CGMS-MAROC: THE DROUGHT EARLY WARNING AND CEREAL YIELD FORECASTING SYSTEM OF MOROCCO

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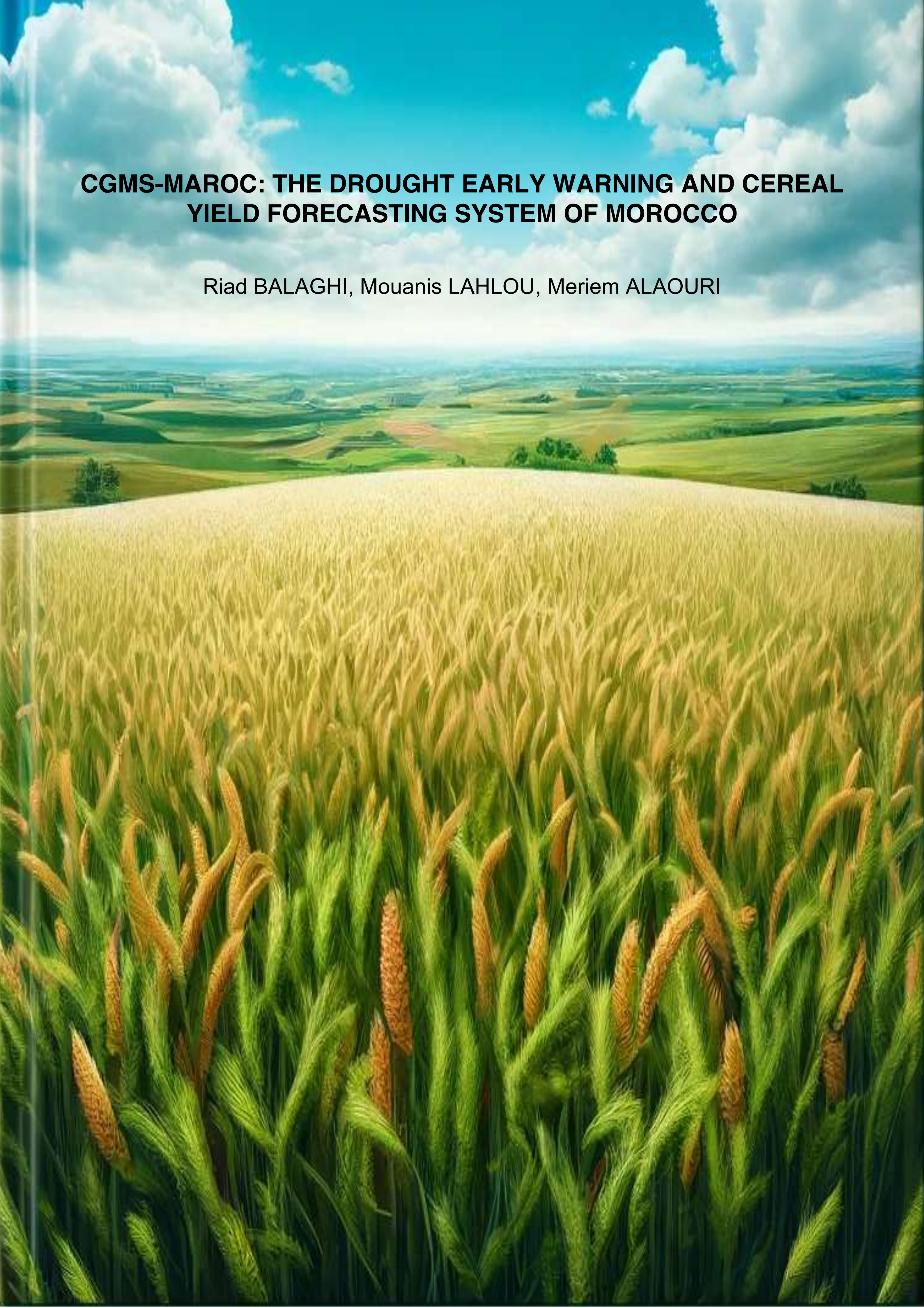

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Content

CGMS-Maroc

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Executive summary

Morocco's rainfed cereal agriculture, a pillar of the country's food security, faces increasing challenges due to the growing scarcity and unpredictability of rainfall resulting from climate change. With wheat and barley yields heavily dependent on climatic conditions, domestic production struggles to meet the needs of an expanding population. To address this issue, Morocco has invested over the past two decades in developing the innovative CGMS-Maroc (Crop Growth Monitoring System), a decision support tool for monitoring agricultural campaigns and forecasting cereal yields.

