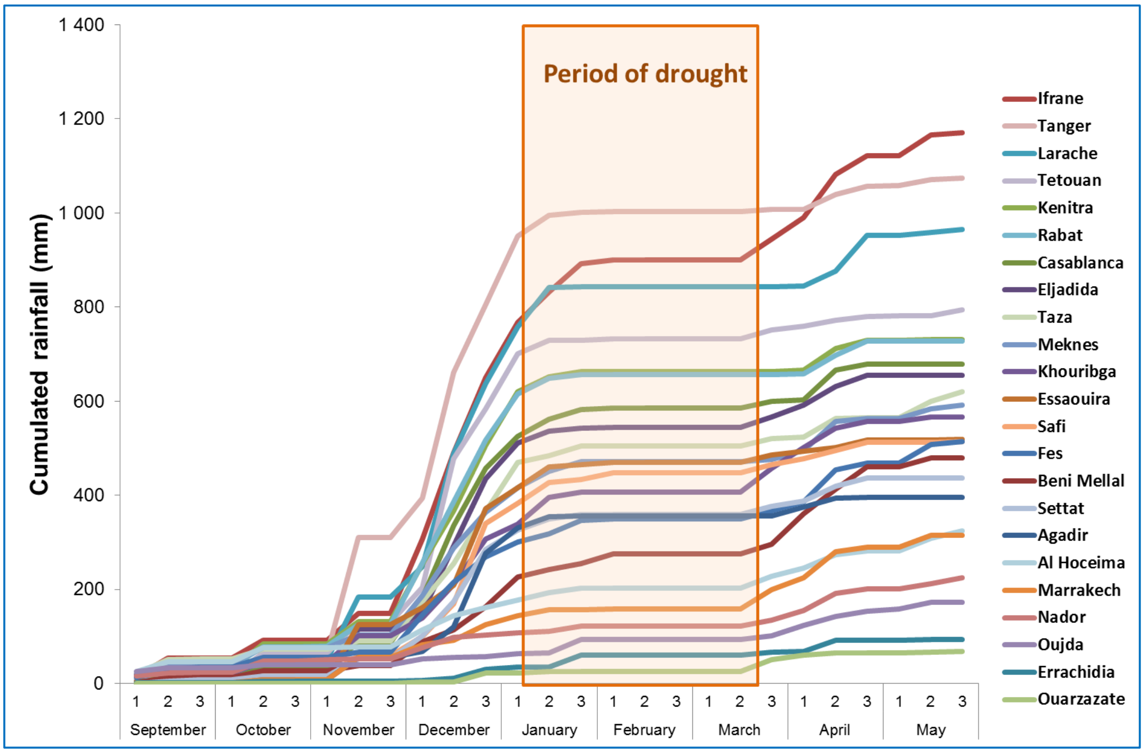

Figure 38: Spatial distribution of cumulated dekadal rainfall (from September till May) for the dry season of 1996-1997. Locations used cover 23 provinces of Morocco, scattered all over the country (Source: Jlibene, 2011).

3. RELATIONSHIP BETWEEN GROWTH AND RAINFALL

The normal growth cycle of wheat in Morocco, in relation with the temperature and precipitation, is shown in Figure 39. Crop growth has adapted, over long years, to intra-annual distribution of rainfall. Rainfall peak occurs in autumn and winter, which allow water reserves in the soil and thus installation of cereal crops. Sowing is generally carried out between the months of September and December, depending on how early the first significant rains of autumn come. The harvests begin in the month of May in southern areas of Morocco, where temperatures rise first, and continue until June in the northern areas.

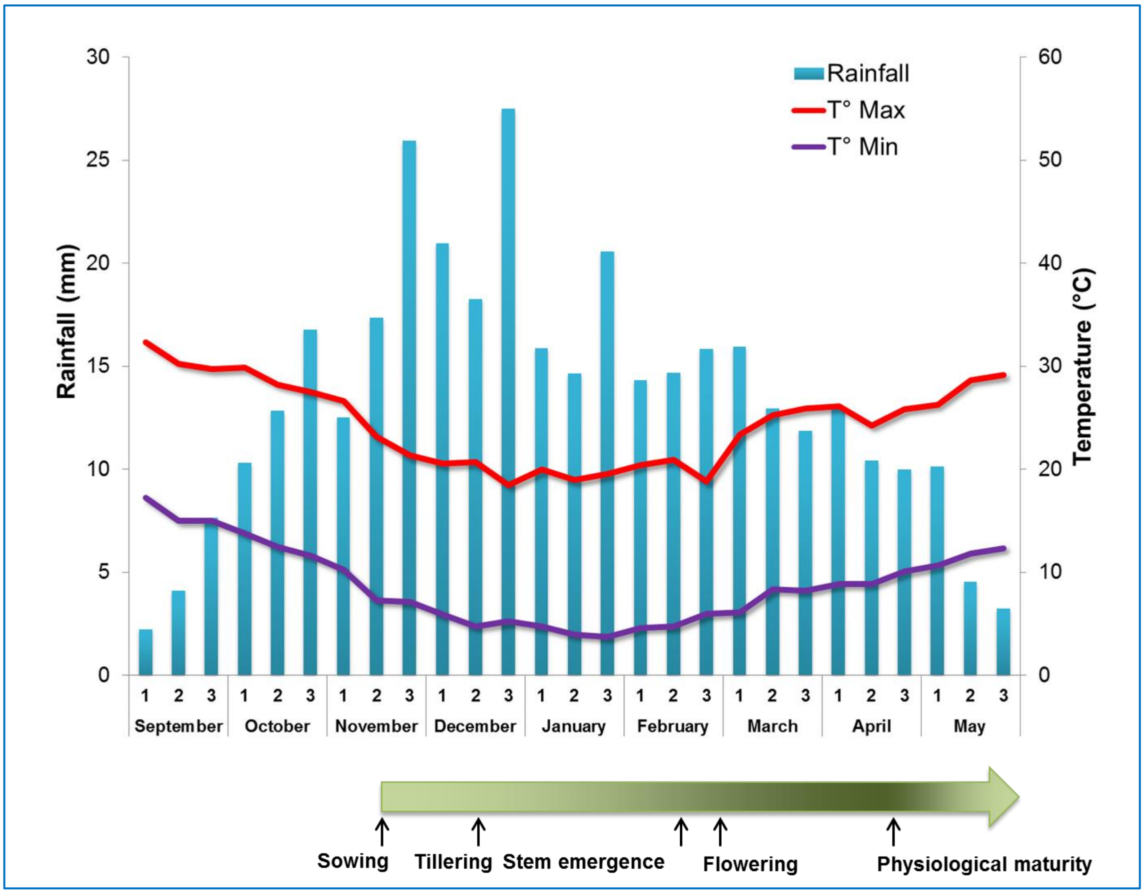

Figure 39: Typical weather conditions, during wheat growing season. Long term average of dekadal rainfall (series from 1988 to 2011) and dekadal temperature (series from 1998 to 2009) were used. Major development phases of wheat crop are also displayed (green arrow).

4. RELATIONSHIP BETWEEN NDVI AND RAINFALL

In Morocco, rainfall varies to a great extent, from south to north and from east to west. Cropping season's rainfall (September till April) has been related to NDVI (derived from NOAA-AVHRR) of agricultural lands (using a crop mask), for a total of 23 stations / provinces of the country, using time series data from 1990 till 2004 (Figure 40). Average dekadal NDVI, over the 9 dekads from February till April, is highly correlated to cumulated rainfall over the cropping season (September till April) in Morocco, as country's climate is mainly semi-arid, and as most of agricultural lands are covered by cereals (5.3 out of 8.7 million hectares).

In Figure 40, is illustrated the strong relationship between these two variables, which is linear for rainfall values less than 550 mm (blue line). Beyond this limit, the relationship is no longer consistent. Similarly, the linear relationship was indeed found, in the range 200-600 mm, in African semi-arid regions (Martiny *et al*., 2006). It can be observed that the relationship gradually slacks off as rainfall increases. Variation of NDVI, for a given level of season's rainfall, is most likely due to intra-annual distribution of rainfall.

NDVI can thus be used as indicator for forecasting cereal yields, using a statistical linear regression methodology, for the majority of Moroccan agricultural lands, and for a wide range of cropping seasons. Also, from Figure 40, one can thus explain why, in most European countries where generally rainfall exceeds 600 mm, NDVI is useless for crop forecasting.

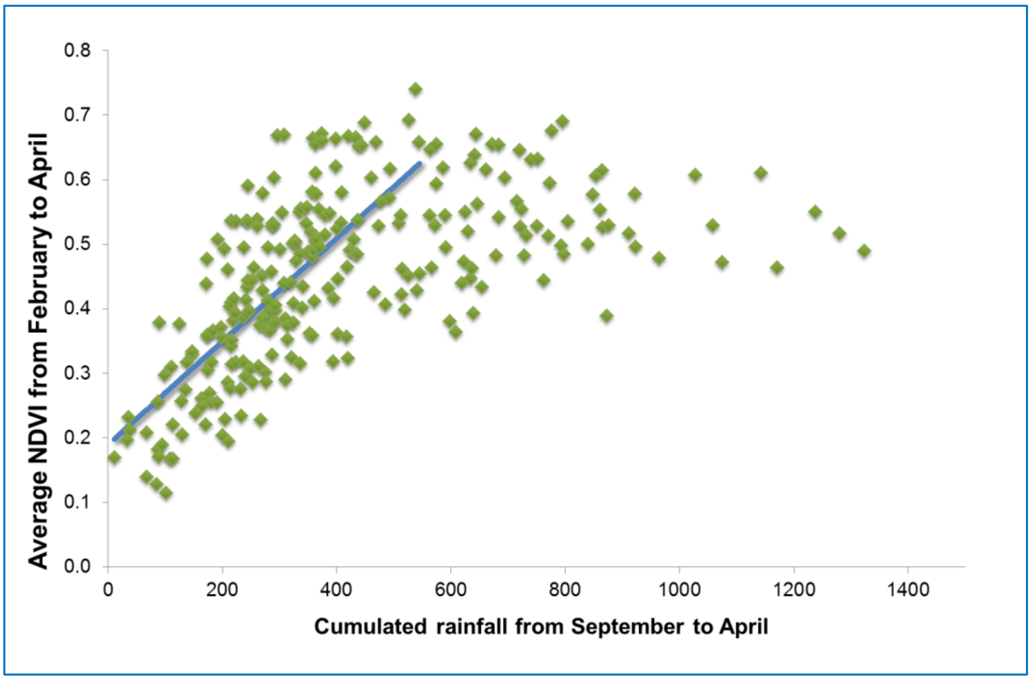

Figure 40: Relationship between NDVI (NOAA-AVHRR), averaged over the period from February till April and over agricultural zones, and cumulated rainfall over the cropping season from September till April, in Morocco. The 345 dots in this figure are data from 23 weather stations, over the period from 1990 to 2004.

NDVI can be used to monitor vegetation status, during the cropping season, at dekadal time step. In Figure 41 are presented NDVI maps, of the 3rd dekad of March, for two contrasted seasons, 1999-2000 (dry: 264 mm) and 2005-2006 (wet: 378 mm). Differences between these two seasons NDVI maps are obvious. In 2006, high NDVI values (shown in dark green in the figure) cover almost all croplands. NDVI is relatively high, even in the Saharan and eastern provinces of the country. In 2000 instead, high NDVI values appear only in limited areas, around few coastal and mountainous areas and in the northwest of the country. One can also notice the foehn[43] effect, encountered on the Atlas Mountains, which creates aridity in the eastern areas of the country.

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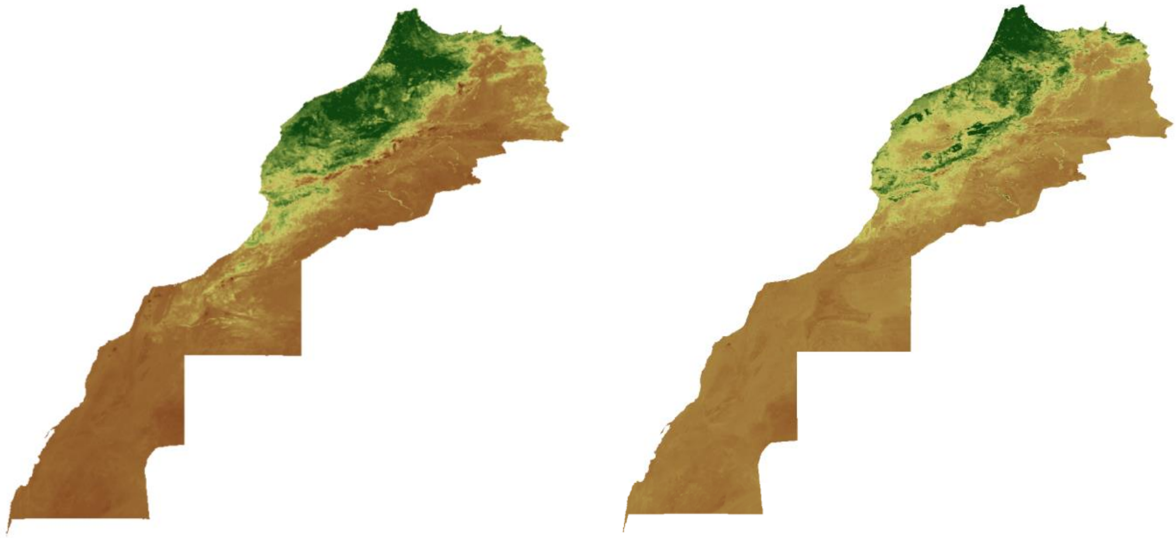
[43] The foehn (or Föhn), from Swiss dialect, is a wind that results from the warming of air mass that has lost its moisture on *Mountain* slopes, creating thus an arid region on the leeward side of the Mountain.



NDVI of the 3rd dekad of March 2006 — NDVI of the 3rd dekad of March 2000

Figure 41: Comparison of the vegetation status in Morocco, between a wet season (2005-2006) and a dry season (1999-2000), using NDVI (SPOT-VEGETATION) of the 3rd dekad of March. Dark green colored pixels indicate high NDVI values.

5. NDVI PROFILE

5.1. INTRA AND INTER-ANNUAL VARIATION OF NDVI

NDVI profile during the cropping season (average on all agricultural lands of Morocco) shows a gradually increase of NDVI, driven by early rains of November, a peak around the first dekad of March and then a decline (Figure 42). NDVI profile can reflect the evolution of cereal growth, since cereals are grown on most of croplands in Morocco (5.3 out of 8.7 million hectares). The vegetative cover of cereals is in fact low in November (planting time), with a peak in March (flowering period) and a decline thereafter (maturation period).

Starting from December, cropping seasons are easily recognizable by the NDVI profile, over a given geographical area which may vary from one plot to the whole country. Through NDVI profile, the specific characteristics of each cropping season can be described, particularly those which suffered from drought spells and those which were wet, such as (Figure 42):

- Cropping season of 1999-2000, which experienced a severe drought in the middle of the cycle, during which NDVI fell very early in the season, in February ;
- Cropping season of 2001-2002, during which the rainy season was delayed, displaying a late NDVI growth, in January ;
- Cropping season of 2006-2007, which experienced drought throughout almost all the season, displaying very low levels of NDVI ;
- Cropping season of 2008-2009, during which rains were abundant and well distributed,

displaying a fast growing NDVI, with record values in spring, and began to decrease only late March.

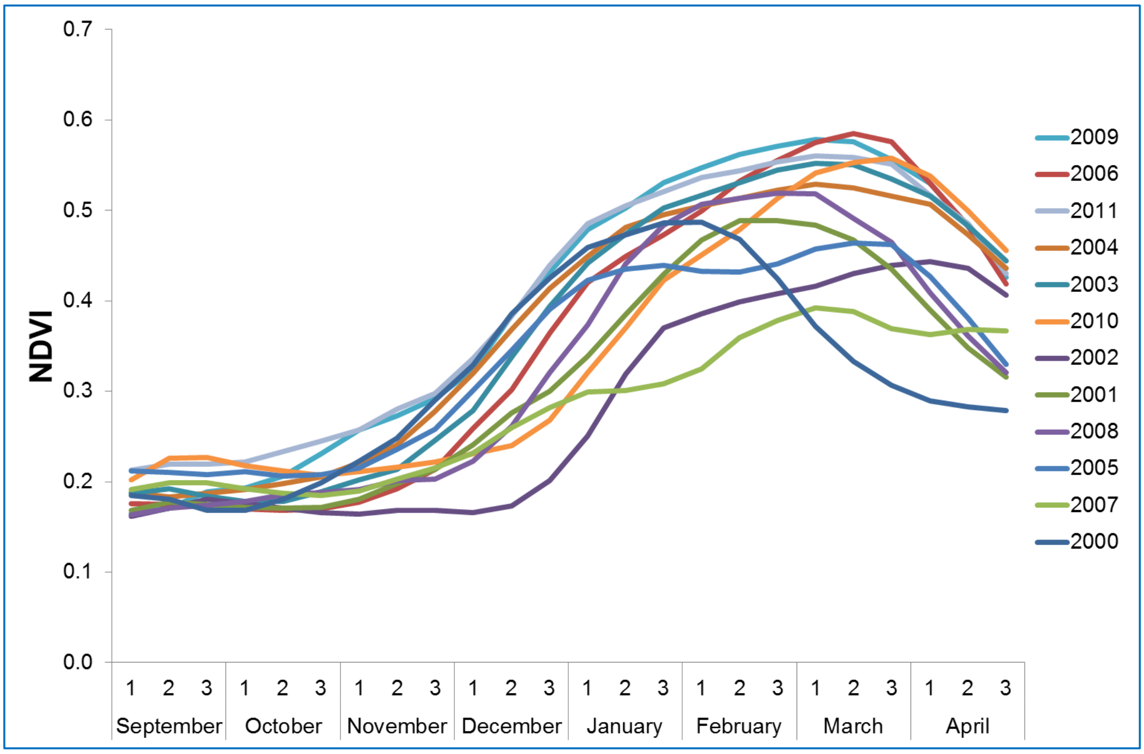


Figure 42: NDVI profile, during the cropping season for all croplands of the country (SPOT-VEGETATION) and for 12 cropping seasons (1999-2000 to 2010-2011), arranged in descending order of observed cereal yields.

5.2. REGIONAL VARIATION OF NDVI

NDVI profile (average on all croplands), during the cropping season, is shown in Figure 43, for each of the six agro-ecological zones of Morocco. On average, from 1999-2000 to 2010-2011, NDVI varied in a ratio of 1: 2.5: 2, between the months of September, March and April. NDVI differences are more pronounced between agro-ecological zones, around vegetation peak, i.e. around the month of March. In average, all over the season, NDVI values are higher in *Favorable*, *Intermediate* and *Mountain* zones than in *Unfavorable South*, *Unfavorable East* and *Saharan* zones, consistent with their respective usual spatial rainfall distribution. During the months of September and October, NDVI is relatively low and stable throughout the country, due to little rainfall, or because vegetation is still at its starting phase. During the start of the season, NDVI is however higher in *Favorable*, *Mountain* and *Saharan* zones, average in *Intermediate* zone and low in *Unfavorable South* and *Unfavorable East* zones. In the particular case of the *Saharan* zone, NDVI is relatively high early in the season, due to the systematic use of irrigation.