An integrated system resulting from an exceptional partnership

The CGMS-Maroc platform, born from a strategic collaboration between national institutions (INRA, IAV Hassan II, GDM, Ministry of Agriculture) and renowned international organizations (European JRC, University of Liège, VITO, Alterra, etc.), harnesses state-of-the-art technologies in data collection, agro-climatic modeling, and machine learning. Its modular and integrated architecture is built on three pillars: harmonizing multi-source data, predicting yields using mathematical models, and disseminating results through a user-friendly web interface.

Operational process in three key steps

CGMS-Maroc's primary strength lies in its capability to merge complementary data sources, providing a comprehensive view of crop conditions:

1. **Data integration:** Precise and localized observations from weather stations are combined with meteorological reanalysis data, ensuring accuracy and extensive spatial coverage.
2. **Historical data analysis:** Historical yield series are measured periodically through surveys to establish baselines and trends.
3. **Data harmonization:** An advanced interpolation and quality control process creates a harmonized dataset with optimal spatial and temporal resolution. This enables detailed monitoring of cereal growth at the sub-national level.

This robust information base is then exploited by a diverse range of mathematical models to generate high-precision forecasts of wheat and barley yields for each province. The approach is resolutely integrative, combining complementary techniques to leverage the strengths of each method:

- **Frequency analysis:** Identifies seasons in the historical data that exhibit similar patterns to the current season, providing an initial analogical estimation of yield outcomes.
- **Multiple linear regressions:** Establishes statistical relationships between key agrometeorological variables and cereal yields, quantifying the impacts of different factors on crop productivity.
- **Advanced machine learning:** Advanced AI algorithms, including neural networks and random forests, identify complex, non-linear patterns that may elude traditional models, enhancing predictive accuracy.

By leveraging data analysis from multiple complementary perspectives, CGMS-Maroc generates robust yield forecasts accompanied by a range of estimates derived from the three approaches, providing a measure of uncertainty. This approach allows decision-makers to assess the reliability of the predictions and make informed juGDMents based on the level of confidence associated with each forecast. To support decision-makers in interpreting the results, an intuitive user interface provides critical seasonal parameters through interactive visualization tools, including dynamic maps, graphs, and tables. The system automates the production of monitoring bulletins, facilitating their timely dissemination to decentralized agricultural services. Furthermore, advanced functionalities for retrospective analysis and scenario modeling empower stakeholders to make informed adjustments to crop management strategies, optimizing resource allocation and mitigating potential risks.

Prospects for continuous improvement

Notwithstanding its recognition by the FAO as one of the five preeminent systems globally, CGMS-Maroc remains committed to a dynamic and forward-thinking R&D strategy to maintain its position at the vanguard of the field. In pursuit of this objective, four key priority areas have been identified to guide future enhancements and ensure the system's continued relevance and effectiveness in the face of evolving challenges:

1. **Strengthening the automatic weather station network**, particularly in mountainous and arid regions, to densify the grid of ground observations to a mesh < 10 km.
2. **Developing a dynamic mask of cereal crops**, updated annually through remote sensing, to better isolate their specific signal.
3. **Integrating collaborative agronomic field observations** via a mobile application to enrich the diagnosis through the situated expertise of local actors.
4. **Increasing user involvement in the system's design and evaluation** through a multi-stakeholder steering committee and wider dissemination of products.

Contribution to the resilience of Moroccan agriculture

In the medium term, CGMS-Maroc will advance to the forefront of integrated crop monitoring, setting a new standard in the domain. Its superior spatiotemporal accuracy in cereal monitoring will establish it as a vital tool for ecological intensification tailored to specific terroirs. By providing early, reliable yield forecasts, CGMS-Maroc will enable strategic decision-making in food sovereignty, optimizing inventory and import strategies.

Looking beyond immediate agricultural management, CGMS-Maroc seeks to anchor agronomic intelligence, enhancing the resilience of the Moroccan cereal sector against climate risks challenges. Its localized, long-term data will support the formulation of precise agricultural policies, evaluate program impacts, and stimulate agronomic and varietal innovation.

As a cohesive force in the research-development-advisory continuum, CGMS-Maroc embodies the integration of digital technology and agronomic knowledge. This synergy will shape an efficient, sustainable agricultural system that ensures Morocco’s food security. Leveraging data-driven insights and collaborative approaches, CGMS-Maroc will redefine cereal farming, facilitating informed decision-making and optimizing resource allocation for long-term sector viability.

Acknowledgements

We wish to express our sincere gratitude to the following institutions for their crucial support in the development of CGMS-Maroc:

- The National Institute for Agronomic Research,
- The Hassan II Institute of Agronomy and Veterinary Medicine,
- The Directorate of Strategy and Statistics, at the Ministry of Agriculture, Maritime Fisheries, Rural Development, Water and Forests,
- The General Directorate of Meteorology,
- The Belgian Technical Cooperation,
- The French Development Agency,
- The European Union, through its framework program for research and development,
- The Joint Research Centre of the European Commission,
- The World Bank.

Key abbreviations and acronyms

AJAX	Asynchronous JavaScript and XML
API	Application Programming Interface
AURELHY	Analyse Utilisant le RELief pour l'HYdrométéorologie
CCD	Cold Cloud Duration
CGMS	Crop Growth Monitoring System
CHIRPS	Climate Hazards Group Infrared Precipitation with Stations
CST	CGMS Statistical Toolbox
GDM	General Directorate of Meteorology
DSS	Directorate of Strategy and Statistics
ERA5	ECMWF ReAnalysis
ESA	European Space Agency
ET0	Reference Evapotranspiration
EVI	Enhanced Vegetation Index
FAO	Food and Agriculture Organization of the United Nations
FEWS NET	Famine Early Warning Systems Network
GDAL	Geospatial Data Abstraction Library
IDW	Inverse Distance Weighting interpolation method
IAV	Hassan II Agronomic and Veterinary Institute
INRA	National Institute for Agronomic Research
JSON	JavaScript Object Notation
LAI	Leaf Area Index
MARS	Monitoring Agricultural Resources System
MLR	Multiple Linear Regression
MODIS	Moderate Resolution Imaging Spectroradiometer
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration (agence océanique et atmosphérique américaine)
OGC	Open Geospatial Consortium
PCA	Principal Component Analysis
PostGIS	PostgreSQL extension for spatial data storage and processing.
REST	Representational State Transfer
RFE	Rainfall Estimation (estimation des précipitations)
RMSE	Root Mean Square Error
SWI	Soil Water Index
TRMM	Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis
WMO	World Meteorological Organization
WOFOST	WOrld FOod STudies

Definitions and technical terms

Analyse Utilisant le RELief pour l'HYdrométéorologie (AURELHY): A specialized spatial interpolation technique that incorporates the impact of terrain features to enhance the accuracy of meteorological data analysis.

Application Programming Interface (API): A set of predefined methods and protocols that enable different software systems to communicate, facilitating data exchange and functionality sharing between applications.

Asynchronous JavaScript and XML: A group of web development techniques used to create asynchronous web applications that can send and retrieve data from a server asynchronously without interfering with the display and behavior of the existing page.

Crop mask: An overlay used in remote sensing that identifies the geographic locations of specific agricultural crops within satellite or aerial imagery, enhancing accuracy in agricultural monitoring.

Cross-validation: A robust statistical technique used to assess how the results of a predictive model will generalize to an independent data set. It involves partitioning a sample of data into complementary subsets, performing the analysis on one subset, and validating the analysis on the other subset.

Framework: An essential structure comprising a set of software components designed to support the development of applications, providing a foundation on which software developers can build programs for specific platform.

Geospatial Data Abstraction Library: A translator library for raster and vector geospatial data formats that provides an abstract data model to the calling application for comprehensive data handling.

Interactive visualization: The process of creating visual representations of data that users can manipulate and explore dynamically, enhancing the engagement and understanding of complex data sets.

JavaScript Object Notation (JSON): A lightweight data-interchange format that is easy for humans to read and write, and easy for machines to parse and generate, commonly used in web applications for data transmission.

Kriging: A sophisticated geostatistical technique that predicts the value of a variable at unmeasured locations by using a linear combination of known values, taking into account the spatial correlation.

Machine learning: A branch of artificial intelligence that empowers computers to learn from and make decisions based on data, without being explicitly programmed for each task. This field utilizes statistical models to predict outcomes.

Multiple linear regressions: A statistical method that models the linear relationship between a dependent variable and multiple independent variables, allowing for the analysis of complex relationships between multiple factors.

Multi-source data: This term describes the practice of integrating diverse datasets from various origins, such as meteorological stations, satellite imagery, and field surveys, to enrich data analysis.

Neural networks: Advanced algorithms modeled loosely after the human brain that are designed to recognize patterns and interpret sensory data through machine perception, labeling, and clustering.

Open Geospatial Consortium (OGC): An international consortium that develops publicly available geospatial standards, promoting global interoperability and enhancing the utility of geospatial data.

Pixel: Pixel is the smallest discrete element of an image, capturing quantitative measurement of electromagnetic radiation from specific ground location. In remote sensing, these values are crucial for analyzing and interpreting spatial features and phenomena associated with each pixel's geographic area.