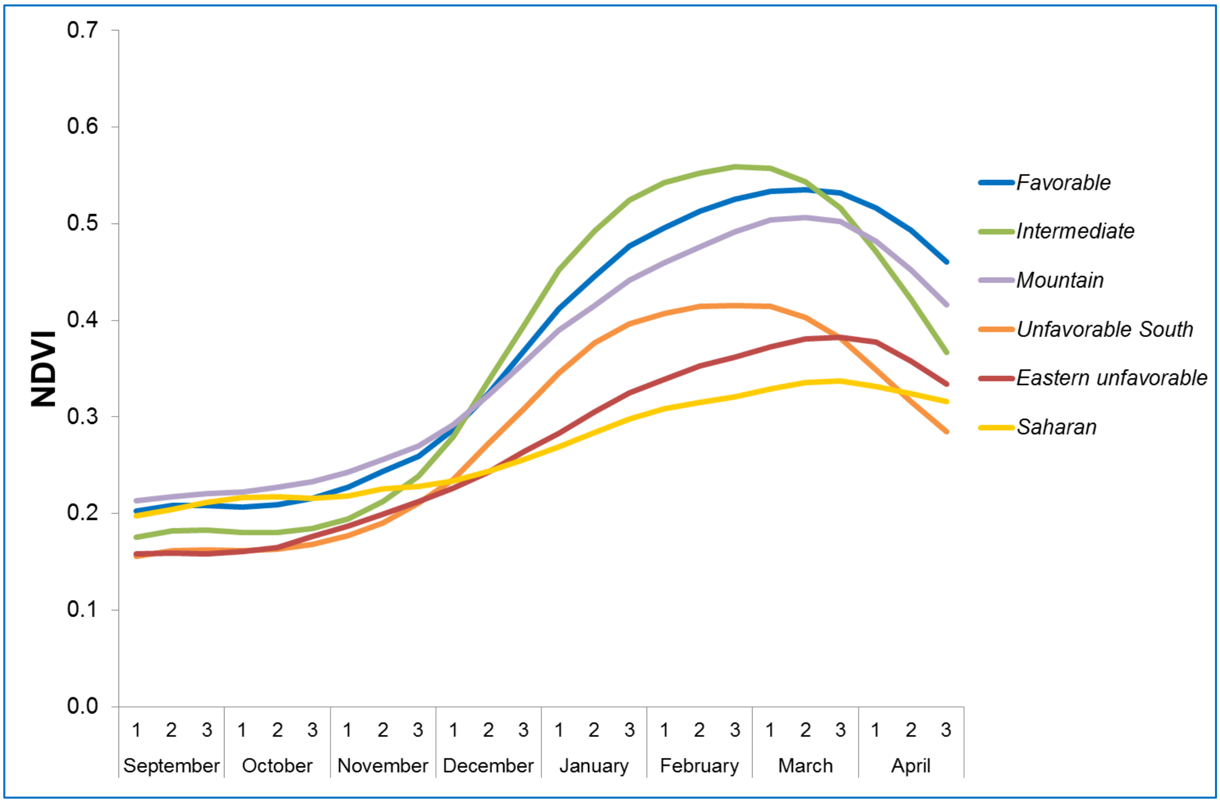


Figure 43: Average NDVI profile (SPOT-VEGETATION), during the cropping season and over all agricultural lands, for the six agro-ecological zones of Morocco (Data from 1999-2000 to 2010-2011).

NDVI increases gradually from November and reaches a maximum, between the 3rd dekad of February and the 3rd dekad of March, depending on the zone, and then decreases. Maximum NDVI is reached earlier in the season, during the 3rd dekad of February, in the *Intermediate* and *Unfavorable South* zones, which are semi-arid, then during the 2nd dekad of March, in the *Favorable* zone (sub-humid) and *Mountain* zone (wet), and finally during the 3rd dekad of March, in *Unfavorable East* and *Saharan* zones. These differences are due to differences in the length of the growing cycle, due to water availability in irrigated areas, to higher rainfall in the north than in the south, and to lower temperatures in mountains than in plains. The increase rate in NDVI is relatively fast in *Favorable* and *Intermediate* zones and slow in the *Saharan* zone.

VI. CEREAL YIELD FORECASTING APPROACHES

Cereal yields can be forecasted based on combined approaches, which relies on a concurrent use of four approaches and various types of predictors (rainfall, temperature, NDVI)

The non-parametric *approach is used for qualitative description of the effect of weather on cereals. Cereal yields can be forecasted, according to whether drought spells happen in the beginning, middle or end of the cycle, in relation with critical growth and development phases of the crops.*

The similarity analysis *approach consists in identifying, among the long term historical weather data, the cropping seasons that are similar (or analog) to the current one, in terms of rainfall, temperature and NDVI, selected as predictors. This type of analysis assumes that similar environmental conditions would result in similar yields, considering that predictors used, as proxy of the environment, account for most of yield variation. Yields of similar cropping seasons are then averaged and adjusted for technological trend. A forecasting error can be estimated and associated with the forecast, when many similar seasons are considered.*

The regression models approach *relies on simple or multiple linear regression analyses, between yields and some climatic or bio-climatic indicators, for forecasting cereal yields. At both national and agro-ecological zones levels, the correlations are high when considering average dekadal rainfall, cumulated over the cropping season, from October till late March. Forecasts can further be improved, by splitting season's rainfall into several non-overlapping time periods: Two periods, from September till November and from January till March; or three periods, from October till November, from December till January, and from February till March. Cereal forecasts are obviously more accurate, when considering three time periods' rainfall, rather than two or only one. In addition to rainfall, bio-climatic indicators, from FAO's AgroMetShell water balance model, can be used as predictors. However, correlations are higher when using average dekadal NDVI, from February till March, peaking at an R^2 of nearly 90%. Although forecasts can begin as early as February, forecasting error is progressively improving as approaching the end of the season. The regression model approach leads to accurate cereal yield forecasts, even at provincial level. Several indicators can be combined to improve the forecasts, such as NDVI, rainfall and temperature. Among these indicators, NDVI best explains yields variation, followed by rainfall and temperature. Temperature, which always has a negative impact on yields, since it increases evapotranspiration, is relevant only in high rainfall areas, like in provinces located in the far north-west of the country, such as Tangier and Tetouan.*

Simulation models approach*, which simulates the behavior of crop depending on weather variables and crop and soil parameters.*

The combined approach *relies on the concomitant use of non-parametric, similarity, regression models and simulation approaches. It allows minimizing the forecasting error of the forecasts. Operational cereal forecasts were performed using this approach, for the cropping season of 2008-2009, 2009-2010, 2010-2011 and 2011-2012, by INRA in partnership with national and international institutions.*

1. NON-PARAMETRIC APPROACH

The non-parametric statistical approach (Gommes, 2006) is of descriptive interest, allowing for a qualitative assessment of the effect of weather on crops. It is particularly useful for the evaluation of qualitative and indirect effects of weather on crops. One of the reasons why the non-parametric approach can be very powerful is that climatic variables do not vary independently but constitute a "complex", like the case of drought. This approach requires prior expertise on the environment and the main factors that affect agricultural production, and their inter-correlations. Wheat yield at the national level can be forecasted, using non-parametric statistical approach, i.e. using indicators of season's environment. The season can be divided in three phases of the cropping cycle, which are known to be critical for growth and development of cereals: The beginning, middle and end of season, which correspond approximately to the months October-November-December, January-February-March, and April-May.

Table 10 : Non-parametric relationship between wheat grain yield (Q/ha) and drought indicators, during critical season's phases (beginning, middle and end of cycle). (0: No drought; 1:Drought).

Season	Start	Middle	End	Rainfall (mm)	Yield (Q/ha)
1987-1988	0	0	0	387.7	18.60
1988-1989	0	0	0	350.9	14.80
1989-1990	0	1	0	384.9	13.59
1990-1991	0	0	1	392.4	19.50
1991-1992	1	1	0	279.4	7.72
1992-1993	0	0	0	233.9	8.00
1993-1994	0	0	0	343.3	20.06
1994-1995	1	1	0	196.0	5.68
1995-1996	0	0	0	587.2	18.57
1996-1997	0	1	0	465.4	9.43
1997-1998	0	1	0	377.4	14.46
1998-1999	0	0	1	226.9	8.39
1999-2000	0	1	0	263.6	5.23
2000-2001	0	0	1	320.6	13.21
2001-2002	0	1	0	332.2	13.33
2002-2003	0	0	0	411.3	17.83
2003-2004	0	1	0	419.2	18.00
2004-2005	0	1	1	228.4	11.03
2005-2006	0	0	0	377.5	20.76
2006-2007	0	1	0	237.1	6.18
2007-2008	0	1	0	268.1	13.11
2008-2009	0	0	0	547.9	21.60
2009-2010	0	0	0	604.8	16.62
2010-2011	0	0	0	492.9	18.60

Drought in Morocco usually occurs at the end of the cycle, but it can occur during the other phases as well. Experience shows that drought has a dissimilar impact on wheat yields according to whether it occurs at the beginning, middle or end of the cycle (Table 10). This approach obviously doesn't take into account the intensity of drought, as parametric approach does.

From Table 10, a multiple regression analysis can be performed using four predictors: three non-parametric variables (0/1 drought in beginning, middle and end of the cycle) and the cumulated rainfall from September till May. After removal of predictors that do not significantly explain yield variance, through "Stepwise" regression analysis procedure, it results the following equation:

Yield (Q/ha) =6,38 – 3,62 Middle (-) + 0,025 Rainfall (mm) R^2=61% (Pr. <0.001)

This equation explains significantly a high proportion (R^2 = 61%) of wheat yield variance. Aside from the fact that yield depends on the rainfall (partial R^2 = 50%), this equation shows that it is mainly affected by mid-cycle drought (partial R^2 = 11%) comparatively to the other two drought periods occurring during wheat cycle, which is in accordance with observations from field experiments. Through non-parametric statistical approach, wheat yields can therefore be forecasted in Morocco with an average error of 3.27 Q/ha, nationwide.

2. SIMILARITY APPROACH

2.1. SIMILARITY ANALYSIS USING RAINFALL

2.1.1. CUMULATED RAINFALL OVER THE SEASON

The easiest and fastest way for forecasting cereal yields consists in performing a similarity analysis, using cumulated rainfall over the cropping season. For example, a simple graphical comparison of historical cropping seasons (from 1987-1988 till 2011-2012), based on cumulated rainfall from October till April, shows that cropping season of 2011-2012 is similar to those of 1999-2000 and 2004-2005, which also both experienced severe drought (Figure 44). This approach is obviously very approximate as it ignores the intra-annual distribution of rainfall. However, cropping seasons can be qualitatively assessed, using this approach. From official statistics, cereal yields of the cropping season of 2011-2012 were lower than average, with a national yield of 10.1 Q/ha for the three cereals combined (against 11.9 Q/ha, on average for period 2000-2011), due to mid-cycle drought (Balaghi *et al.*, 2012).

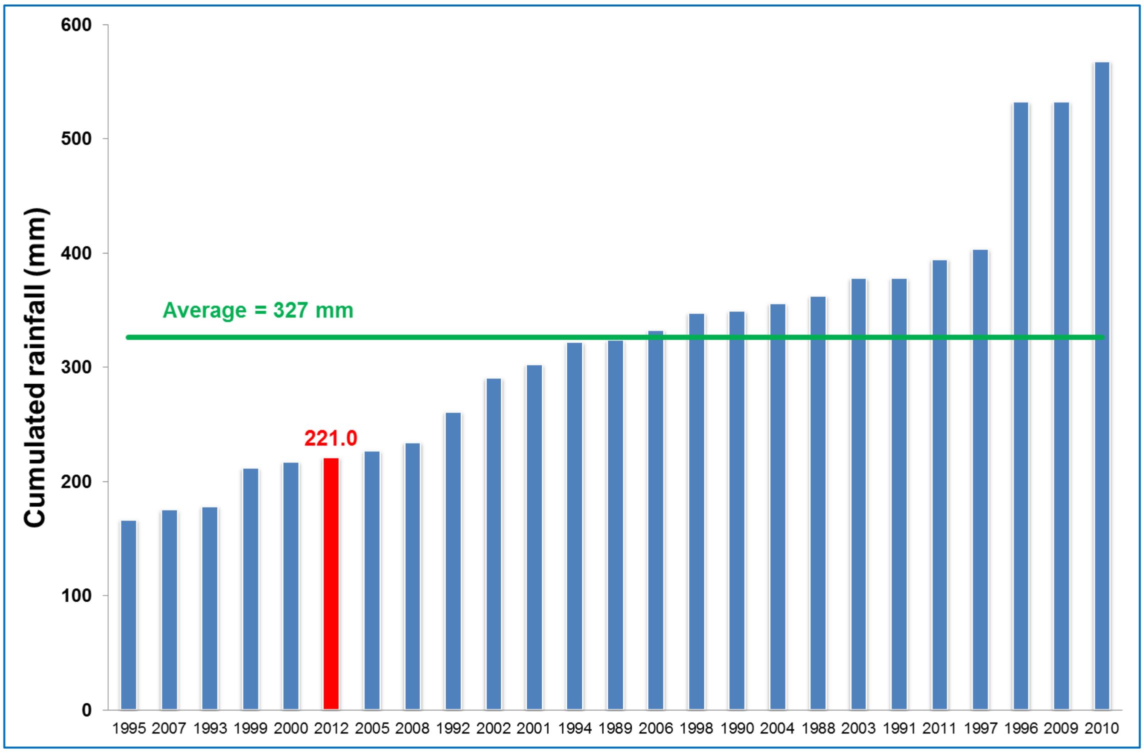


Figure 44 : Cropping seasons, from 1987-1988 to 2011-2012, arranged in ascending order of cumulated rainfall between 1st of September and 10th of April of the following calendar year (Source: Balaghi *et al*., 2012). Numbers in x-axis correspond to years of harvest. Green line indicates average cumulated rainfall over the 25 years. The red bar points to cumulated rainfall of the latest season i.e. 2011-2012.

2.1.2. INTRA-ANNUAL RAINFALL DISTRIBUTION

In Figure 45, cropping seasons of 1960 till 2000 were classified based on cluster analysis, using monthly rainfall of the eight months from September till April (Balaghi, 2000). Cluster analysis technique consists in identifying homogeneous groups (clusters) which are relatively more similar to each other than to those in other groups[44], in terms of monthly rainfall for the eight months considered (September till April). In this case, no specific weights have been assigned to the different months, i.e. rainfall of each of the eight months are supposed to have same impact on crops. Cluster analysis suggested a strong similarity between seasons of 1999-2000 and 1994-1995, which in fact were both very dry. The cluster analysis also shows two distinct groups, which can typically be representative, on one hand of good seasons, and on the other hand of dry seasons. The first group contains in particular seasons of 1970-1971 and 1961-1962, and the second group seasons of 1999-2000 and 1974-1975. Season of 1984-1985, which resulted in average country

[44] The distance between two groups is given either by the distance between the most distant objects in the groups (method of "complete linkage") or by minimizing the intra-group variance (Ward's method).

yield, was falsely assigned by cluster analysis to dry seasons, like 1980-1981, because low temperatures observed during season of 1984-1985, were not taken into account.

So, we can see that this approach requires a good knowledge of the climatic conditions that occurred during the different cropping seasons. Cluster analysis can thus only be used as supplementary technique to other methodologies for forecasting cereal yields.

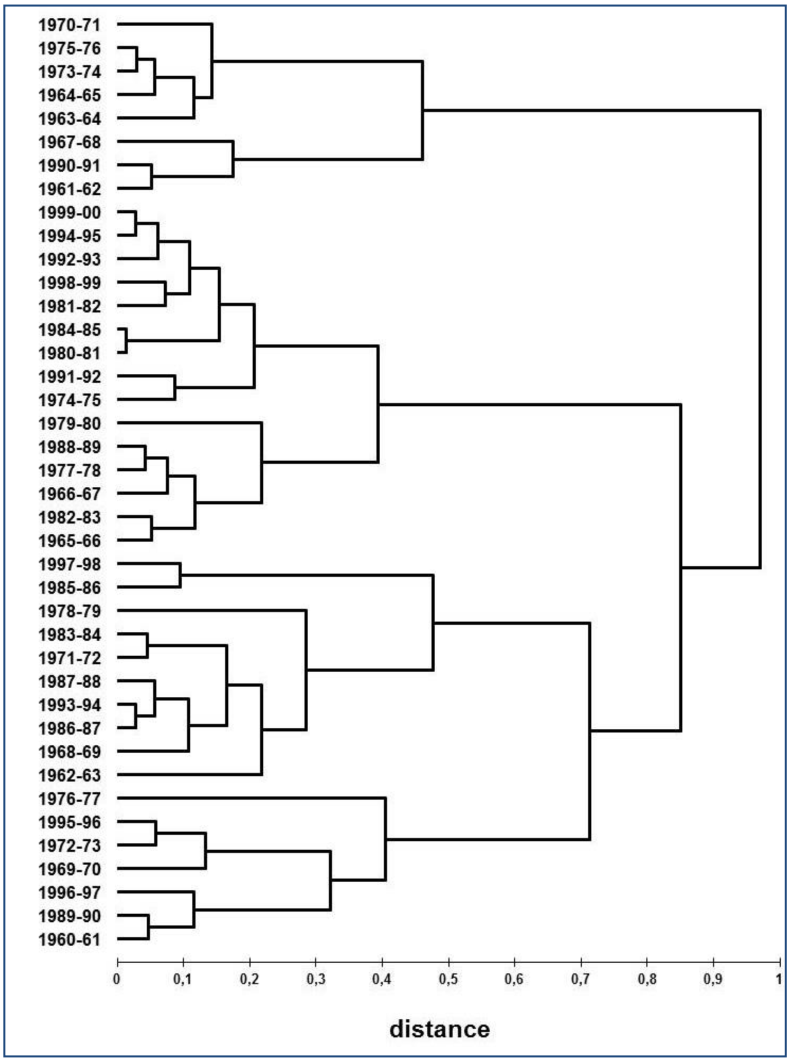


Figure 45: Dendrogram of cluster analysis, discriminating cropping seasons from 1960-1961 to 1999-2000, with regard to monthly rainfall of 8 months, from September to April, for Meknes region (Source: Balaghi, 2000).

Similarity analysis, based on rainfall distribution over the cropping season, can be used to accurately forecast cereal yields. This methodology was used for the first time in January 1995 at the request of the Provincial Direction of Agriculture (Direction Provinciale de l'Agriculture) of Meknes, following persistent drought which prevailed for more than two consecutive months

(November and December). This Direction asked INRA to provide with plausible scenarios of the evolution of the cropping season of 1994-1995. This season (in red in the graph in Figure 46) was not similar to none of the 35 previous seasons, since 1961, in terms of rainfall distribution over the first four months of the season (September till December). From the historical time series, only the cropping season of 1974-1975 has experienced more or less a similar drought at start of cycle. The scenarios for the forecasts have thus been developed on the basis of this season. However, it turned out later on, after the month of January, that cropping season of 1994-1995 was exceptionally dry and far from all experienced seasons, in term of amount and distribution of rainfall. It was thus concluded that trying to forecast yields too early in January, based on similarity analysis, is a risky task.