Random Forests: A robust machine learning method that constructs several decision trees during training and outputs the mode of the classes (for classification) or mean prediction (for regression) of the individual trees, enhancing predictive accuracy and control over-fitting.

Real-time: Refers to the processing of data and delivery of results simultaneously or within a very short time after data acquisition, enabling immediate insights and actions.

Remote sensing: The science of acquiring information about the Earth's surface without making physical contact, typically using aerial sensor technologies.

Representational State Transfer (REST): A software architectural style that defines a set of constraints for creating Web services that are performant, scalable, and easy to modify.

Shapefile: A geospatial vector data format used in GIS software to store the location, shape, and attributes of geographic features like points, lines, and polygons. It consists of several files, including a .shp file for geometry, a .shx index file, and a .dbf file for attribute data.

Spatial interpolation: A method used to estimate the value of properties at unsampled locations within the area covered by existing data points, based on the spatial correlation among measured values.

Spatial resolution: Describes the detail with which a map or data set quantifies phenomena or records locations, influencing how fine or coarse the viewed information is.

Vegetation Index: An analytical metric derived from remote sensing measurements that indicates the relative density and health of vegetation by comparing different spectral bands, such as the Normalized Difference Vegetation Index (NDVI).

I. Pioneering climate risk management in Moroccan agriculture

In Morocco, managing climate risks is of paramount importance, primarily due to the semi-arid climate that poses significant challenges for agriculture, particularly cereal farming. During the period from 2001 to 2017, the country experienced average annual rainfall of approximately 341 mm per agricultural season (from September to May of the following calendar year). However, these precipitation levels vary considerably from year to year, ranging from 198 mm in 1994-1995 to 610 mm in 2009-2010 (Balaghi et al., 2012a). The main cereal crops in Morocco, including durum wheat, soft wheat, and barley, cover roughly 4.96 million hectares, accounting for 55% of the total agricultural land. Among these crops, rainfed cereals represent 91% of the area and contribute 81% of the total cereal production, with an almost equal distribution between bread wheat (36%) and barley (38%).

Despite its economic importance, cereal farming in Morocco exhibits relatively low yields compared to other regions with similar climates. The reasons for this situation include, among others, limited technology transfer, insufficient capacity building, limited access to climate information, inadequate use of fertilizers, and limited insured areas. For the period from 2001 to 2017, the average yields of rainfed cereals were 1.31, 1.41, and 0.96 tons per hectare for durum wheat, soft wheat, and barley, respectively (Data source: DSS). These figures have a significant impact on Morocco's food security, which is closely linked to cereal production and vulnerable to variations in rainfall at the national level (Balaghi et al., 2012a).

Over the past few decades, Morocco has experienced a considerable increase in the frequency of dry agricultural seasons, rising from one dry season per 15 normal seasons in the 1930s to 1970s to one dry season out of every three in the last two decades (Figure 1). These droughts have had a significant impact on the country's economy and agriculture, highlighting the crucial need for effective climate risk management, a major priority of Moroccan agricultural policy since the 1980s. This priority is reflected in the latest strategies for the agricultural sector, namely the "Green Morocco Plan" (2008-2020) and the current "Green Generation" strategy (2020-2030), which incorporate strategic orientations to control climate risks through the development of effective risk management tools and adaptation programs to mitigate the impacts of climate change.

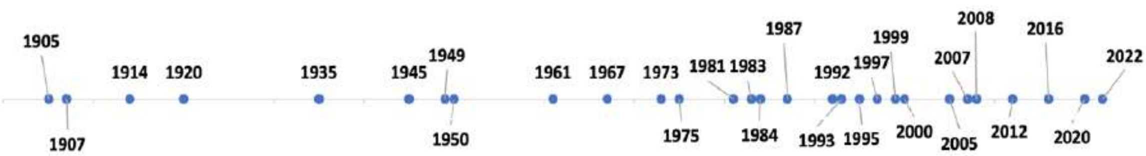

Figure 1 : Drought frequency in Morocco (Balaghi, unpublished).

To address this challenge, the country has invested over the past two decades in the development of the groundbreaking CGMS-Maroc (Crop Growth Monitoring System), an advanced decision support tool designed to monitor agricultural campaigns and forecast cereal yields with high precision.

An integrated system forged through an exceptional partnership

The establishment of the scientific foundations of the CGMS-Maroc (Crop Growth Monitoring System) began in the early 2000s at the National Institute for Agronomic Research (INRA) (Balaghi et al., 2007; Balaghi et al., 2008; Narciso and Balaghi, 2009; Balaghi et al., 2010; El Aydam et al., 2010; El Aydam and Balaghi, 2011; Balaghi et al., 2012a; Balaghi et al., 2012b). However, its true technological development took off in 2011 with the European project E-AGRI[1]. This evolution was made possible through technological collaboration with international research institutions, including the Flemish Institute for Research and Technology (VITO), the Joint Research Centre (JRC) of the European Commission, the Research Institute of Wageningen University (Alterra), and the University of Milan (UNIMI) (Confalonieri et al., 2013; De Wit et al., 2013; Balaghi et al., 2014; Bregaglio et al., 2015). This development continued in 2014 within the framework of the ACCAGRIMAG[2] project, funded by the French Global Environment Facility, and was further enriched by numerous research studies conducted in Morocco (Jarlan et al., 2013; Benabdelouahab et al., 2016; Meroni et al., 2016; Bouras et al., 2020; Bouras et al., 2021; Mamassi et al., 2023).

Inspired by the European Crop Growth Monitoring System (CGMS) of the European Commission (Boogaard et al., 1998; Supit et al., 1994; Van Diepen et al., 1989; Micale and Genovese, 2004; Lazar and Genovese, 2004; Genovese and Bettio, 2004, Baruth et al., 2007), CGMS-Maroc was independently developed through fruitful collaborations between INRA, the General Directorate of Meteorology (GDM), the Ministry of Agriculture (Directorate of Strategy and Statistics), and the Agronomic and Veterinary Institute (IAV) Hassan II of Morocco. The FAO (FAO, 2016) ranked CGMS-Maroc as one of the five best crop monitoring and forecasting systems worldwide, alongside those of the United States, China, Belgium, and South Africa.

Operational for nearly two decades under different versions, CGMS-Maroc has proven to be an invaluable tool for informing decisions in the agricultural sector, thanks to its ability to provide real-time agrometeorological forecasting and monitoring. It relies on a unified platform designed to meet the specific needs of Moroccan agriculture. It utilizes a crop mask to filter data from satellite images and employs innovative machine learning techniques, including artificial intelligence, for predictive yield modeling. Data from ground weather stations and from meteorological reanalyzes are integrated with various satellite data, adopting an integrated approach. Furthermore, CGMS-Maroc plays a crucial role in capacity building by training a new generation of Moroccan agro-meteorologists.

The development of CGMS-Maroc has been based on international best practices, covering several aspects such as the integration of multiple data sources, advanced use of remote sensing, involvement of skilled analysts, continuous system evaluation, close collaboration between institutes, data quality assurance, active engagement of end-users, as well as adaptive management and thorough assessment of climate risks.

[1] https://www.e-agri.info/

[2] https://www.ffem.fr/fr/carte-des-projets/accagrimag-adaptation-au-changement-climatique-de-lagriculture-du-maghreb

Operational process in 3 key steps

CGMS-Maroc's primary strength lies in its capability to merge complementary data sources, providing a comprehensive view of crop conditions:

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By examining data from these diverse perspectives, CGMS-Maroc delivers robust yield forecasts, supported by a dynamically updating confidence interval that increases in precision as the cropping season advances.

To ensure decision-makers can effectively utilize these insights, CGMS-Maroc features an intuitive user interface with interactive visualization tools like dynamic maps, comparative graphs, and tables. The automated generation and distribution of monitoring bulletins keep decentralized agricultural services regularly informed about crop conditions and yield projections. Additionally, advanced retrospective analysis and scenario-building capabilities allow users to assess the potential impacts of various tactical crop management strategies, empowering them to make informed adjustments in response to changing conditions.

Continuous improvement perspectives

Despite its recognition by the FAO as one of the five best systems worldwide, CGMS-Maroc maintains a proactive R&D approach to remain at the vanguard of the field. Four priority areas for future development have been identified to further enhance the system's capabilities and ensure its continued relevance in the face of evolving challenges:

1. **Strengthening the network of automatic weather stations:** Efforts will be focused on expanding and densifying the network of automatic weather stations, particularly in mountainous and arid regions, to improve the resolution of the ground observation grid to a sub-10 km scale. This will provide a more granular and precise understanding of local climatic conditions, enabling the system to generate even more accurate and localized insights.
2. **Developing a dynamic crop mask for cereals:** A dynamic crop mask for cereals will be developed and updated annually using advanced remote sensing techniques. This will

allow the system to better isolate and analyze the specific signals and patterns associated with cereal crops, enhancing its ability to monitor and predict their growth and yield with greater precision.