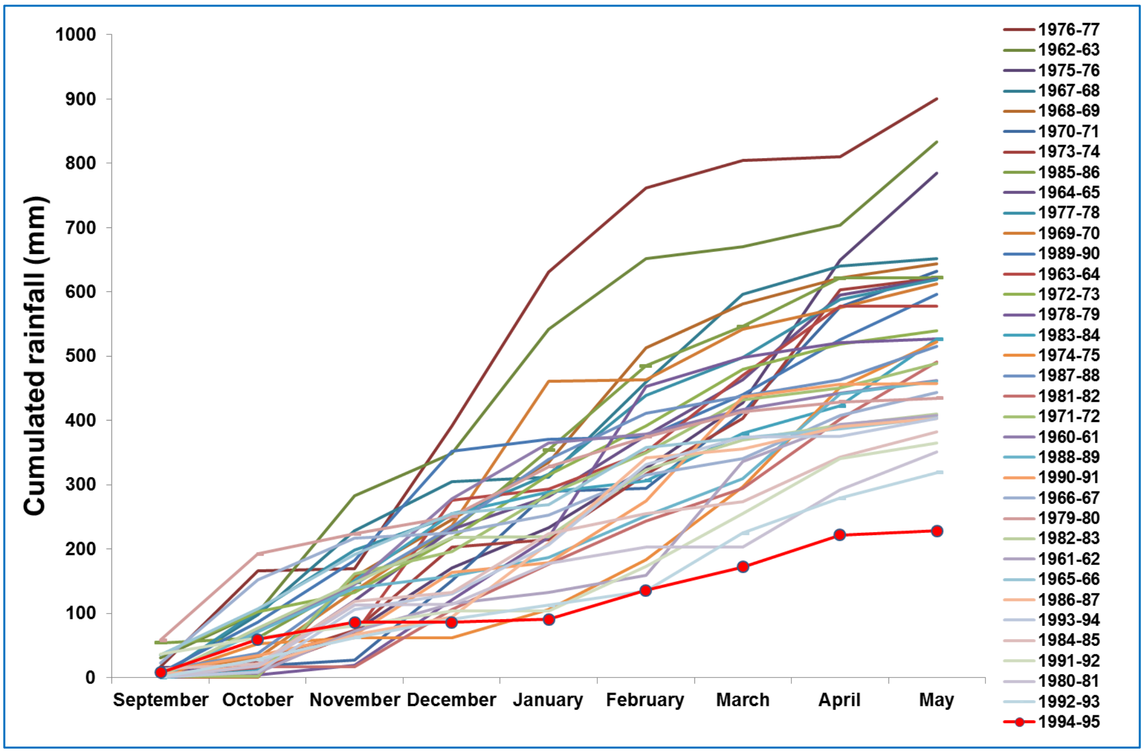


Figure 46: Cumulated rainfall over the cropping season (September till May) for the 1994-1995 cropping season, at Meknes, compared to historical data from 1960-1961 to 1993-1994. Seasons are arranged in ascending order of cumulated rainfall.

In the case of the cropping season of 1999-2000, drought lasted for three consecutive months (January till March), which had never been experienced in living memory in Morocco. During the month of March, a cluster analysis was thus used to look for similar seasons, based on time series of monthly rainfall data (1960-1999), from September till April.

Similarity approach was used to forecast cereal yields, using all dekadal cumulated rainfall between September till the end of February (18 dekads), for the cropping season of 2007-2008, taken as an example. Cropping seasons of 1988-1989 (230 mm) and 2001-2002 (168 mm) were identified as closest to season of 2007-2008 (209 mm) (Figure 47). Similarly, the result has not changed till end of March: similar seasons to 2007-2008 (223 mm) were 1988-1989 (276 mm), 2001-2002 (244 mm) and 2004-2005 (225 mm). However, in late April, similar seasons to 2007-2008 (251 mm) were 1999-2000 (240 mm), 2001-2002 (316 mm) and 2004-2005 (276 mm).

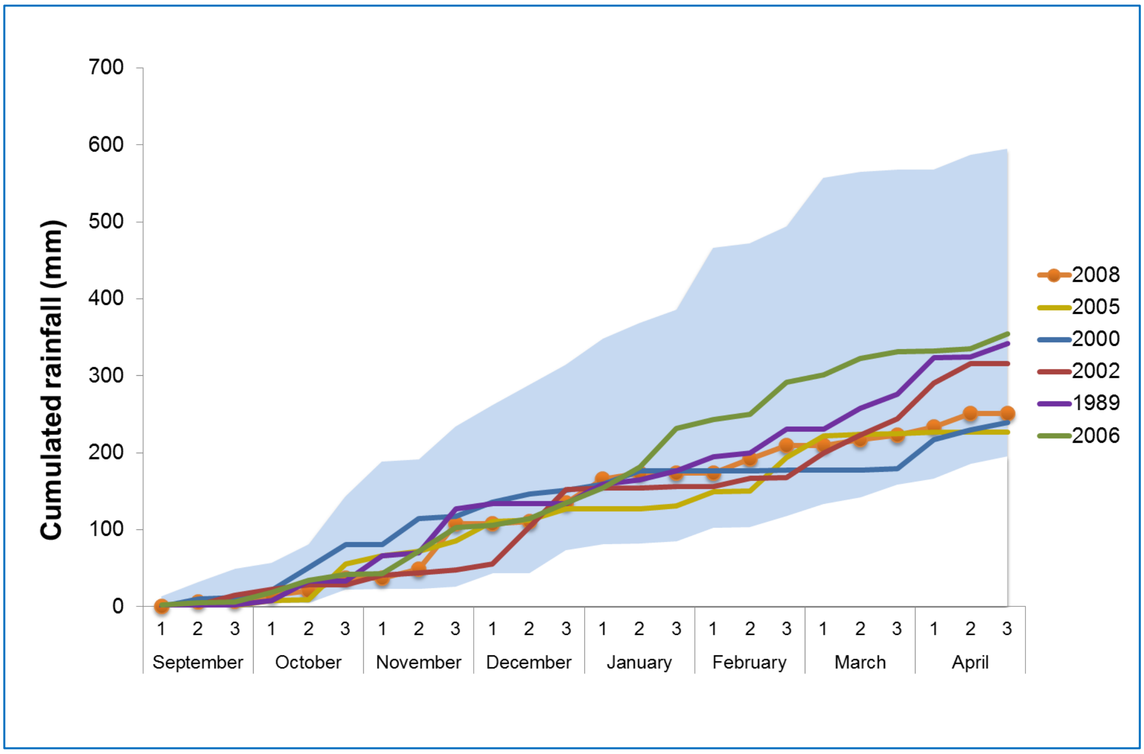


Figure 47: Similarity analysis of 2007-2008 cropping season, using cumulated dekadal rainfall, at the country level.

Most similar (analogous) cropping seasons to 2007-2008 are: 1999-2000, 2001-2002, and 2004-2005. Shaded area in blue embodies range of variation of cumulated dekadal rainfall from historical data (1988 to 2008).

Concerning the season of 2007-2008, at the 2^{nd} dekad of April, forecasted yields for soft wheat, durum wheat and barley, were: 13.0, 12.3 and 9.0 Q/ha, respectively, which were relatively close to observed yields (from official statistics: 13.1, 13.4 and 6.2 Q/ha).

The use of this methodology, should take into consideration that seasons are defined as similar in a subjective way, because no statistical threshold rule is available for splitting the times series between similar and non-similar seasons, i.e. they are only relatively similar or dissimilar to each other.

2.1.3. TECHNOLOGICAL TREND

Similarity approach must take account of yield trend resulting from technology trend (0.15 Q/ha.year for wheat, Figure 27 and Figure 28), given that identified similar seasons could be far enough so that technological trend has increased yields. Before computing weighted average yield of similar past seasons, the respective yields of these seasons must be incremented by the technological yield trend. However, for the case of barley, no technological trend was statistically detected from historical time series (Table 7).

2.1.4. FORECASTING ERROR

Accuracy of similarity analysis method can be evaluated, from computation of the average and confidence interval of some arbitrarily selected similar cropping seasons. The forecasted yield is taken as equal to average historical yields of the similar seasons, weighted by their relative Euclidian distances to the current season. Four arbitrarily closest seasons were selected, but fewer seasons can also be considered if some of them are too distant, which can be visually judged based on figure like Figure 47. Then, a weighted confidence interval of the yield forecast can be computed.

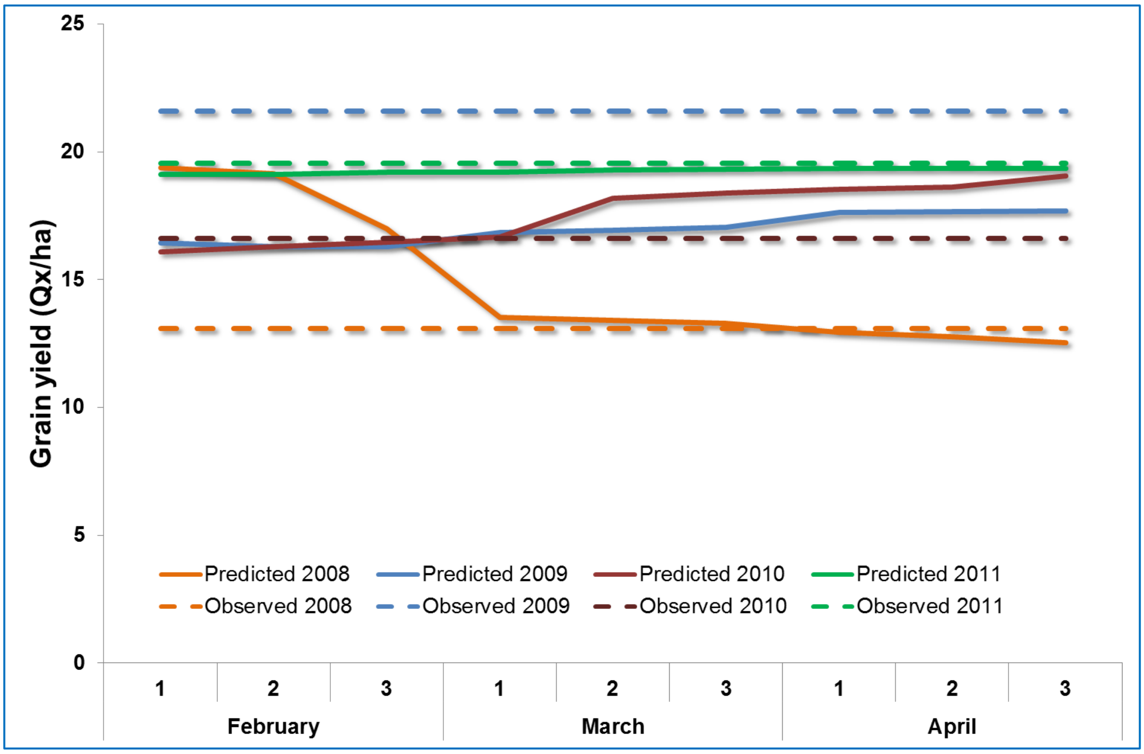


Figure 48: Forecasted country yields of soft wheat, for cropping seasons of 2007-2008, 2008-2009, 2009-2010 and 2010-2011, based on similarity analysis of cumulated rainfall since October.

The forecasting error of the yield forecast can be statistically calculated, considering that yields of similar seasons are a random sample of a population of forecasted yields. The forecasting error is thus estimated on the basis of the variation (confidence interval 90%, for example) of similar seasons' yields. From there, results of similarity analysis show that yields can be forecasted with, reasonable accuracy, using cumulated rainfall during the season. The forecasts were more accurate for season of 2007-2008 and 2010-2011 than those of 2008-2009 and 2009-2010 (Figure 48), because these two latter seasons were exceptionally wet and very dissimilar to all historical seasons. The differences between forecasted and observed yields, is however significant for exceptionally rainy seasons like 2008-2009 (547.9 mm) and 2009-2010 (604.8 mm).

The forecasting error[45] for soft wheat, based on similarity analysis method, is relatively low at the 3rd dekad of March, for seasons of 2007-2008 (12.6 ± 0.9 Q/ha against 13.1 Q/ha observed[46]), 2008-2009 (17.3 ± 0.8 Q/ha against 21.6 Q/ha observed), 2009-2010 (18.2 ± 0.9 Q/ha against 16.6 Q/ha observed) and 2010-2011 (19.3 ± 0.6 Q/ha against 19.6 Q/ha observed) (Figure 48). Note that the yield forecast is not very far from observations, even earlier in the season, in February, for seasons of 2009-2010 and 2010-2011.

2.2. SIMILARITY ANALYSIS USING NDVI

In the framework of a research and development agreement with JRC, INRA uses "MARSOP3" Web viewer (http://www.marsop.info/marsop3/) developed by Alterra, which is connected to agro-climatic database of the European Union. MARSOP3 allows real-time analysis of climatic conditions (temperature, rainfall, solar radiation, potential evapotranspiration, number of cold and hot days, degrees x days, etc.), and vegetation conditions (NDVI) across the country, which are interpolated and displayed in grids of 25x25 km spatial resolution. Among its features, this application allows similarity analysis of cropping seasons, using these weather and vegetation indices (Figure 49).

Similarity analysis should take into account not only rainfall, but also temperature in order to reflect real weather conditions surrounding crops, since temperature affects the evaporative demand of the air, and therefore water balance. An example is given for season of 2011-2012, which was exceptionally dry and cold. Similarity analysis was performed, using dekadal NDVI from early February till the first dekad of April. Results show that this season was similar to season of 2000-2001, then relatively more distant to seasons of 2007-2008 and 2004-2005 (Balaghi *et al*., 2012) (Figure 50). In contrast, similarity analysis, using cumulated rainfall identified similarity with seasons of 1999-2000 and 2004-2005. The difference between these two results is due to very cold temperatures experienced during season of 2011-2012, starting from the 2nd half of January (Figure

[45] Average yield and its related 90% confidence limits are presented.

[46] Confidence limits of observed yields are not available in historical crop statistical databases, provided by DSS at province level.

50). In fact, low temperatures contributed at reducing evapotranspiration and thus at mitigating drought, which therefore contributed at avoiding low NDVI values.

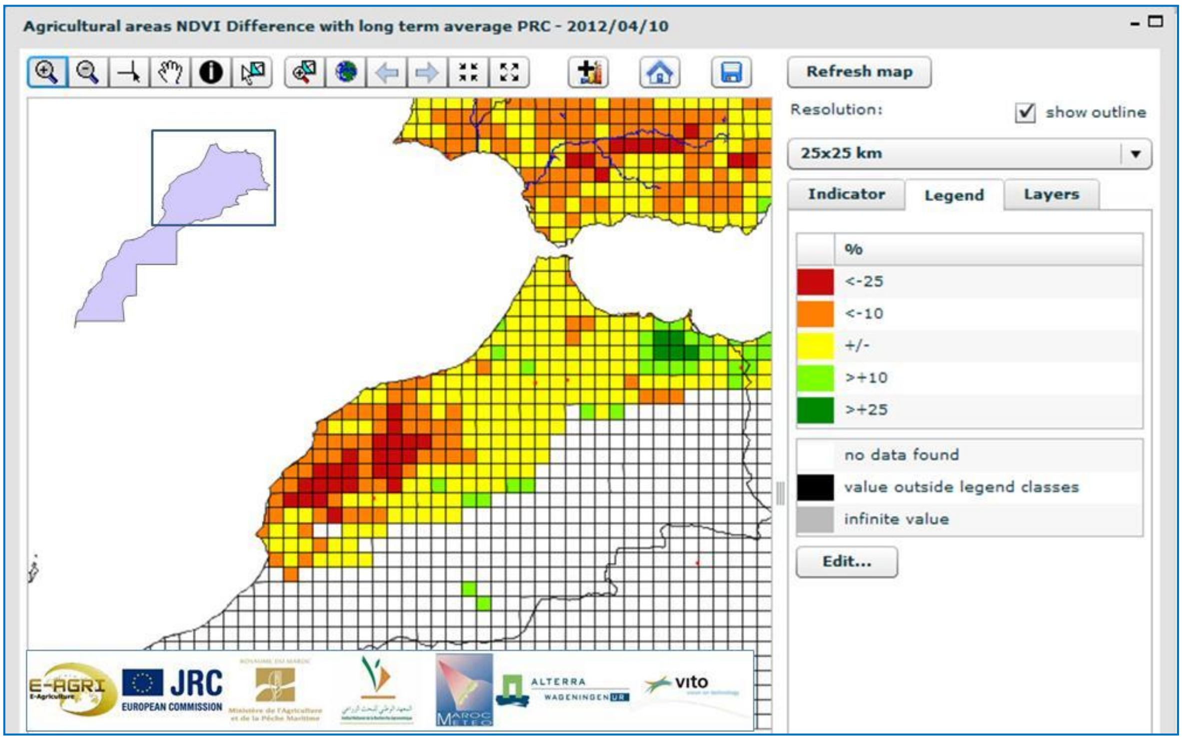


Figure 49: "MARSOP3" Web viewer, for agro-climatic analysis of the cropping season. Deviation of NDVI (SPOT-VEGETATION), at the first dekad of April for agricultural lands, from long term average NDVI is provided by this application. Comparison with other seasons can also be performed. Spatial resolution of grids is 25x25 km (Source: Balaghi *et al*., 2012).

From all these examples, one can appreciate the interest and limitations of the similarity analysis. These examples also show that these statistical methodologies could be used only as complementary tools to the necessary field expertise of the agro-meteorologist.

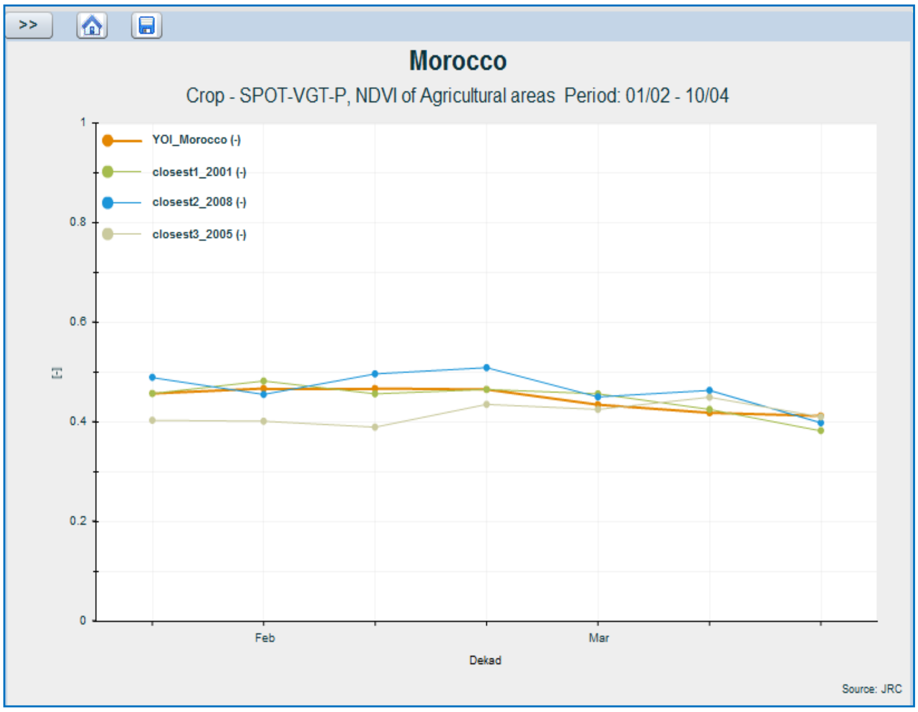


Figure 50: Similar seasons to the 2011-2012 cropping season, based on dekadal NDVI (SPOT-VEGETATION) over agricultural lands, at the country level. The 2011-2012 cropping season (in orange) is compared to historical seasons. The 2000-2001 cropping season is the most similar to 2011-2012 with regard to NDVI profile from 1st of February to 1st of April, followed by 2007-2008 and 2004-2005 (Source: Balaghi *et al*., 2012).

2.2.1. FORECASTS BASED ON SIMILARITY ANALYSIS AND USING NDVI

Soft wheat yield forecasts for seasons of 2007-2008 to 2010-2011, based on similarity analysis and using dekadal NDVI since start of February (datasets of NOAA-AVHRR data from 1988 to 2011), is shown in Figure 51. For each of these four seasons, the forecasted yield is equal to the arithmetic average of the similar seasons weighted by their relative distances to the season to be forecasted. Arbitrarily, the four most similar seasons were selected.

2.2.2. TECHNOLOGICAL TREND

Technological trend was not considered when using NDVI, as it is already detected through NDVI values. In fact, this index reflects not only the state of humidity and temperature prevailing during the season, but also the efficiency use of factors that affect yields such as cultivars and cropping techniques. In other words, NDVI will be high when weather is favorable (range of rainfall less than 550 mm) or when varieties and production factors are improved.