3. **Integrating collaborative agronomic field observations via a mobile App:** To harness the power of crowdsourcing and local knowledge, a mobile application will be developed to enable collaborative agronomic field observations. This will allow farmers, extension agents, and other stakeholders to contribute real-time, on-the-ground observations and insights, enriching the system's diagnostic capabilities with localized expertise and enhancing its ability to provide context-specific recommendations.
4. **Increasing user involvement in system design and evaluation:** To ensure that CGMS-Maroc continues to meet the evolving needs and expectations of its users, efforts will be made to increase user involvement in the system's design and evaluation processes. This will be achieved through the establishment of a multi-stakeholder steering committee, which will provide guidance and feedback on the system's development and performance, as well as through the broader dissemination of the system's outputs to a wider range of stakeholders.

Contributing to the resilience of Moroccan agriculture

In the medium term, these advancements will position CGMS-Maroc alongside the leading integrated agronomic platforms. The system's precise spatiotemporal resolution in cereal monitoring will transform it into an essential tool for fostering ecological intensification, customized to the unique characteristics of each terroir. Its timely and accurate yield forecasts will guide critical decisions impacting food sovereignty, including stock management and import strategies.

Beyond mere agricultural management, CGMS-Maroc is poised to become the cornerstone of agronomic intelligence, fortifying the Moroccan cereal sector against climate-related challenges. Its localized, extensive data will be invaluable for developing bespoke agricultural policies, evaluating the effectiveness of development and incentive programs, and driving varietal and agronomic innovation.

As a cohesive force across the research-development-advisory spectrum, CGMS-Maroc exemplifies the synergy between digital innovation and agricultural expertise. This integration is crucial for fostering an efficient and sustainable agricultural sector that safeguards Morocco's food security.

Document objectives and plan

This document aims to present a detailed overview of the CGMS-Maroc system, which has emerged as a pioneering tool for managing climate risks in Moroccan agriculture. It will provide an in-depth description of the system's architecture, technological components, and operations. Special attention will be given to its capabilities in integrating heterogeneous data and in predictive modeling of cereal yields through artificial intelligence.

Building on this introduction, the document will then outline an ambitious roadmap to elevate CGMS-Maroc to the highest international standards. The recommendations will focus on priority improvement areas to enhance the already high performance of the system.

The goal is to promote widespread adoption of CGMS-Maroc by all stakeholders in the agricultural sector, establishing it as an innovative digital solution to address the increasing climate-related risks to the country's food security. This strategic roadmap will aim to position CGMS-Maroc as a global benchmark in advanced crop monitoring, while also opening exciting opportunities for its continual refinement in support of sustainable and resilient Moroccan agriculture.

II. Functional architecture of CGMS-Maroc: From data collection to yield forecasting

Having established the context and objectives of CGMS-Maroc, this chapter delves into the system's functional architecture, which forms the core of its advanced yield forecasting capabilities. The chapter provides an in-depth exploration of the two main blocks that constitute CGMS-Maroc, focusing on the intricate processes of data collection, processing, and analysis that enable accurate and timely yield predictions.

CGMS-Maroc's effectiveness lies in its ability to seamlessly integrate and leverage diverse data sources, creating a comprehensive picture of Morocco's agricultural landscape. By harnessing meteorological data, satellite imagery, and ground-based observations, CGMS-Maroc constructs a robust foundation for monitoring agricultural campaigns and anticipating cereal yields with unprecedented precision.

To ensure clarity, the key processes described in this chapter are presented in a structured manner, mirroring the numbering order depicted in Figure 2 (Synoptic diagram of the functioning of CGMS-Maroc). This approach allows readers to easily navigate between the textual descriptions and the schematic overview, fostering a deeper understanding of the system's functional components and their interrelationships.

CGMS-Maroc employs a two-block approach to predict cereal yields at the provincial level, integrating various data sources and processing techniques:

1. **Block 1 - Meteorological data collection and processing:**
   - **1.1.** ERA5 meteorological reanalysis data is collected, providing a consistent and continuous record of atmospheric variables.
   - **1.2.** The ERA5 data is extracted for the geographical area of interest, specifically within the country boundaries of Morocco.
   - **1.3.** The extracted ERA5 data is then formatted to match the spatial resolution and structure of the CGMS-Maroc reference grid.
   - **1.4.** The formatted ERA5 data undergoes spatial interpolation to estimate meteorological variables at each cell of the reference grid, ensuring a high-resolution representation of the atmospheric conditions across the country.
   - **1.5.** In parallel to the ERA5 data collection, meteorological observation data is gathered from ground-based synoptic stations, providing accurate measurements of key variables such as temperature, precipitation, and calculated evapotranspiration.
   - **1.6.** The meteorological data from synoptic stations is interpolated to the reference grid, allowing for a direct comparison and integration with the interpolated ERA5 data.
   - **1.7.** The interpolated ERA5 data is then corrected using the interpolated meteorological observation data from synoptic stations. This correction step is crucial for reducing potential biases and errors in the reanalysis data, ensuring a more accurate representation of the actual atmospheric conditions.

2. **Block 2 - Data integration, analysis, and yield forecasting:**
   - **2.1.** Vegetation indices, such as NDVI and LAI, and soil water indices, like SWI, are collected from satellite data. These indices provide valuable information about crop health, growth, and moisture conditions.
   - **2.2.** The collected vegetation and soil water indices are harmonized and formatted to align with the spatial resolution and structure of the CGMS-Maroc reference grid, enabling seamless integration with other data sources.

2.3. A cereal crop mask is developed using remote sensing techniques and ancillary data. This mask identifies the specific areas where cereal crops are cultivated within each administrative province, allowing for targeted analysis and yield forecasting.
2.4. Cereal statistical data, including historical yield records and crop-specific information, is collected at the provincial level. This data serves as a reference for model calibration and validation.
2.5. Cereal yield forecasting models are developed using multiple approaches, such as regression analysis and machine learning algorithms. These models integrate the interpolated and corrected ERA5 data, interpolated evapotranspiration data calculated from ground synoptic stations, vegetation and soil water indices, and cereal statistics. By considering various agro-climatic factors and their interactions, the models can capture the complex relationships between environmental conditions and crop yields.
2.6. The developed yield models are applied to forecast cereal yields at the provincial level. The models consider the specific agro-climatic conditions, crop characteristics, and historical yield patterns of each province, providing localized and context-specific yield predictions.
2.7. The collected data, processed information, and yield forecasts are visualized through a user-friendly interface. This interface allows stakeholders, such as agricultural decision-makers and agricultural advisors to access and interpret the results easily, facilitating informed decision-making and risk management strategies.

CGMS-Maroc's integrated functional architecture enables the system to generate accurate and reliable yield predictions at the provincial level by leveraging a diverse set of inputs from both Block 1 and Block 2. The system's ability to seamlessly integrate and process heterogeneous data sources positions it as a powerful decision support tool for managing the Moroccan cereal season and guiding agricultural policies.

a. Data Integration:

CGMS-Maroc combines data from various sources to create a comprehensive dataset for yield prediction.

From Block 1, it utilizes:

- Potential evapotranspiration data interpolated from synoptic station observations (1.6)
- Key meteorological variables, including rainfall and maximum and minimum temperatures, derived from interpolated and corrected ERA5 data (1.7)

From Block 2, it utilizes:

- NDVI (Normalized Difference Vegetation Index)
- LAI (Leaf Area Index)
- SWI (Soil Water Index)

These indices provide valuable insights into crop health, vegetation growth, and soil moisture conditions.

Additionally, CGMS-Maroc incorporates historical cereal yield statistical data at the provincial level (2.4) to developed yield models.

b. Cereal mask development:

A crucial component of CGMS-Maroc is the development of a cereal mask (2.3) through the classification of high-resolution satellite images. This mask enables the spatial filtering of meteorological data and vegetation indices, retaining only the relevant information for crop areas. By focusing on cereal-specific areas, the system can generate more precise and targeted yield predictions.

c. Yield forecasting modeling:

CGMS-Maroc employs various forecasting techniques (2.5) to predict cereal yields, including:

- Similarity analysis
- Multiple linear regressions
- Machine learning algorithms

The yield predictive variables are derived from the variables in Block 1 and Block 2 and are extracted for each of the five periods of the cereal cycle (P0 to P5, see Table 6). These periods are detected by analyzing EVI2 (Enhanced Vegetation Index 2) data, which provides information on the crop growth stages.

CGMS-Maroc can capture the complex interactions between meteorological factors, vegetation dynamics, and soil moisture variability by leveraging this comprehensive set of inputs and advanced modeling techniques. This enables the system to generate robust and spatially explicit yield predictions for each province in Morocco.

d. User interface and visualization:

The CGMS-Maroc web user interface (2.7) plays a vital role in disseminating the yield prediction results and facilitating decision-making. It provides visualization of all the parameters for monitoring the agricultural season, sourced from both Block 1 and Block 2, as well as the yield predictions themselves.