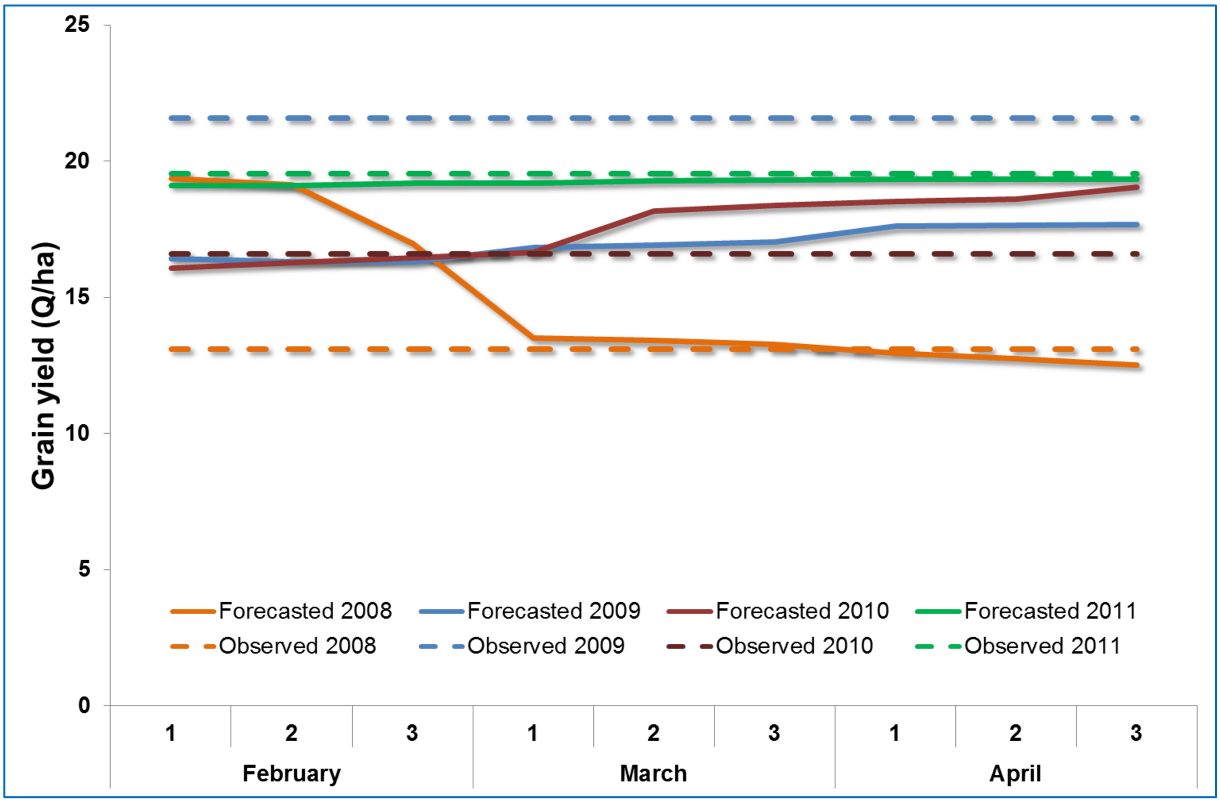


Figure 51: Forecasted soft wheat grain yields at the country level, for cropping seasons of 2007-2008, 2008-2009, 2009-2010 and 2010-2011, based on similarity analysis and using dekadal NDVI (NOAA-AVHRR) since 1st of February.

2.2.3. FORECASTING ERROR

In general, the forecasting error decreases as the cropping season is ending, except for season of 2007-2008. For example, at the end of February 2011, the forecasted yield was 17.5 ± 1.09 Q/ha. At late March 2011, it was 19.6 ± 0.51 Q/ha, and at late April 2011 it was 20.0 ± 0.44 Q/ha, against 19.6 Q/ha observed. The forecasting error based on similarity analysis was relatively low at the 3rd dekad of March, for seasons of 2007-2008 (13.5 ± 1.1 Q/ha, against 13.1 Q/ha observed), 2008-2009 (17.9 ± 0.5 Q/ha, against 21.6 Q/ha observed) and 2009-2010 (16.1 ± 0.7 Q/ha, against 16.6 Q/ha observed). Note that the forecast was not far from observed, even early in the season, in February, i.e. when it is not yet possible to use other parametric methodologies, like regression analysis, to forecast yields. However, for the very particular cropping season of 2008-2009, the forecast was again very far from observed yield. Nonetheless, the forecasting error is smaller when using NDVI instead of rainfall.

2.3. SIMILARITY ANALYSIS USING NDVI AND RAINFALL COMBINED

The CGMS Statistical Toolbox (CST, http://e-agri.wikispaces.com/CGMSStatTool), is a software dedicated to statistical crop yield forecasting analysis (Figure 52). Other similar types of software like CST exist worldwide, such as STATCAT (Curnel *et al.*, 2004). CST has been adapted for Morocco context in the framework of E-AGRI project. It allows forecasting cereal yields based on two types of statistical analysis: A scenario analysis relying on Principal Component Analysis (PCA), and a multiple regression analysis. Both types of analyzes could be performed on time series of cereal yields and environmental predictors. These predictors are of three types: (1) outputs of WOFOST simulation model (http://www.wofost.wur.nl/UK/), (2) cumulated rainfall during the cropping season, and (3) vegetation indices derived from remote sensing (NDVI, DMP). Yields can be forecasted at multiple spatial scales (provinces, agro-ecological zones, country), at dekadal time step, starting from late February until the end of April.

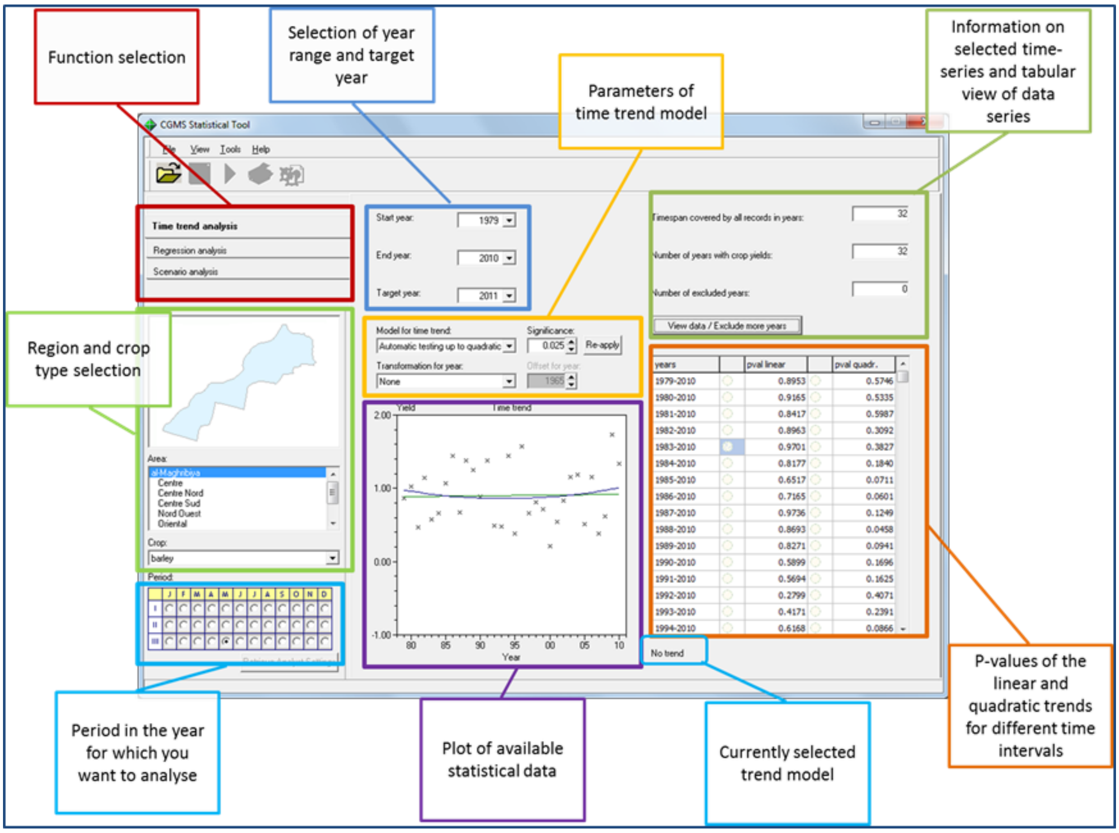


Figure 52: The "CGMS Statistical Toolbox" software, for cereal yield forecasting, adapted to Morocco.

The result of the PCA analysis is presented in Figure 53, for season of 2010-2011, combining both average NDVI (NOAA-AVHRR) since February till late March and cumulated rainfall since September till March (times series from 1985 to 2010). Again, season of 1996-1997 was removed from the time series due to the peculiarity of its intra-annual rainfall distribution. For example, at the 3rd dekad of March 2011, result of PCA analysis (Figure 53) shows seasons which were similar to 2010-2011. They are, in order of similarity, those of 1997-1998, 2002-2003, 2005-2006 and 2003-2004. The forecasted yield for 2010-2011 is equal to the average yield of these similar seasons, weighted by their relative distances from 2010-2011, and to which technological trend was added (0.15 Q/ha.year). PCA analysis considers only unique values of NDVI (the average over several dekads) and rainfall (the total over several dekads), unlike similarity analysis which relies on their distribution, at dekadal time step, along the cropping season.

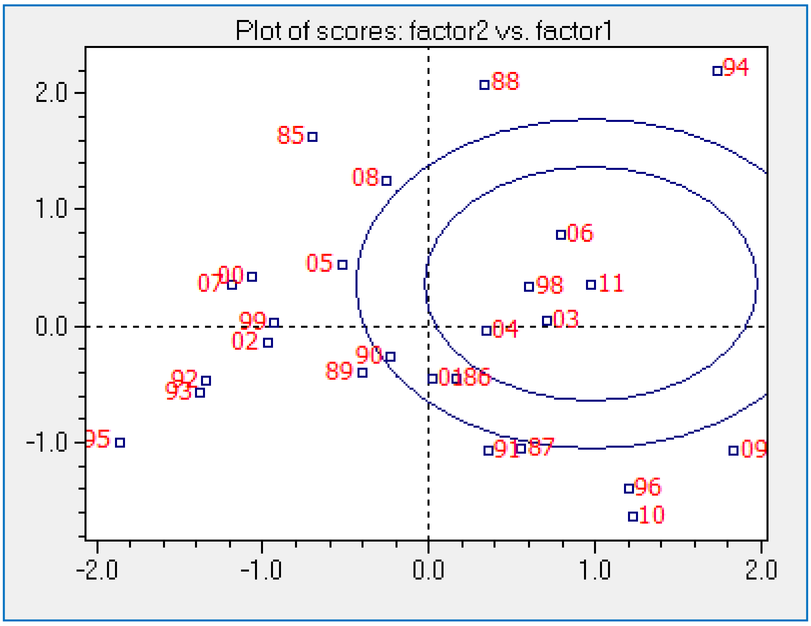


Figure 53: Similarity analysis of 2010-2011 cropping season, based on Principal Component Analysis, using in "CGMS Statistical Toolbox" software CST (http://e-agri.wikispaces.com/CGMSStatTool).
Similarity analysis was performed using country average NDVI (NOAA-AVHRR) and cumulated rainfall over the cropping season (data from 1988 to 2011). Similar seasons to 2010-2011 are, in order of similarity: 1997-1998, 2002-2003, 2005-2006 and 2003-2004.

The exercise was repeated for seasons of 2008-2009, 2009-2010 and 2010-2011, for forecasting durum wheat yields at the national level (Figure 54). PCA identified diverse similar seasons, depending on the dekad at which forecasts has been performed. For example, at the 2nd dekad of February, no match was found between the season's rainfall of 2008-2009 and all historical data sets since 1985, because of the extreme rainfall experienced during this season (468 mm). At the 3rd dekad of March, cumulated season's rainfall of 2008-2009 (530.5 mm) was similar to that of 1995-1996 (523.6 mm) and more distantly, to that of 1986-1987 (413.6 mm). However, at the 3rd dekad of April 2008-2009 (cumulated rainfall 542.7 mm), a similarity was detected with, in order: 1995-1996 (546.9 mm), 1986-1987 (438.8 mm), 1990-1991 (371.5 mm) and 2002-2003 (404.2 mm). PCA is therefore able to provide a yield forecast, even indicative, early in the season, starting from March.

The forecast is all the more accurate if it exists in the available time series seasons which are relatively similar to the current season, in terms of NDVI and rainfall. If the season is singular, PCA is unlikely to lead to a reliable forecast. This was the case for seasons of 2008-2009 and 2009-2010, which were remarkably wet (> 550 mm). In the case of season of 2010-2011, the difference between forecasted and observed yields of durum wheat, at the national level, was 2.1 Q/ha at the 3rd dekad of February, 1.4 Q/ha at the 3rd dekad of March, and only 0.7 Q/ha at the 3rd dekad of April (Figure 54).

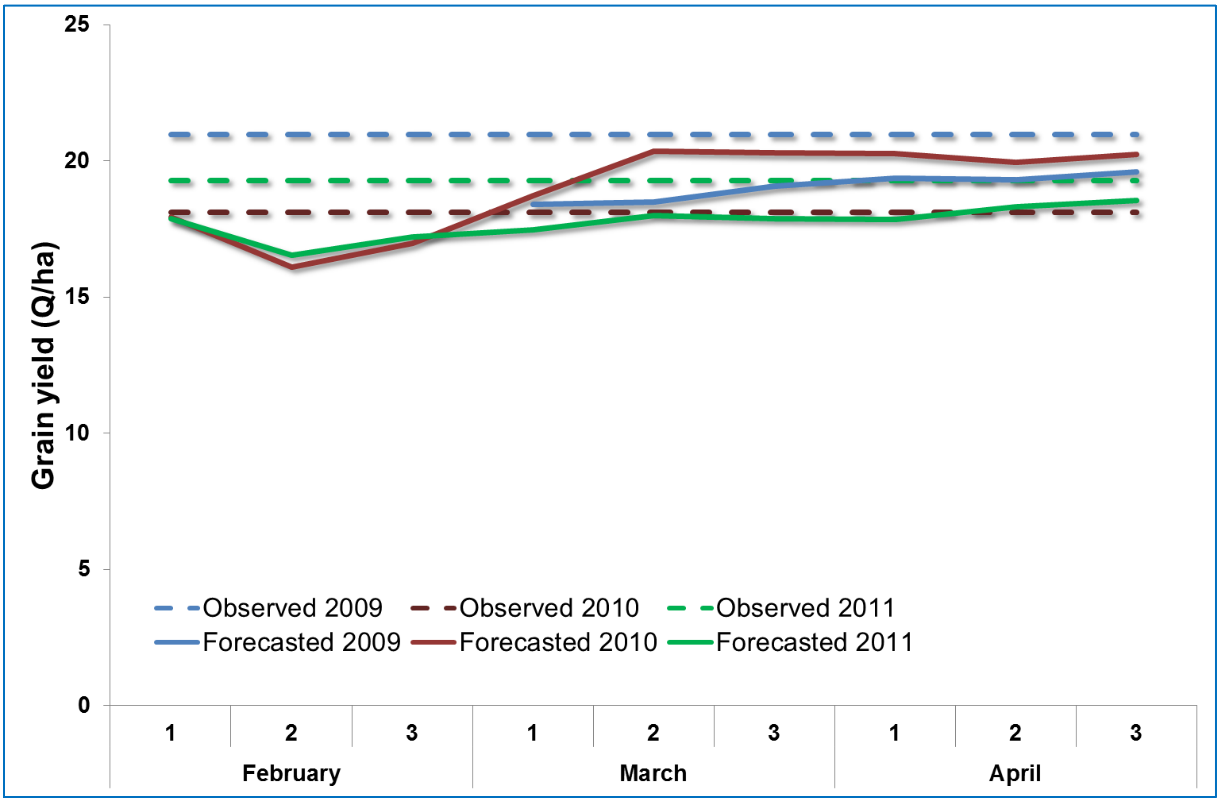


Figure 54: Observed and forecasted durum wheat grain yield at the country level, based on Principal Component Analysis, for the 2008-2009, 2009-2010 and 2010-2011 cropping seasons, using NDVI (NOAA-AVHRR) and cumulated rainfall (Data from 1988 to 2011), at dekadal time step.

3. REGRESSION MODELS APPROACH

The regression models approach consists in identifying climatic variables (precipitation, temperature, etc.) or agro-climatic indices (NDVI, etc.) which are significantly correlated to crop yields. Forecasting crop yields using regression models strongly relies on agronomic expertise, as well as statistical analysis, Geographic Information Systems and satellite image processing skills.

The main precaution before using this approach is to ensure that non-climatic factors do not interfere during regression analysis, such as technological trend (change of varieties, irrigation, new agronomic practices, etc.), or socio-economic factors (prices, subsidies, etc.). This approach requires to always considering "*the law of the limiting factors*" also known as the "*law of the minimum*". This law is one of the most important principles of practical agronomy, which was set in 1828 by Carl Sprengel, and then adapted by Liebig in 1850. The principle of this law states that crop yield is limited by factors that first are insufficiently available.

A study covering 12 European countries revealed that simple climate, soil and economic variables could explain most of the variation of wheat yields and their trend in Europe (Bakker *et al*., 2005). Among these, climate variables (precipitation, temperature, evapotranspiration and global radiation) account for the largest percentage of yield variability, more than the contribution of variables related to soils and economy. In some countries, where climate is not a limiting factor, either because rainfall is abundant or because irrigation is available, crop yields are mostly dependent on biotic stresses (diseases, pests) or agronomic inputs (fertilization, pest treatment). In general, in these countries, yields increase continuously due to technology improvement, and vary little from one year to another. For example, in Belgium, the sophisticated B-CGMS crop monitoring and forecasting system (http://b-cgms.cra.wallonie.be/en/), which is an adaptation of the European CGMS, explains less wheat yield variation than only a technological trend, computed based on statistical linear regression (Decrem *et al*., 2002).

In the case of Morocco, inter- and intra-annual rainfall distribution is obviously the factor that explains much of crop yields' variability, in general, and cereal variability in particular, due to the aridity of climate and limited irrigation capabilities (only 1.46 million hectares irrigated, representing 17% of agricultural lands).

The regression models approach can be used at multiple spatial scales, depending on data availability. With the development of weather interpolation methods and satellite imagery, the main limitation to the use of this approach for finer spatial scales, comes from the availability of agricultural statistics. Cereal statistics were provided by DSS at provincial level, based on sub-provincial sampling technique, called "area frame sampling" (see chapter II_1.6).

The regression models approach start with the constitution of a database containing all relevant agro-climatic factors or indices and crop yields statistics, at the largest (finest) spatial scale (the provinces, in the case of cereals for Morocco). Once the database is established, the agrometeorologist can start data analysis. Crop yields are then linked to single or multiple predictors (factors or indices), using usual spreadsheets or using more sophisticated statistical software packages. The "golden rules" to consider, when using linear regression models for crop forecasting, are described by Gommes *et al*. (2010).

In crop forecasting, simple or multiple linear regression models are often used as an adjunct to crop growth simulation models. This is the methodology used by the JRC for crop monitoring and forecasting over all countries of the European Union and neighboring countries, including the Maghreb. This is a two-step methodology, which involves first computation of indicators informing on the state of the growing season (water balance, vegetative phases, etc.) through the WOFOST model. Indices derived from this model are then used as predictors in multiple linear regressions for crop yield forecasting, calibrated against official agricultural statistics. Forecasted yields are therefore not provided directly by WOFOST model, but from linear regression between official yields and outputs coming this.

Selection of the predictors of the linear regression models involves two steps, called "calibration" and "validation". The calibration step consists in finding, among all potential predictors (1 to several hundred depending on the case), those that are most correlated to crop yields, in order to maximize the coefficient of determination (R^2) of the regression model. Statistical procedures for automatic selection of predictors (Forward, Stepwise, etc.) are available in most statistical software products, so as to avoid collinearity[47] problems. However, regression models with high R^2 have not necessarily good predictive power. For this reason, the validation step is performed. Validation is performed based on a "cross-validation" technique, which is recommended in crop forecasting (Balaghi *et al*., 2008). This validation technique is used to check the reproducibility of results, and thus to verify the predictive power of the regression model, for a "new" year which has not been used during the calibration step. A coefficient of determination of the cross validation[48] (R_p^2) as well as the forecasting error of the model are thus computed. Preference should be given to regression models with low “shrinkage” (difference between R^2 and R_p^2).

3.1. FORECASTING USING RAINFALL AS PREDICTOR

Operational crop forecasting attempts, using rainfall as predictor, are numerous in Morocco (Douguedroit and Messaoudi, 1998; Douguedroit *et al*., 1998; Skees *et al*., 2001; Stoppa and Hess, 2003; Balaghi *et al*., 2008). These various forecasting models were all based on empirical statistical approaches. These statistical approaches are based on single or multiple linear regressions, at different spatial scales (country, agro-ecological zones or provinces), between cereals yields and one-time rainfall values (daily, ten-day, monthly or yearly), or cumulative rainfall over several periods within the season. These linear regression models generally provide reliable forecasts,

[47] The presence of high correlations, between explanatory variables of a multiple linear regression model.

[48] The coefficient of determination in cross-validation is defined as the coefficient of determination between observed and predicted values (see Balaghi *et al*., 2008). R_p^2 gives an indication on the replicability of results and checks the prediction performance of a model.

varying in accuracy according to available time series, to the spatial scale of the study and to the species considered (soft wheat, durum wheat and barley).

The relationship between cereal yields and cumulated rainfall during the cropping season is improving continuously, proportionally to the accumulation of rainfall along the season, from mid-October to late March (Figure 55). High coefficients of determination (R^2) reached at the end of March as well as the continuous improvement of R^2 during the course of the cropping season, demonstrate the reliability of using cumulated rainfall as predictor in forecasting models based on statistical linear regression. At late March, R^2 computed over the period 1988-2011, reaches values of 61, 68 and 70%, for soft wheat, durum wheat and barley, respectively. Also, the R^2 curves for the three species suggest using cumulated rainfall between October and March for cereal yield forecasting.

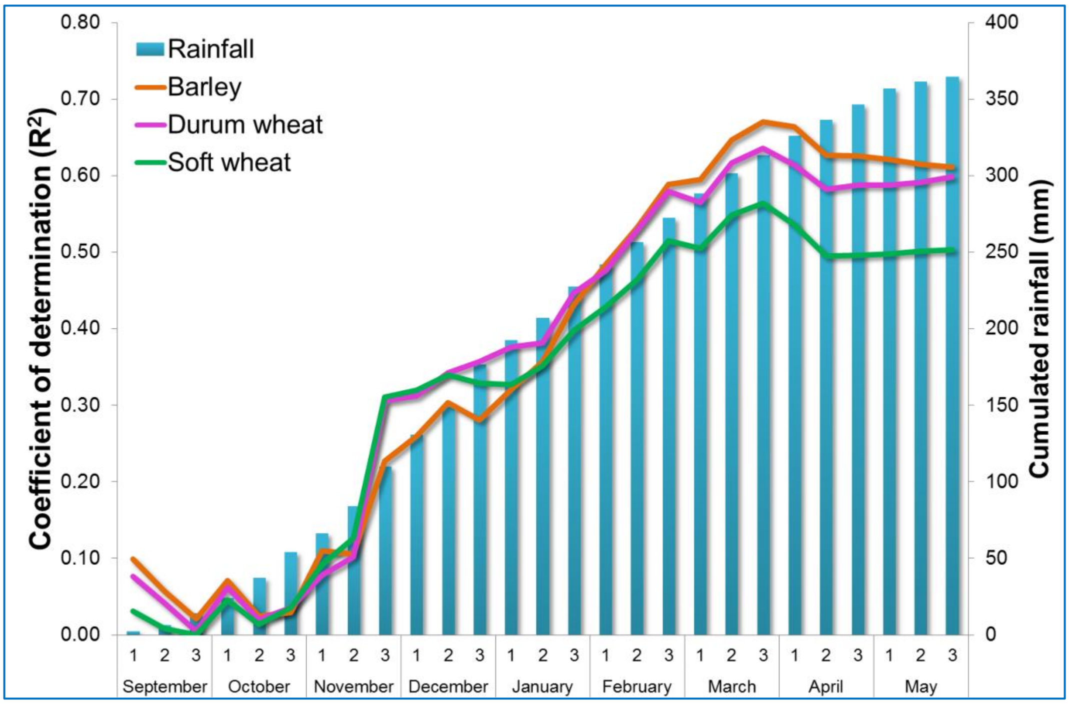


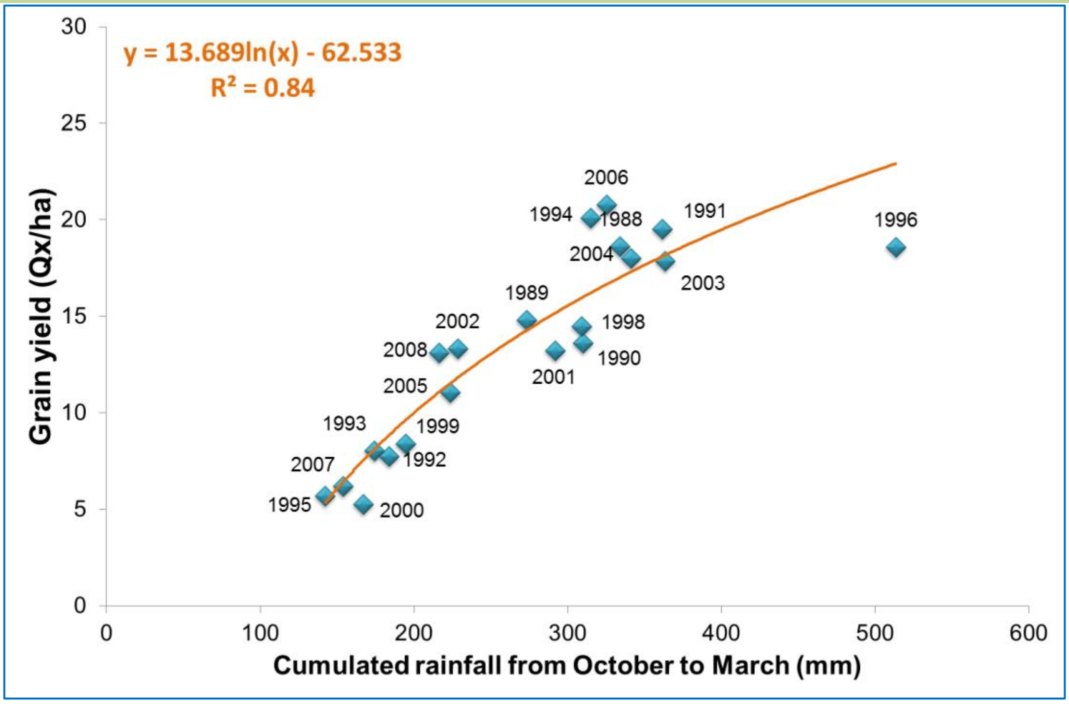
Figure 55: Coefficient of determination (R^2), by step of one dekad, of the regression line between grain yields of the three main cereals (soft wheat, durum wheat and barley) in Morocco and cumulated rainfall since September till May, at the country level. Average (1988-2011) cumulated rainfall is displayed in blue bars, for illustrating the steady increase of R^2 with rainfall during the season, from the 2nd dekad of October to the 2nd dekad of March.

3.1.1. FORECASTING USING RAINFALL CUMULATED OVER ALL THE CROPPING SEASON

Cereal yield forecasting based on linear regression models, can be achieved in a simple way using only the cumulated rainfall from October till March. Forecasts can further be improved using a logarithmic regression model, which fits more closely the scatter plots (El Aydam, Balaghi and

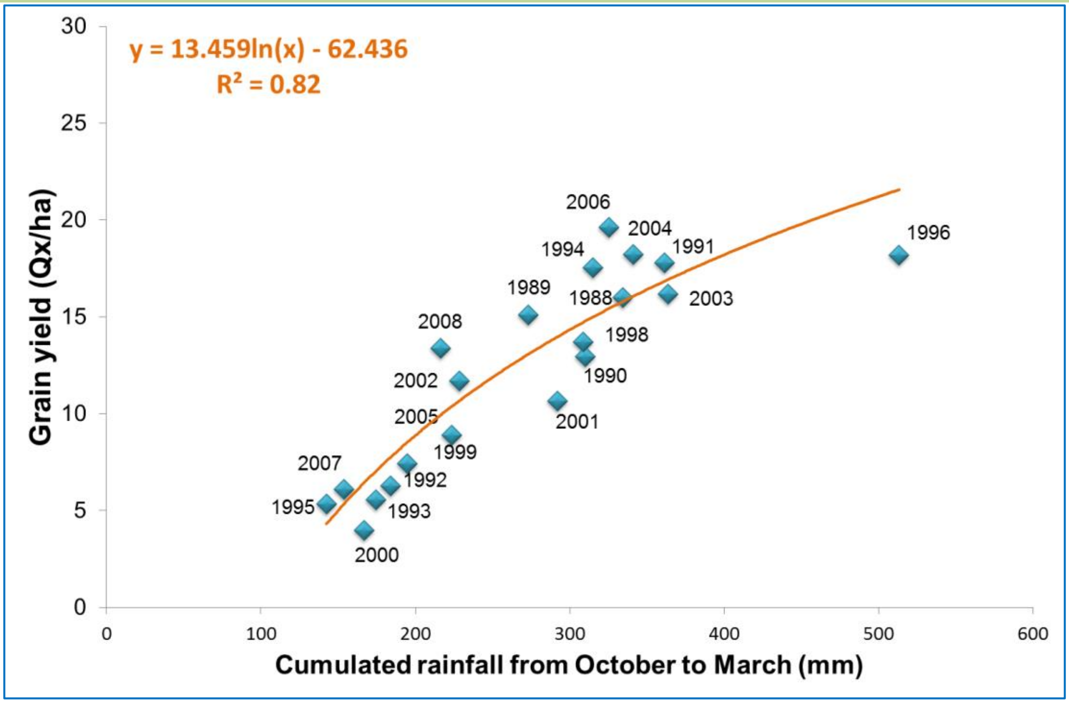
Baruth, 2010). Also, the logarithmic form suggests that rainfall should be first linearized[49] before its use in combination with other predictors (NDVI, ET0, etc.), in case of using multiple regression models. At national level, the correlation between yields of the three cereals and rainfall are high, based on a logarithmic regression (Figure 56). However, some cropping seasons, like those of 1996-1997 and 1999-2000, do not fit into this type of relationship, due to their particular rainfall distribution. For example, in season of 1996-1997, although the rainfall was above average (466 mm), drought which lasted from February to early April (Figure 38) affected cereal yields (9.4, 9.1 and 6.6 Q/ha for soft wheat, durum wheat and barley, respectively). Disregarding season of 1996-1997, correlations between yields and rainfall become strong, with R^2 values of 84, 82 and 77% for soft wheat, durum wheat and barley, respectively (Figure 56).

Soft wheat



[49] A regression model is called "linear" when it is linear in parameters (coefficients of regression). A model is called "intrinsically linear" when it is not linear in the parameters, but it could be linearizable using variable transformation. Precautions should be taken when linearizing an intrinsically linear model. Finally, a model is called "intrinsically non-linear" when its linearization is not possible.

Durum wheat



Barley

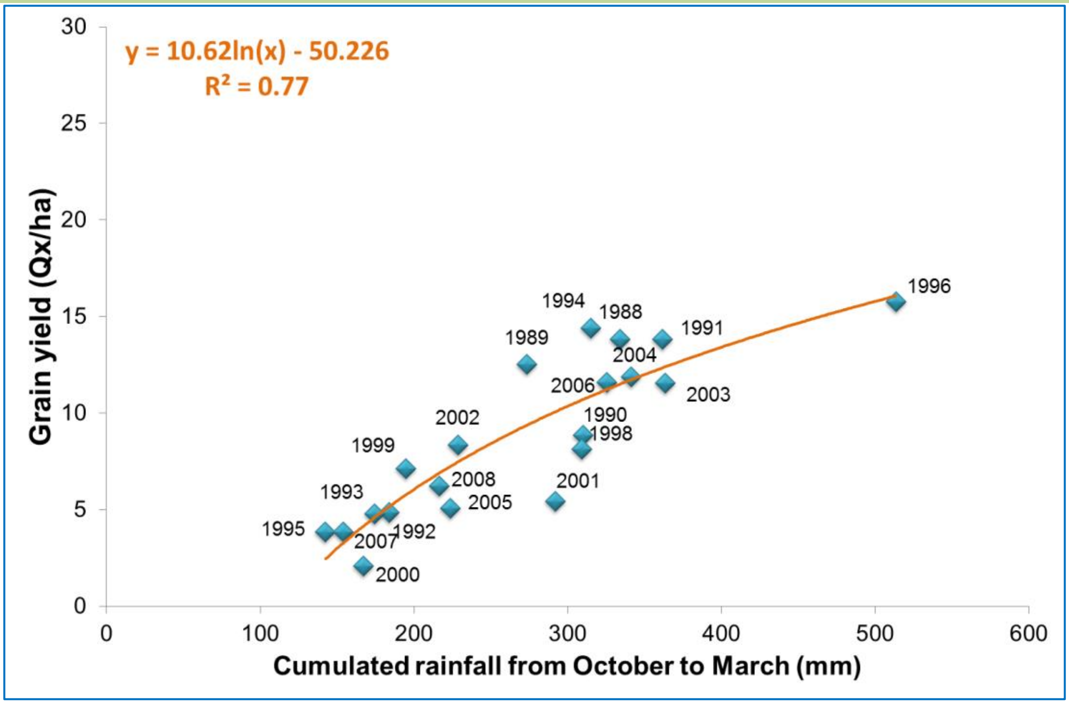


Figure 56 : Relationship between country yields of soft wheat, durum wheat and barley, and cumulated rainfall over the cropping season (from September to March), for data series of 1988 to 2008.

The forecasting methodology based on regression models and using cumulated rainfall as predictor, was used for the forecasting of cereal harvests, since season of 2008-2009 by INRA in collaboration with the JRC, in conjunction with other methodologies based on crop simulation models (WOFOST), similarity analysis, and the use of remote sensing data as predictor (NDVI) (Narciso and Balaghi, 2009; El Aydam, Balaghi and Baruth, 2010; El Aydam and Balaghi, 2011; Balaghi *et al*., 2012). For example, in 2010 the expected country yields during late March, based on cumulated rainfall during the season, were 2.2, 2.0 and 1.6 tons/ha for soft wheat, durum wheat and barley, respectively, against 1.7, 1.8 and 1.4 tons/ha, recorded in official statistics. As seen in this example, although the forecasts were not far from observations, there is still room for improvement which could be sought in a combination of other methodologies and yield indicators.

Similarly, cereal yields can be forecasted at the level of agro-ecological zones, with reasonable accuracy, except for the *Saharan* zone where production depends heavily on irrigation. Crop yield forecasting for the agro-ecological zones is feasible based on simple linear regression models, using cumulated rainfall from October till March (Table 11). The form of the relationship can be approximated by a logarithmic function in 5 of the 6 areas. R^2 of the regression models are above 62%, in the *Mountain* and *Saharan* zones, which contribute very little to national production. R^2 is highest in the *Intermediate* zone, where average season's rainfall is equal to 366 mm.

Table 11 : Coefficient of determination (R^2) of the linear regression models between cereals yields (soft wheat, durum wheat and barley) and cumulated rainfall over the cropping season (from October till March), at the level of the agro-ecological zones (Data from 1988 to 2008).

Agro-ecological zone	Shape of the relationship	R^2		
		Soft wheat	Durum wheat	Barley
Favorable	Logarithmic	0.70	0.66	0.71
Intermediate	Logarithmic	0.80	0.73	0.70
Unfavorable East	Logarithmic	0.62	0.75	0.59
Unfavorable South	Logarithmic	0.71	0.65	0.79
Mountain	Logarithmic	0.53	0.61	0.63
Saharan	Linear	0.44	0.03	0.66

3.1.2. FORECASTING USING RAINFALL CUMULATED BY PHASES DURING THE CROPPING SEASON

Cereal yield forecasting based on single or multiple regression models, using cumulated rainfall over non-overlapping periods during the cropping season (Balaghi *et al*., 2008). Forecasts can be performed using rainfall, cumulated over several periods of 2 to 8 consecutive months during the season (Figure 57). In all cases, the periods to be taken into account orbit the high rainfall period of the cropping season, which runs in average from November till February (Figure 39). For periods of 4 months and over, simple regressions models are satisfactory. For these periods, the forecast is better (R^2=61%), when considering a 6 months period, between October and March. For periods of 3 months and less, multiple regressions are more appropriate to achieve significant R^2. For periods of 3 months, best forecasts are achieved (total R^2=70%) when using rainfall cumulated over January till March (partial R^2=38%) and September till November (partial R^2=32%). Maximum accuracy of the forecasts are obtained (R^2=78%), when using 3 periods of 2 consecutive months, from February till March (partial R^2=34%), from October till November (partial R^2=35%), and from December till January (partial R^2=9%). The consecutive periods were selected so as to not overlap and avoid thus multicollinearity between predictors. The optimal number of periods (predictors) to consider depends on the length of the data series available to ensure to avoid overfitting[50] problems.

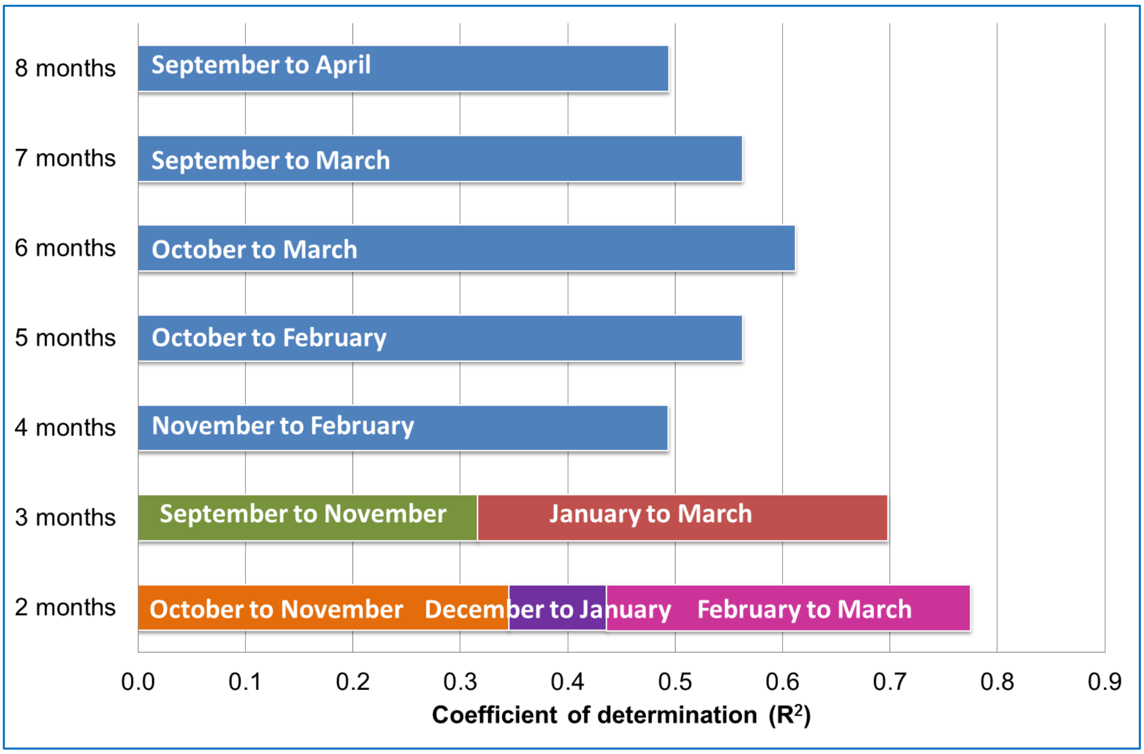


Figure 57: Coefficient of determination (R^2) of linear regression models between grain yields of the three main cereals (soft wheat, durum wheat and barley) in Morocco and rainfall cumulated over significant periods during the cropping season, at the country level (data from 1988 to 2011). ***R^2 is higher when using cumulated rainfall over 6 months, and in partitioning the cropping season's rainfall into two groups of three months and three groups of 2 months each (in these two latter cases, lengths of colored bars correspond to partial R^2 of multiple regressions).***

[50] Overfitting occurs when a statistical model describes random error or noise instead of the underlying relationship. Overfitting usually occurs when a model is overly complex, with too many predictors (multicollinearity between predictors) compared to the number of observations.

3.2. FORECASTING USING AGRO-CLIMATIC INDICES

Some agro-climatic indices computed from water balance models, combining climatic factors with crop and soil characteristics, are highly correlated with cereal yields. Agro-climatic indices are expected to provide an added value, in terms of vegetation monitoring or crop forecasting, compared to climatic factors used separately. Examples of such agro-climatic indices are given by AgroMetShell software, which is part of a set of tools developed by FAO for decision making in the context of food security.

Three indices directly computed from this software were used for illustration: Water Surplus-Deficit Water (WSD), Water Requirement Satisfaction Index (WRSI), and Soil Water Storage (SWS). As well, a fourth new index was added, computed as the cumulated WSD over consecutive dekads (ΣWSD) starting from the start of the season in November. Meknes province was selected as sub-humid test site, assuming 150mm soil water holding capacity (Balaghi, 2006). These four indices were statistically correlated with soft wheat yields at the provincial level (Balaghi, 2006; Figure 58). Among these indices, ΣWSD (maximum R^2=80% at the 3rd dekad of March) and SWS (maximum R^2=77% at the 3rd dekad of February) were best correlated to soft wheat yields.

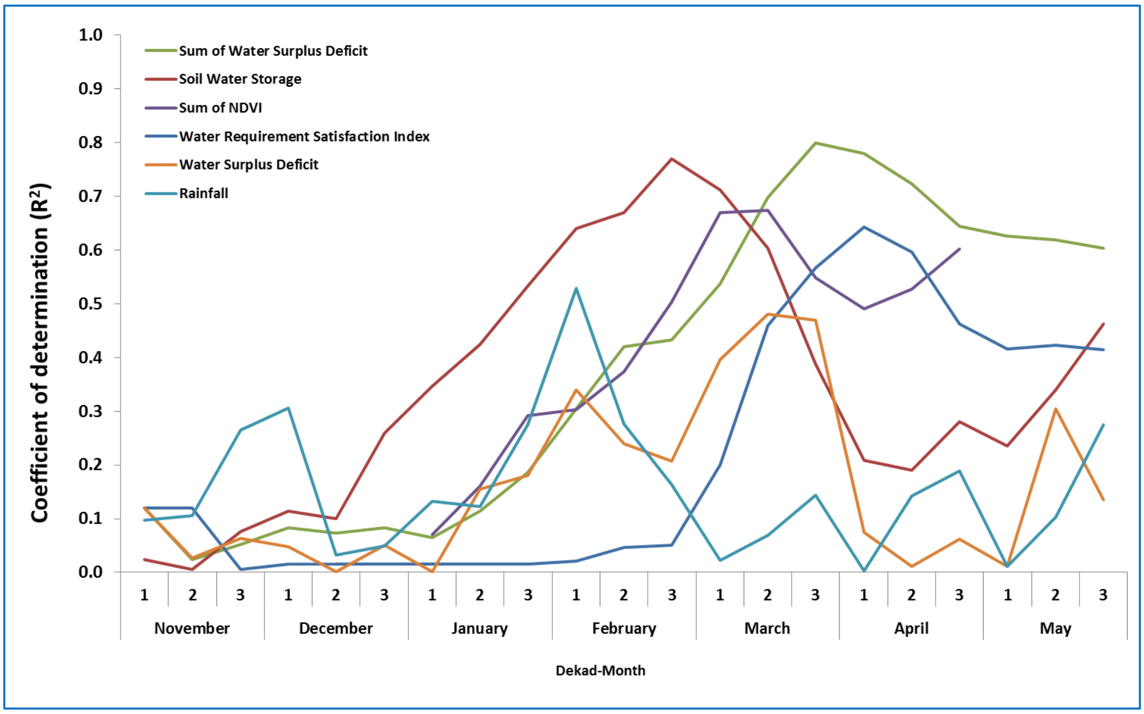


Figure 58: Coefficient of determination (R^2) of regression models between soft wheat grain yields and agro-meteorological indices derived from AgroMetShell program of the FAO, in Meknes province (Source: Balaghi, 2006).

3.3. FORECASTING USING REMOTE SENSING

Compared to weather data, indices derived from remote sensing, such as NDVI, have two main advantages: first, they express the effects of the main environmental factors affecting yields (rainfall, temperature, soils, diseases, cropping practices, etc.); second, they are discontinuously available at the extent of country and at high spatial and temporal resolution (as "raster", also known as pixel). Indeed, in Morocco, synoptic weather stations belonging to DMN (44 in total) are sparse, and most of them are located in the Atlantic plains and very little in mountainous areas or in rangelands (Figure 12).

3.3.1. RELATIONSHIP BETWEEN YIELDS AND NDVI

NDVI is a powerful indicator of the resulting effect of the environmental factors and their interactions with crops. It expresses the combined effect of weather, varieties, diseases, soils, terrain, cropping techniques, etc. Indeed, there is a close and linear relationship between NDVI (SPOT-VEGETATION) and yields for the three winter cereals (soft wheat, durum wheat and barley), at the national level (Figure 59).

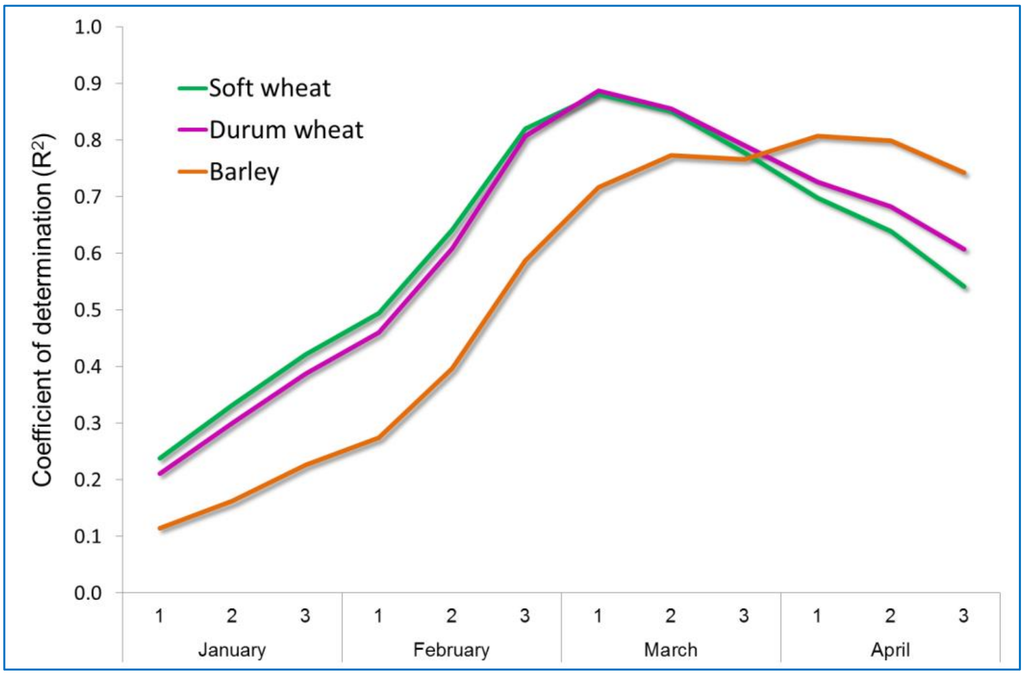


Figure 59: Coefficient of determination (R^2) of regression models between grain yields of the three main cereals (soft wheat, durum wheat and barley) in Morocco, and dekadal NDVI (SPOT-VEGETATION), at the country level (data from 1999 to 2011), by step of one dekad, since 1st dekad of January.

The relationship becomes stronger in February and peaks at the first dekad of March (R^2=89%), for soft and durum wheat, and at the first dekad of April (R^2=81%) for barley. Peaks of correlation coincide with long term NDVI peak during within the season, given that peak of NDVI varies from one year to another, depending on season's rainfall and temperature and on sowing dates. However, seasons of drought slacken the relationship between cereal yields and NDVI. When removing dry seasons (1999-2000, 2004-2005 and 2006-2007) from time series, yield forecasts are improved and can be performed as early as January, with a coefficient of determination (R^2) of 70% for wheat at national level.

The relationship between cereal yields and dekadal NDVI (Figure 59) at national level improves over time, and reaches a peak at the first dekad of March for wheat and at the 2nd dekad of March for barley. The relationship persists until the end of April for barley, whereas it relaxes for wheat.

In order to improve accuracy of the forecasts based on linear regression models, a transformation of variable is performed on NDVI (Genovese *et al*., 2001). It consists in performing regression analysis on average dekadal NDVI values over several dekads, usually taken around period when NDVI is usually at maximum during the cropping season (Figure 60). The use of average NDVI over dekads is a way of taking into account differences in NDVI profile, from one season to another. Relationship is gradually improving during the cropping season starting from February till April, with maximum R^2 reached in late April. In Morocco, best correlations with cereal yields were obtained, when averaging NDVI from February till April, followed by February till March. This time period has been identified by testing all possible combinations average NDVI over several dekads, between November and April, at both national and provincial levels (Balaghi *et al*., 2008).

Wheat yields can be forecasted, based on linear regression models, with coefficients of determination (R^2) greater than 80%, using average dekadal NDVI from 1st February till end March (Figure 60). Coefficient of determination exceeds 90%, when using average dekadal NDVI from 1st February till end April. For barley, the forecast is more accurate till the 2nd dekad of April. The reasons why optimal period, for averaging NDVI, varies from one species to another remain to be elucidated. Besides, the relationship between cereal yields and NDVI is likely to improve gradually as time series become longer.

NDVI time series are delivered by NOAA-AVHRR sensor, since 1982 at 1x1 km spatial resolution and at dekadal time step (10 days). However, a number of scenes of this sensor suffer from poor quality due to poor geometric correction and cloud detection. NDVI values delivered by this sensor can be used for forecasting cereal yields in Morocco (Balaghi *et al.*, 2008), at both national and provinces levels. NDVI delivered by MODIS sensor, which has better spatial resolution (250 meters), can also be used in crop forecasting. Research findings (unpublished) indicate that NDVI values delivered by SPOT-VEGETATION (onboard SPOT-5) are better correlated to cereal yields, than those of NOAA-AVHRR and are equivalent to those of MODIS. However, SPOT-VEGETATION mission will end in 2013-14. It will be replaced by Proba-V[51] sensor (Project for On-Board Autonomy - Vegetation) to

[51] For more information, see VITO website: http://www.vgt.vito.be/.

be launched in 2013, shipping a lighter version of the VEGETATION instrument. A restatement of SPOT-VEGETATION images is expected to ensure interoperability with Proba-V, in order to take advantage from SPOT-VEGETATION time series available since 1998.

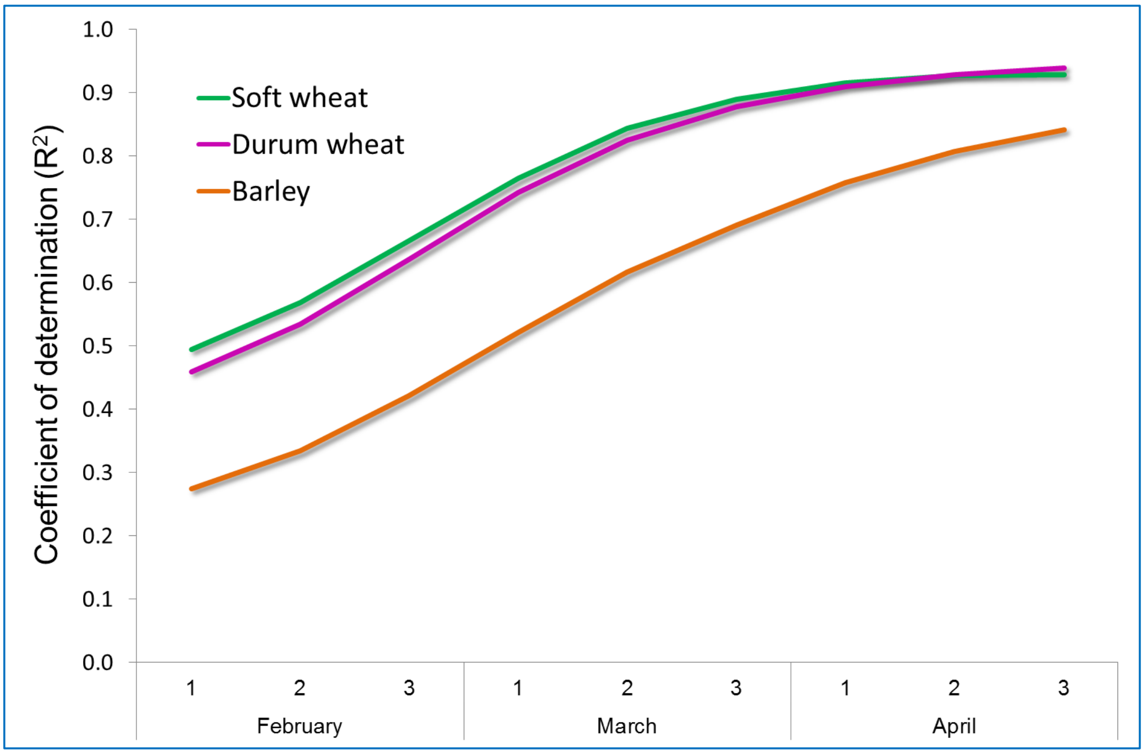


Figure 60: Coefficient of determination (R^2) of regression models between grain yields of the three main cereals (soft wheat, durum wheat and barley) in Morocco, and average NDVI (SPOT-VEGETATION), at the country level (data from 1999 to 2011), by step of one dekad, since the 1st dekad of February.

3.3.2. RELATIONSHIP AT NATIONAL LEVEL

Cereal yields can be forecasted based on linear regression with NDVI at national level. The relationship between cereal yields (soft wheat, durum wheat and barley) and NDVI (SPOT-VEGETATION) is linear and very strong (Figure 61), unlike the relationship with rainfall (Figure 56) which is logarithmic.

Coefficient of determination (R^2) of the relationship between yields and average dekadal NDVI from February till March reaches 89% for soft wheat, 88% for durum wheat and 69% for barley. The relationship is even stronger when average dekadal NDVI from February till April is used instead, with values of R^2 equal to: 93% for soft wheat, 94% for durum wheat and 84% for barley. This relationship was used by INRA, in combination with other methods, for performing cereal yield forecasts, which were published in 2009, 2010, 2011 and 2012 (Balaghi *et al*., 2012; El Aydam *et al*., 2010, 2011; Narciso and Balaghi, 2009).

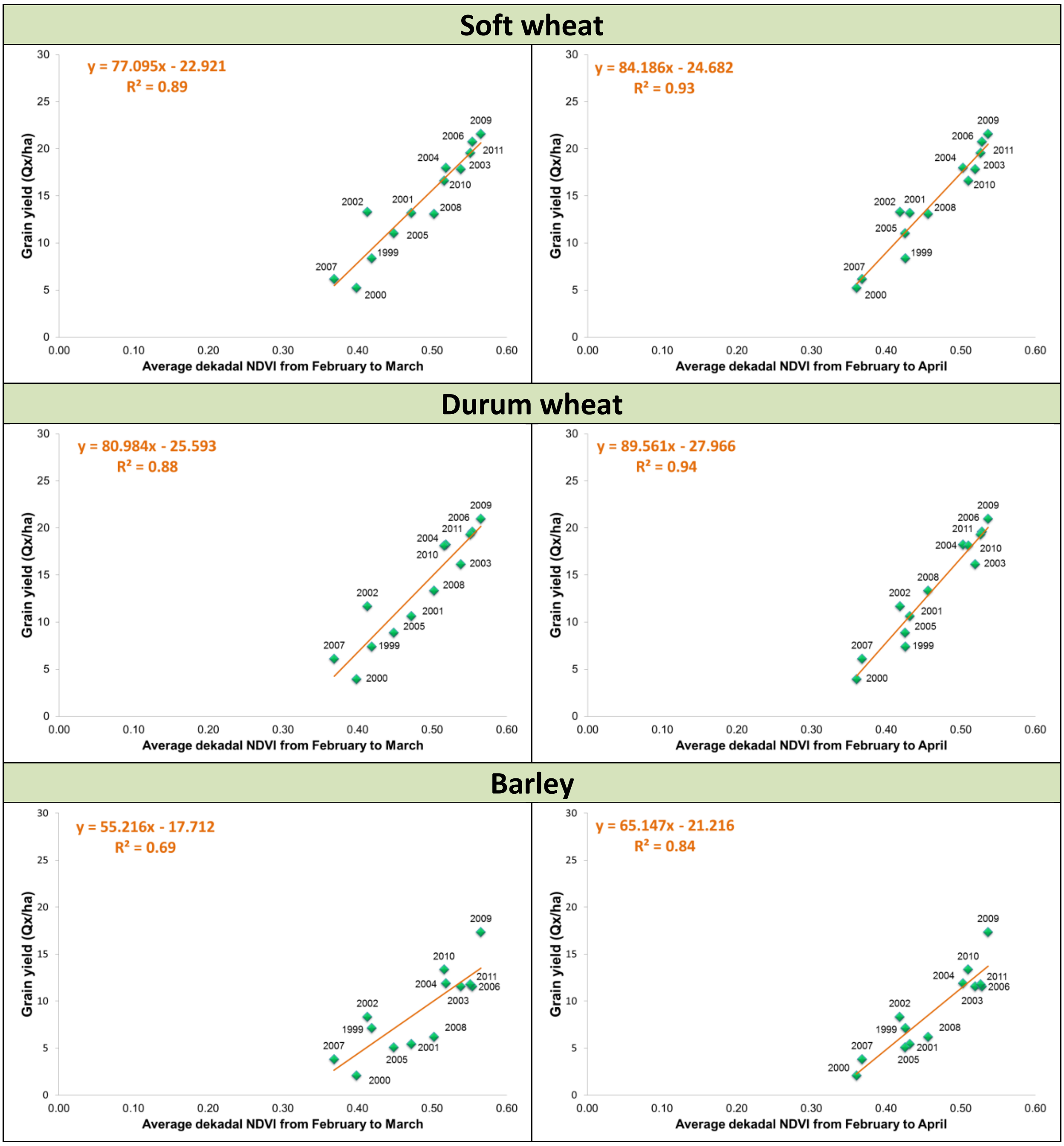


Figure 61: Linear regression between country grain yields of the three main cereals (soft wheat, durum wheat and barley) and average dekadal NDVI (SPOT-VEGETATION) between 1st of February and end of March, and between 1st of February and end of April (data of 1999 to 2011).

3.3.3. RELATIONSHIP AT THE LEVEL OF THE AGRO-ECOLOGICAL ZONES

Cereal yield forecasts can be performed at the level of the agro-ecological zones of Morocco with good accuracy, starting from the end of March. The relationship between yields of winter cereals (soft wheat, durum wheat and barley) and NDVI (SPOT-VEGETATION) is very strong at this spatial level, except for the *Saharan* zone (Table 12). Forecasts can be achieved with minimum error, in late April, for the three species. The relationship is less consistent for agro-ecological zones than for national level. The relationship is stronger for the *Favorable*, *Intermediate* and *Unfavorable South* zones than for the *Mountain*, *Unfavorable East* and *Saharan* zones.

Table 12: Coefficient de determination (R^2) of the regression models between grain yields of the three winter cereals (soft wheat, durum wheat and barley) and average NDVI (SPOT-VEGETATION) from February till March and from February till April, at the level of the agro-ecological zones of Morocco (Data of 1999 to 2011).

Agro-ecological zone	February till March			February till April		
	Soft wheat	Durum wheat	Barley	Soft wheat	Durum wheat	Barley
Favorable	0.73	0.74	0.66	0.85	0.83	0.83
Intermediate	0.79	0.77	0.72	0.87	0.83	0.84
Unfavorable South	0.70	0.69	0.69	0.74	0.77	0.79
Unfavorable East	0.24	0.46	0.38	0.41	0.69	0.67
Mountain	0.51	0.58	0.45	0.52	0.65	0.57
Saharan	0.13	0.03	0.30	0.16	0.03	0.35

3.3.4. RELATIONSHIP AT ADMINISTRATIVE PROVINCE LEVEL

Cereal yields can be forecasted at province level, based on linear regression models, and using average dekadal NDVI (SPOT-VEGETATION) as predictor from February till March, or with higher accuracy from February till April. Four classes of coefficient of determination (R^2) are shown in Figure 62, for soft wheat, durum wheat and barley. R^2 higher than 62% are statistically very highly significant (probability level < 0.001). Those between 45 and 62% and between 30 and 45% are highly significant (probability level < 0.01) and significant (probability level < 0.05), respectively. R^2, lower than 30%, is considered not statistically significant.

Classes of high R^2 (> 62%) are located in the south-west to north-east axis (Essaouira to Al Hoceima) of the country, where most of cereal areas are located. The relationship between cereal yields and NDVI are relatively lower in the Northern provinces (Tangier, Tetouan, Larache), eastern provinces (Nador and Oujda), mountainous provinces (Taza, Khenifra, Beni Mellal, Azilal) and in southern provinces (Marrakech, Chichaoua, Taroudant, Agadir, Tiznit). In late March, R^2 are above 62% in most provinces, for soft wheat. Instead, at that period of the cycle, high R^2 (> 62%) are encountered in fewer provinces, in the Settat - Taounate axis for durum wheat, and further south in the Essaouira - Khemisset axis for barley.

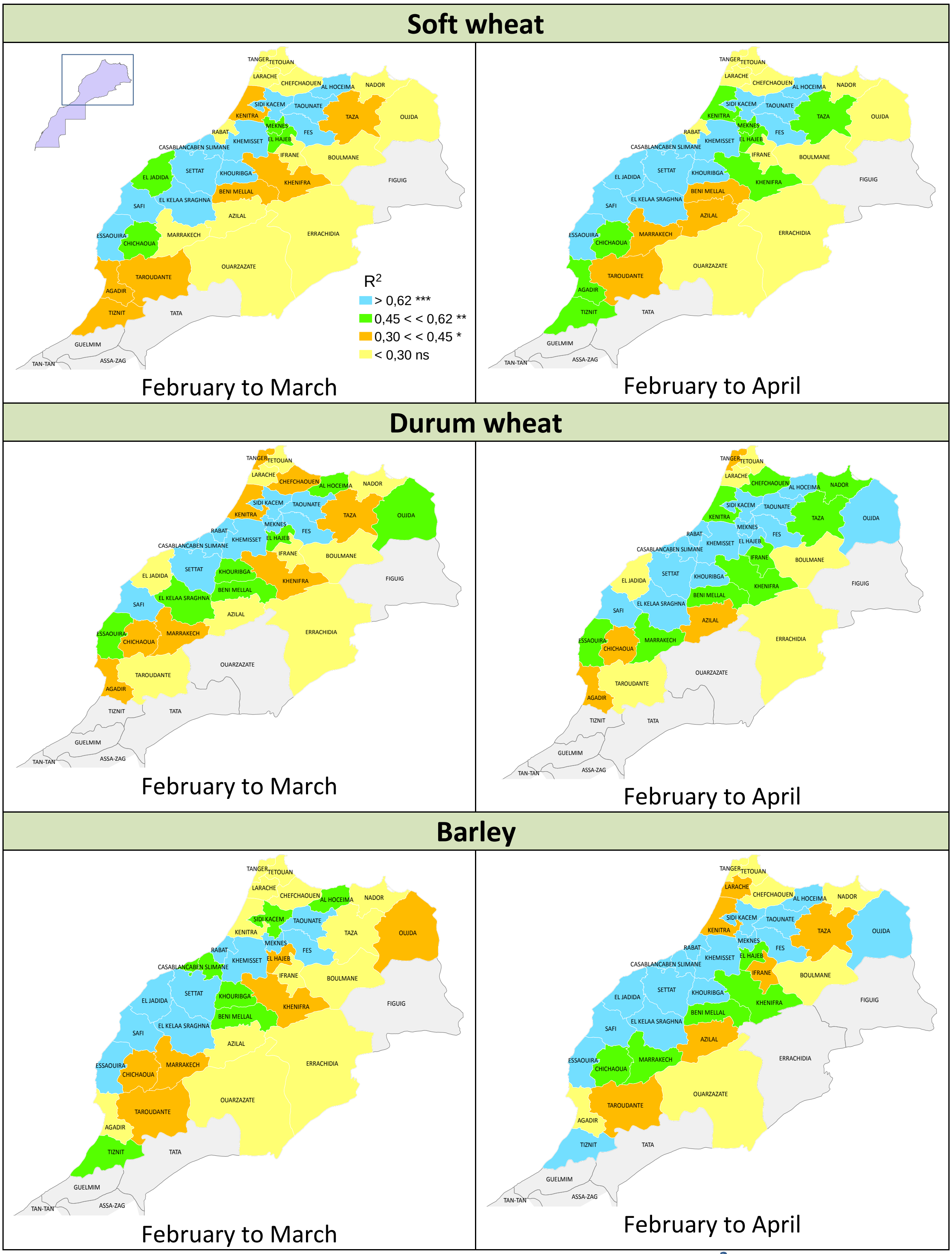


Figure 62 : Mapping of four classes of coefficient of determination (R^2) of the linear regression models between yields of soft wheat, durum wheat and barley, and average dekadal NDVI (SPOT-VEGETATION) from February till March and from February till April.

Provinces in blue, green and orange, indicate statistical significance of R^2, at probability levels of 0.001, 0.01, and 0.05, respectively. Provinces in yellow indicate non statistical significance of R^2. Non colored provinces correspond to non-agricultural areas, as identified by GICropV2 crop mask (Data of 1999 to 2011).

3.4. FORECASTING USING WEATHER DATA AND NDVI

The cereal yield forecasting approach, based on multiple regression models[52] and using a combination of predictors (rainfall, NDVI or temperature), improves accuracy at fine spatial scales. This approach was recently tested in Morocco using NDVI alone or in combination[53] with rainfall or temperature, at province level (Balaghi *et al*., 2008). This was made possible through to the collaboration with University of Liege (ULg, Belgium), JRC and VITO. NDVI images provided by JRC cover the entire agricultural areas, from northern Morocco to south to 20° latitude north. Compared to data coming from ground weather stations, indicators derived from remote sensing, like NDVI, have the advantage of being available throughout the extent of the country, without discontinuity at high spatial and temporal resolutions (in "raster" form, known as pixel), which is well suited for crop yield forecasting.

Forecasts can be performed operationally at the levels of the provinces, agro-ecological zones and country. Regression models can be developed separately, for each province or agro-ecological zone. Forecasted yield for each province can even be aggregated to national level, proportionally to their respective cropped areas, for providing yield forecast for the entire country, with more computational workload but with better accuracy. The coefficients of determination (R^2) of these models were very high, between 72 and 98%, except in the arid southern provinces of the country which contribute little to national production (Balaghi *et al*., 2008). These regression models were relatively stable, since their coefficients of determination in cross-validation (R_p^2) were still between 59 and 94%. Also, forecasts were relatively accurate and early, from two months before harvests.

Among the variables used, NDVI explains the largest share (partial R^2>40%) of yield variation for wheat in 14 out of 23 provinces studied, i.e. in provinces which account for more than 69.4 % of the total national production. Rainfall explains most of yield variation in the provinces of Larache, Agadir, Oujda, Beni Mellal, Tangier, Marrakech and Ouarzazate. Temperature explained most of yield variation only in Tangier and Tetouan, which are located in wet environment. In these two provinces, temperature affects negatively wheat yields, because it increases evapotranspiration and reduces period of growth.

A recrudescent interest of these statistical approaches has been prompted by the growing availability of climate data, over long time series, and by software development, allowing storage and process of large amounts of datasets, as well as by the availability of software products dedicated to statistical analysis and remote sensing processing. Generally, statistical forecasting approaches are criticized because they do not apply outside the range of variation of the data used for their calibration. This criticism can be largely avoided in the case of Morocco, due to the high variability of climate and geography. In fact the probability of encountering climatic seasons outside

[52] This approach has been successfully applied also in Canada (Mkhabela *et al*., 2011), in Romania (Lazar *et al*., 2009), Senegal (Kouadio, 2007) and in Burkina Faso (Ramde, 2007).

[53] In these models, the « Stepwise » procedure for automatic selection of predictors has been applied in order to avoid multicollinearity between explanatory variables.

the range of historical variation is always possible, but nevertheless reduced due to the extreme cropping seasons experienced, both very dry (1994-1995, 1996-1997, 1999-2000, 2000-2001 and 2004-2005) and very wet (1995-1996, 2008-2009, 2009-2010 and 2010-2011).

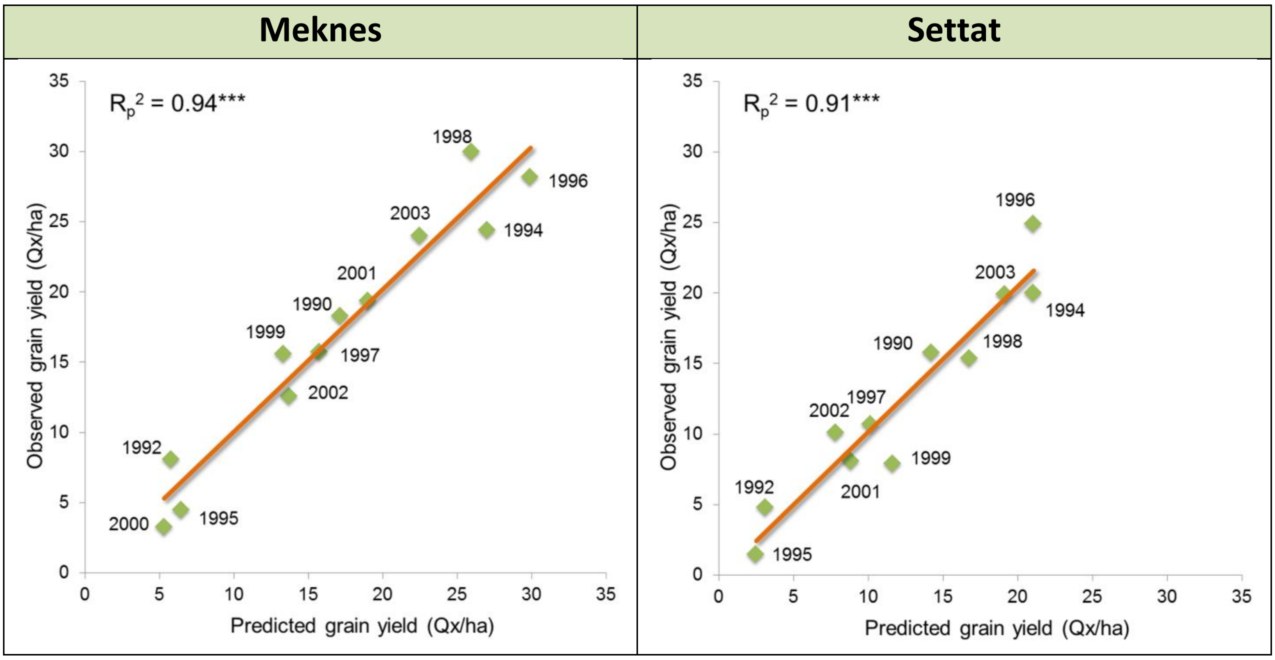


Figure 63 : Relationship between observed and forecasted yields of soft wheat at Meknes and Settat, based on multiple linear regression models, involving NDVI, rainfall and temperature (Source: Balaghi *et al.*, 2008).

3.4.1. ESTIMATION OF THE FORECASTING ERROR

The forecasting error of the linear regression models using average dekadal NDVI (SPOT-VEGETATION) is improving gradually, as the cropping season is ending, from February till end of April, regardless of the spatial scale. In Figure 64 are shown examples of soft wheat forecasts, at national level, for cropping seasons of 2008-2009, 2009-2010 and 2010-2011. These cropping seasons were of course not used during the calibration process. Coefficients of determination (R^2) and consequently forecasting errors, have gradually improved starting from February and peaked in late April (R^2> 88%).

During the extreme rainy season of 2008-2009 (548 mm), the forecast was close to the official yield (difference of 1.65 Q/ha). This cropping season was particular, outside the range of historical rainfall variation (between 227 and 419 mm, from 1999 to 2008). Also, the forecasts were very close to official yields for cropping seasons of 2009-2010 and 2010-2011. Whatever are the season and the cereal, confidence intervals of the forecasts have improved gradually as the cropping seasons reach completion. Also, confidence interval at 70% always comprises official yields.

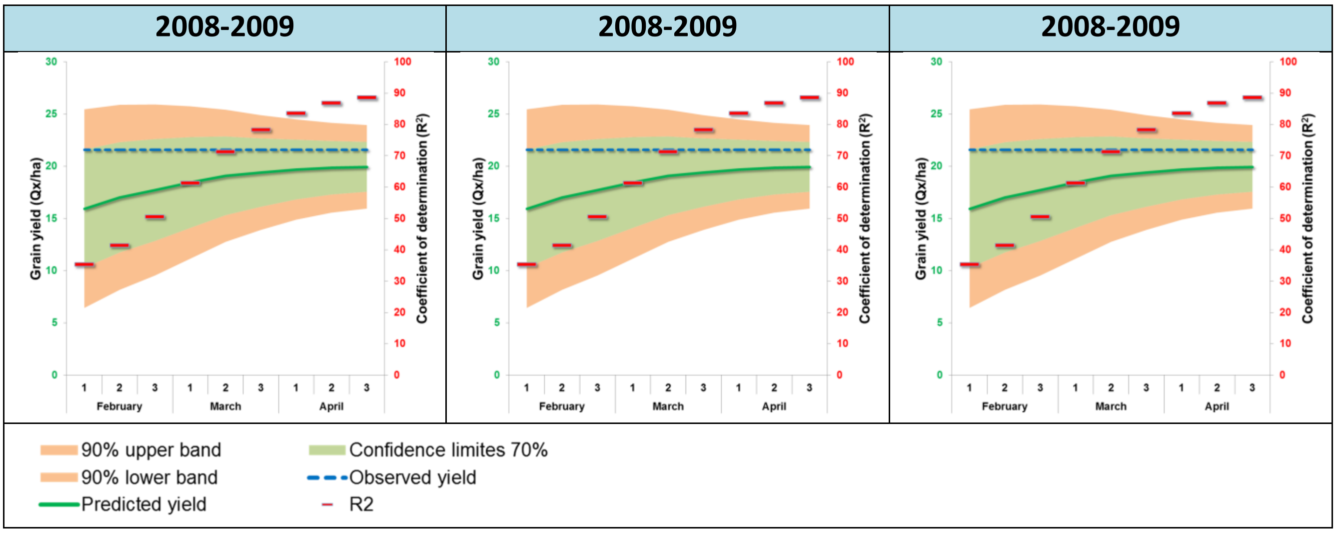


Figure 64 : Increase of precision and accuracy of the country soft wheat yield forecast, based linear regression models, using NDVI (SPOT-VEGETATION), as the cropping seasons reach completion. Examples of the 2008-2009, 2009-2010 and 2010-2011 cropping seasons are shown.

4. COMBINED APPROACH

Cereal yields can be forecasted based on a combined approach (Table 13), which relies on a combination of four approaches and use of various types of predictors (rainfall, temperature, NDVI):

1. **Non-parametric approach**: multiple regression models, using qualitative predictors (rainfall) for describing the status of the cropping season;
2. **Similarity approach**: similarity analysis based on Euclidean distance and Principal Component Analysis, using rainfall and NDVI ;
3. **Regression models approach**: Single or multiple linear regression models, using rainfall, temperature and NDVI ;
4. **Simulation approach**: Crop growth simulation models (WOFOST), using raw climatic, crop and soil data.

This approach has the advantage of providing yield forecasts by various independent ways (Gommes *et al.*, 2010), allowing an estimation of the uncertainty of the forecasts. This combined approach has been formalized in the CST software for Morocco, in the framework of E-AGRI project.

Table 13: Schematic table of the combined approach and predictors developed for cereal yield forecasting in Morocco. Shaded areas indicate the predictors used for each method.

Combined Approach	Method	Predictor			
		Rainfall	Temperature	NDVI	morpho physiological
Non-parametric		■			
Similarity	Euclidian distance	■		■	
	PCA	■		■	■
Parametric	Simple regression	■		■	■
	Multiple regression	■	■	■	■
Simulation WOFOST					■

This approach was used to forecast cereal yields with high accuracy, for cropping seasons of 2008-2009 (Balaghi and Narciso, 2009), 2009-2010 (El Aydam, Balaghi and Baruth, 2010), 2010-2011 (El Aydam and Balaghi, 2011) and 2011-2012 (Balaghi *et al*., 2012). Forecasts concerned soft wheat, durum and barley, while the data on the area of each species were provided by DSS from field surveys.

The accuracy of the forecasts is continuously refined, since it depends on three key conditions that are still improving:

1. Time series are increasing, allowing to take account of more contrasted cropping environments, improving hence the robustness of regression models and similarity analysis ;
2. The number of weather stations is increasing in Morocco, which will give floor to better spatial characterization of climatic conditions at fine spatial scale ;
3. The crop mask, which separates agricultural areas from other lands (forest, rangeland, wasteland, lakes, cities, etc.) can be replaced by a cereal mask which will closely filter NDVI images ;
4. The NDVI images are continually affordable and also improved, in terms of quality and spatial resolution.

VII. INSTITUTIONALIZATION AND OPERATIONALIZATION OF THE FORECASTING SYSTEM

The combined approach for cereal yield forecasting has been automated in an operational forecasting system, in order to forecast cereal yields in Morocco, called "CGMS-MAROC". This system is an adaptation and improvement of the European CGMS system. The native CGMS consists of three levels: (1) the acquisition of meteorological data and their interpolation on a square grid of 25x25 km spatial resolution, (2) the simulation of crop growth using the European WOFOST model, and (3) cereal yield forecasting based on outputs derived from WOFOST model. CGMS-MAROC has the same architecture than the European CGMS but has been improved, since it includes statistical models for forecasting crop yields developed at INRA. Also, CGMS-MAROC runs with spatialized weather data on finer climate grids of 10x10 km resolution. CGMS-MAROC can currently forecast cereal yields at the level of the country, agro-ecological zone and province levels. It is operated by INRA and managed in collaboration with DMN and DSS, in the framework of an official partnership. It is intended to support DSS, as this administration is officially mandated to provide crop statistics and forecasts. CGMS-MAROC is installed on a central server at DMN, which is responsible for updating and delivering the weather grid. A Web viewer installed at INRA, was specifically developed for checking data and making preliminary analysis concerning the season. CGMS-MAROC is the first operational agrometeorological crop forecasting system available in Morocco, institutionalized by a strategic partnership which allows its development and sustainability.

To effectively deal with climate change and climate risks in general, initiatives to improve governance systems[54] and policies for better adaptation and proactivity, should be promoted. The success of the adaptation of agriculture to climate risks depends on national institutions which are responsible for food security, directly or indirectly. Participants to the 3rd World Climate Conference organized by the World Meteorological Organization (http://www.wmo.int/wcc3/) highlighted the need for capacity building and linkages between meteorological, agricultural and scientific research institutions (Balaghi *et al.*, 2010).

The combined approach for cereal yield forecasting has been automated in an operational forecasting system, in order to forecast cereal yields in Morocco, called "CGMS-MAROC" (www.cgms-maroc.ma), which is an adaptation and improvement of the native European CGMS system. The European CGMS consists of three levels: (1) the acquisition of meteorological data and their interpolation on a square grid of 25x25 km spatial resolution, (2) the simulation of crop growth using the European WOFOST model, and (3) cereal yield forecasting based on outputs derived from WOFOST model.

[54] Such initiatives include the useful work undertaken by FAO for dissemination of data and tools, and knowledge transfer for the processing of agrometeorological information, through the "*Climpag*" network http://www.fao.org/nr/climpag/index_en.asp

The forecasting system of Morocco, called "CGMS-MAROC", is developed in the framework of E-AGRI project. The European institutions partners of E-AGRI project are: JRC, Alterra and VITO. CGMS-MAROC is coordinated by INRA and jointly managed by DSS and DMN, in the framework of a tripartite official agreement. It is intended to support DSS, as this administration is officially mandated to provide crop statistics and forecasts. CGMS-MAROC is installed on a central server at DMN, which is responsible for maintaining and delivering the climatic weather grid. CGMS-MAROC is the first operational system for cereal yield forecasting in Morocco, institutionalized through a strategic partnership in order to promote its development and sustainability.

The role of the national institutions in charge of CGMS-MAROC:

- **The National Institute for Agronomic Research (INRA) is responsible for:**
  - Acquisition and provision of agronomic data, for the calibration of the system at Level 2 of CGMS-MAROC ;
  - Contribution with DMN and DSS to the statistical analysis for cereal yield forecasting at Level 3 of CGMS-MAROC ;
  - Data analysis of remote sensing, to forecast crop yields at Level 3 of CGMS-MAROC.

- **The Direction of Strategy and Statistics (DSS) is responsible for:**
  - Acquisition and provision of data on official crop statistic ;
  - Area estimates based on remote sensing and field surveys.

- **The National Direction of Meteorology (DMN) is responsible for:**
  - Acquisition and provision of weather data and hosting of CGMS-MAROC ;
  - Interpolation of weather data, collected from synoptic weather stations.

CGMS-MAROC system has been improved compared to the native European CGMS system. CGMS-MAROC has the same architecture than the European system but has been improved, since it includes in addition to WOFOST simulation model, statistical models for forecasting crop yields developed at INRA. Also, CGMS-MAROC runs with spatialized weather data on finer climate grids of 10x10 km resolution. CGMS-MAROC can currently forecast cereal yields at the level of the country, agro-ecological zones and provinces. CGMS-MAROC is installed on a central server at DMN, which is responsible for maintaining the system and updating and delivering the weather grid.

CGMS-MAROC is accompanied by a web interface (Figure 65) for visualization and preliminary analysis of the cropping season, which was developed in Morocco in the framework of E-AGRI project. The Web interface is hosted on a server located at INRA and supplied by daily climatic data (rainfall, maximum and minimum temperature, reference evapotranspiration) coming from all synoptic stations of DMN, as well as by satellite imagery products (NDVI, DMP) delivered every 10 days by VITO. This Web interface allows thus a bio-climatic monitoring of the season at fine grid cells of 10x10 km over all the agricultural areas of Morocco. Similarity analysis capabilities have been implemented in this Web interface, allowing preliminary analysis of the cropping season and rapid cereal forecasts.

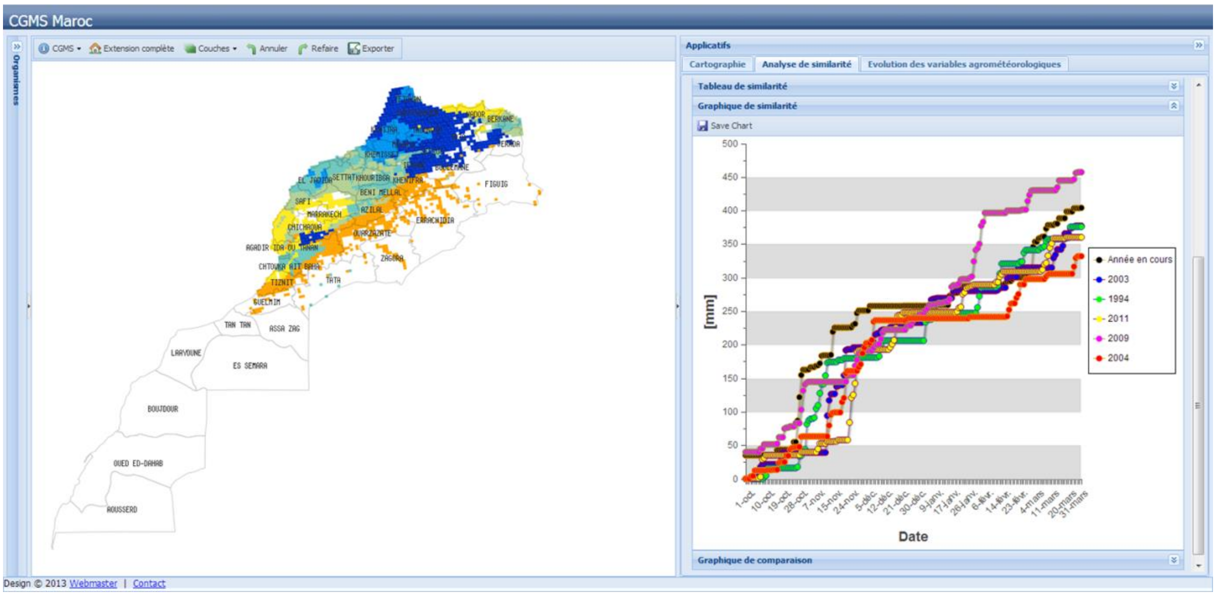


Figure 65: The Web viewer of CGMS-MAROC (www.cgms-maroc.ma) for bio-climatic monitoring of cereals, and preliminary statistical analysis of the cropping season. On the left side window is displayed the cumulated rainfall over the season on agricultural lands (10x10 km grid). On the right window is shown, the similarity analysis using cumulated rainfall, in the district of Ben Ahmed (province of Settat).

VIII. CONCLUSIONS AND OUTLOOK

The combined agrometeorological approach, for cereal yield forecasting developed at INRA in collaboration with national and international research and development institutions, is described in this document. It is a pragmatic and powerful approach, which is adapted to the different types of available observed data: meteorological, agricultural, and satellite. It has a major advantage over other approaches of crop yields forecast, which use models that require simulation data often not readily available in Morocco. It also adapts to the spatial scale of the data (national, agro-ecological zone, province).

The development of this combined approach began with the analysis of the Moroccan climate which revealed the relevance of using amount and distribution of rainfall for cereal yield forecasting. Analysis of cereal crops and their interactions with weather helped developing agrometeorological indices that can be used to forecast yields. Such indices were derived from climatic factors most limiting cereal production (rainfall, temperature, water balance), indices derived from satellite imagery (NDVI), and from WOFOST simulation model. Indices derived from rainfall and NDVI appeared to be more relevant and more practical for forecasting cereal yields in Morocco. Indices derived from temperature are useful only in wet areas of the northern parts of the country where rainfall is not a limiting factor.

This combined approach is currently implemented in a computerized system for cereal yield forecasting, named "CGMS-MAROC." This system is designed in a modular way, to adapt to the available data, to the spatial scale, and to desired accuracy and time of forecast delivery. Accuracy, reliability, objectivity, traceability and forecast delivery time are important qualities that have been targeted during the development of this system. The system is based on the combined approach developed at INRA, in scientific and technical collaboration with the Luxembourg University Foundation (now became Arlon Campus Environment of the University of Liège, ULg - Belgium) since 2000 and JRC and VITO, since 2007. The forecasts are provided based on regression models between official agricultural statistics and rainfall and NDVI during the growing season as well as outputs of WOFOST simulation model. Bulletins on cereal yields forecasts have been published on the websites of JRC (http://ec.europa.eu/dgs/jrc/index.cfm) and INRA (http://www.cgms-maroc.ma/ newsbulletin.htm).

CGMS-MAROC system for cereal yield forecasting is currently the only institutionalized system in Morocco providing published season's monitoring and operational cereal yields forecasts. To sustain the system and allow further development, a formal consortium was established, composed of INRA, DSS and DMN. CGMS-MAROC is installed on a central server at DMN. A Web viewer (http://www.cgms-maroc.ma/) installed at INRA was specifically developed for checking data and making preliminary analysis of the growing season. It is managed by a panel composed of members, of recognized scientific and technical authority. INRA provides scientific support to the development of the system. DMN is responsible for updating and delivering spatial data of climatic parameters on the weather grid provides covering the entire territory, and also manages the modelling (WOFOST) aspects. DSS provides official data areas and grain yields. The first joint bulletin for forecasting cereal yields was published in April 2011 on the website of the INRA website (www.inra.org.ma).

Cereal yields are forecasted for different spatial resolutions: the country, the agro-ecological zones and provinces. The country average cereal yields have been accurately forecasted for the growing seasons of 2008-2009, 2009-2010, 2010-2011, and 2011-2012.

CGMS-MAROC system is currently being improved to overcome some accuracy limitations encountered in some specific cases, for example:

- Relatively high rainfall growing seasons but with severe drought in the middle of the crop cycle like in 1996-1997 ;
- High rainfall growing seasons, like those of 2008-2009 and 2010-2011 ;
- Low temperature growing seasons like the 2011-2012.

These limitations of the system could be overcome by taking into account phenological stages of the crop during periods of forecasting and during periods of drought, excess water or cold.

The prospects for this system are promising. Methods for forecasting yields can be developed for other annual crops similar to cereals, since one of the modules of the WOFOST model provides parameters for many other crops, particularly corn grain, rice, sugar beet, potato, bean, soybean, rapeseed and sunflower.

CGMS-MAROC allows not only to instantly forecast grain yields two to three months before harvest, but can also be adapted to other uses, through additional improvements, like drought insurance, agricultural warning, mapping potential of land and land use, seasonal forecasting of crop yields and impact of climate change on agricultural productivity.

CGMS-MAROC can be improved and used in agricultural early warning, by incorporating modules for forecasting short-term weather events (rain, drought, heat waves and cold) and biotic hazards (diseases, insects). These products can be generated directly from local weather stations, national networks of weather stations or numerical models of spatial interpolation of climate data. This implies a consorted effort in local data collection, transmission, processing and dissemination of agrometeorological information to farmers and agricultural advisors.

The scope of agricultural warning is large, which may include in addition to the plant protection, fertilization management, supplemental irrigation, and the choice of sowing date. This is a field of research and development to develop in Morocco, which can have significant positive impact on agriculture and the environment. It is in this context that the National Health Security Office of Food Products (in French Office National de Sécurité Sanitaire des Aliments, ONSSA) and DMN included in their priorities the development of a national program on agricultural warning.

CGMS-MAROC can also be adapted for forecasting cereal yields in countries with similar climate to that of Morocco, such as the Mediterranean countries. In these countries, behavior of cereals crops to weather and crop management are similar.

Satellite imagery data, NDVI in particular, has been proven to be relevant in forecasting cereal yields for Morocco. Based on this result, the possibility of estimating cereal areas using satellite imagery data can be hypothesized.

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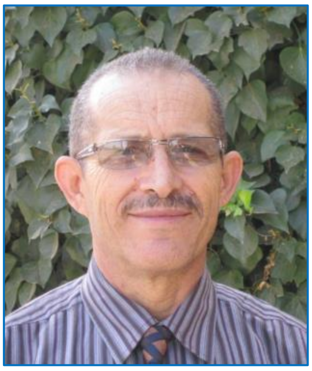
Dr Riad BALAGHI was awarded for his work on climate change, the medal of merit by FAO in 2008. He is associated researcher at the Royal Institute for Strategic Studies and member of the International Society for Agricultural Meteorology and the Moroccan Association of Agro-economy.

Dr Mohammed JLIBENE



Dr Mohammed JLIBENE, holds a degree of Agricultural Engineer from the 'Institut Agronomique et Vétérinaire Hassan II' in 1979, and a Ph.D. in Genetics and Agronomy from the University of Missouri USA, in 1990.

He worked during his entire carrier for the National Institute for Agronomic Research (INRA), starting 1979. He was head of the wheat breeding program at INRA, developed more than twenty cultivars of soft wheat, which are largely adopted by Moroccan famers for their high productivity and resistance to drought and diseases. « Marchouch », « Achtar », « Amal », « Rajae », « Mahdia » et « Arrehane » are examples of highly successful cultivars which are currently largely grown in Morocco, contributing to food security, combating drought and raising farmers revenues, in addition to limiting cereal imports.

Dr. Jlibene, has also developed multidisciplinary research teams, and scientific laboratories, at INRA-Rabat, -Settat and –Meknes, and managed them.

Dr Jlibene was awarded in 2009 the first *Grand Prix Hassan II for invention and research in agriculture*, for his achievements in wheat breeding, specifically wheat cultivars resistant to drought and high temperatures, and resistant to main parasites of wheat (septoriose, rusts, Hessian fly). His interest in agrometeorology and breeding for drought resistance dates back to 1995.

He published more than a hundred publications (journal articles, technical documents, books and book chapters), supervised degree training university students and non-degree trainees from Morocco and abroad, advised farmers in cereal production. Refer to his web-site SAADA https://sites.google.com/site/aridoculture/, for more information.

Dr Bernard TYCHON

Dr Bernard TYCHON, born in 1964, holds diploma of engineer in agronomy (Catholic University of Louvain, 1987) and doctorate of science in Environment Sciences (Luxembourg University Foundation, 1993). He has been assigned a teaching position in the Department of Sciences and Environment Management at Liège University of Belgium.

He provides academic courses in agro-meteorology, data processing and modelling, remote sensing and geographic information system, and diffuse pollution. He trained many students from developing countries for DES, DEA, Master of Science, Complementary Master and Doctorate degrees. He has published over a 100 scientific communications (books, research projects reports, proceedings, national and international scientific revues.

For the last 15 years, he has been leading a team of research in agro-meteorology, studding the relationship between agriculture and physical environment. More precisely, his main research activities are concerned with identifying requirements and needs of crops under different latitudes for water, solar radiation and temperature, in the purpose of forecasting agricultural production levels. Outputs of theses research activities include development of operational tools to forecast yields in many parts of the world (Belgium, Morocco, Ethiopia, Senegal, China,…), and conception of an operational warning system on wheat diseases in Belgium and Luxembourg, and proposition of an integrated management tool of water in agriculture at Burkina Faso. Dr Bernard TYCHON also contributed training in these tools, in Niger, Pakistan, Bangladesh, Turkey, Afghanistan and Armenia via programs of FAO.

He obtained the *Outstanding Young Person Award of the Belgian Junior Economical Chamber* in 2004, and he represents Belgium in European Society of Agronomy since 2004. He is also acting President of College of Sciences Doctorate and Environment Management and co-responsible for Complementary Master of Sciences and Environment Management in developing countries.

Mr Herman EERENS

Mr Herman EERENS holds a Master of Science in Agriculture and Applied Biology, from the University of Leuven (Belgium) in 1980. He worked at the university for nearly 15 years, first in the Department of Forestry and, from 1985, in the field of remote sensing.

His main activities are focused on research areas such as radiometry of crops and soils, modelling the reflectance of crops, and atmospheric correction and classification of images of high spatial resolution. In 2007, he joined the Flemish Institute for Technological Research (VITO, Belgium).

Since then, he has worked mainly on the satellite image processing of low spatial resolution images provided by sensors from SPOT-VEGETATION, NOAA / METOP-AVHRR, MODIS and MSG and on extracting useful information from these images to agricultural statistics.

Mr. Herman EERENS is currently working to provide the information needed for project Monitoring Agricultural ResourceS (MARS) of the European Union as well as for projects in China and Africa. He has developed software programs for processing satellite images such as Glimpse and Spirits in these projects.

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SUMMARY

The present document provides a summary of research work carried out, at National Institute for Agronomic Research of Morocco (INRA), since early 1990s, in the area of operational agrometeorology oriented toward forecasting crop harvests. Forecasting the production of crops early before harvest allows decision makers to be prepared in advance for eventual consequences of abnormal deviations of the climate, particularly for strategic commodity crops to food security like cereals. To our knowledge, to date there is no official method to forecast cereal production in Morocco on the basis of agrometeorological data. However, cereal productions are estimated based on a sampling method some weeks before harvest, every year by the Ministry of Agriculture and Marine Fishery (MAPM) through the Direction of Strategy and Statistics (DSS). It is a direct method, precise, and applied directly before harvest, but requires consequent human and financial resources. The need to elaborate an indirect method to early forecast yields that is fast and economical, has been understood at INRA as early as in 1995, triggered by the severe drought of that particular season, described as the worst dry season of the 20th century in Morocco. Neither the classical frequency analyses of the climate used to identify seasons of close similarity to 1994-1995 season, nor the available mechanistic models for crop forecasting used in developed countries, have been able to monitor crop development during that season and a fortiori predict the catastrophic harvest of 1995. Therefore, it became necessary to come up with a new approach for forecasting cereal yields using an innovative methodology which combines empirical and statistical approaches with agronomic and meteorological expertise. First we had to study the interaction between the climate and the cereal crops behaviors, particularly climatic and crop cycles were analyzed together in a series of long term data, initially for Meknes region where the first two authors were posted, extended later to other regions of Morocco. Preliminary results indicated for the first time in Morocco that inter-annual variation of cereals yields could be explained by variation in the amount of rainfall cumulated during the crop cycle, with a relatively high accuracy. The relationship could be enhanced by partitioning the season into three or more phases. In collaboration with the University of Liège (ULg, Belgium) and later with the Joint Research Centre of the European Commission (JRC), a new indicator was identified as highly correlated to cereal yields, which is the Normalized Difference Vegetation Index (NDVI) derived from satellite images. Unlike many European countries, this index was highly correlated to cereal yields in Morocco, mainly due to the aridity of Moroccan climate and the predominating coverage of cereals of agricultural areas. NDVI is correlated with cereal yields as long as cropping season rainfall did not exceed 550 mm, which explains the irrelevance of NDVI to forecast crop yields in Northern Europe. The combination of both rainfall and NDVI allowed forecasting of cereal yields as early as March, three months before harvest, and at a low cost, with a level of accuracy similar to the one of the direct sampling method used at crop maturity by DSS. These astonishing results have led INRA to publish for the first time in Morocco three crop forecasting bulletins between 2009 and 2011, in collaboration with JRC. In these bulletins, an approach combining four individual approaches was used: (1) similarity approach using rainfall and/or NDVI as criteria of comparison, (2) regression models using rainfall and NDVI as predictors of cereal yields, and (3) the JRC approach which is based on a simulation model of crop growth called WOFOST. The deterministic model WOFOST is now being adapted to the Moroccan agro-climatic context and incorporated in an operational forecasting system. To ensure durability of the system, a strategic partnership between INRA, DSS and DMN was formalized in addition to that bounding INRA and JRC. This new collaboration has allowed establishment of the first national cereal yields forecasting system named “CGMS-MAROC”, based on the combined approach developed in the present document. The system is carried out by the three national institutions (INRA, DSS and DMN), leading to the edition of a fourth bulletin of cereal yields forecasts issued for the 2012 season. The combined approach can be extended to forecast yields for other crops in morocco as well as in countries of similar climatic pattern, provided some adjustments. In parallel to yield forecasting, a new field of research can be explored, dealing with estimating cropped areas, using low resolution and inexpensive satellite images.

Key words: Agrometeorology, yield forecasting, similarity analysis, NDVI, rainfall, temperature, cereals, soft wheat, durum wheat, barley, drought, Morocco, INRA.