The interface offers interactive tools for analyzing and visualizing the results in the form of maps, graphs, tables, and dashboards. These tools allow users to explore the data, assess crop conditions, and evaluate yield forecasts at various spatial and temporal scales. By presenting the information in an easily interpretable format, CGMS-Maroc enables stakeholders to make informed decisions and take appropriate actions.

Through this integrated functional architecture, CGMS-Maroc combines the strengths of diverse data sources, advanced modeling techniques, and user-friendly visualization to provide a comprehensive decision support system for managing the cropping season. By accurately predicting yields at the provincial level and delivering actionable insights, CGMS-Maroc contributes to the development of effective agricultural policies and helps anticipate the country's food security needs.

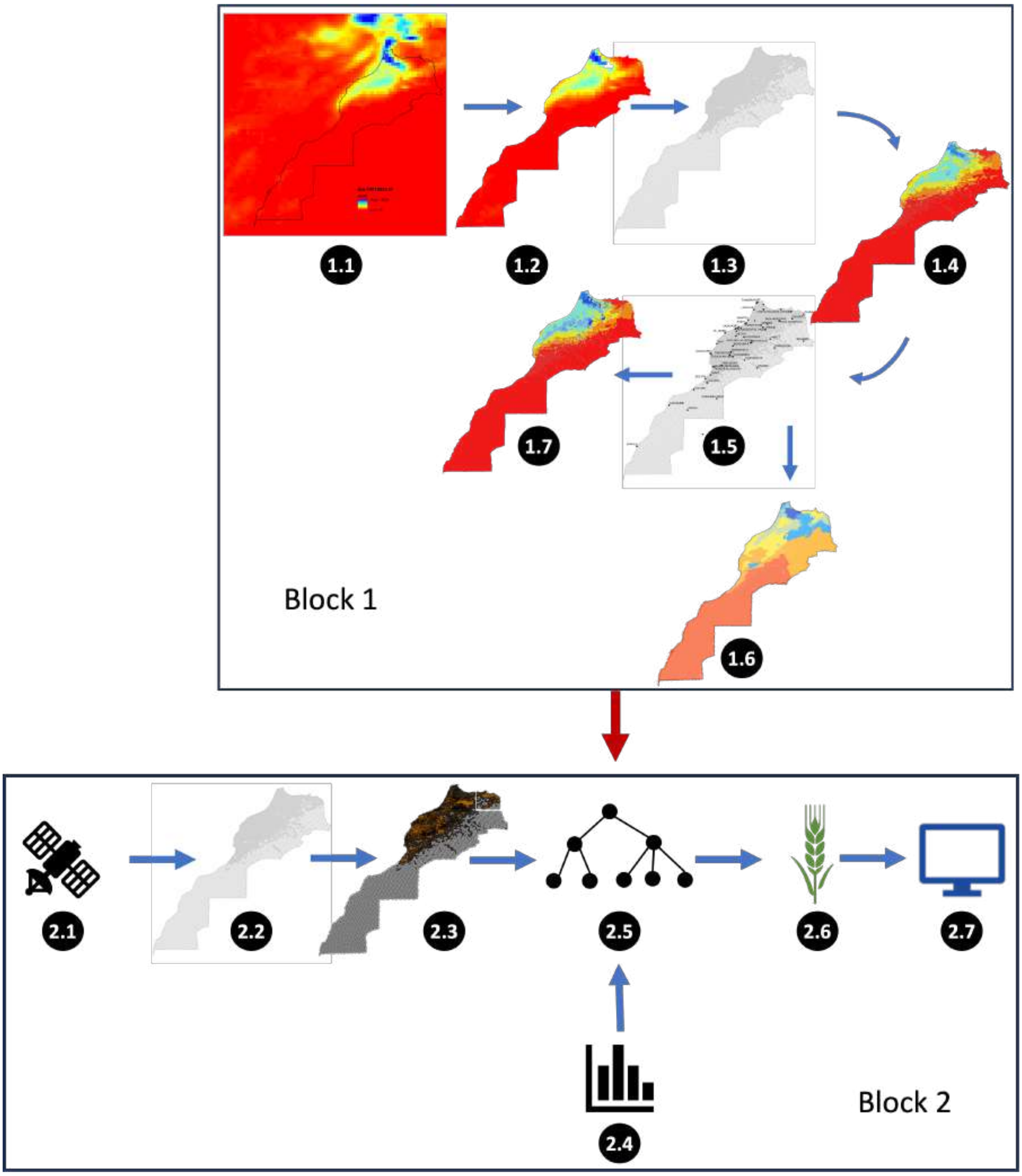

Figure 2 : Synoptic diagram of the functioning of CGMS-Maroc.

1. Block 1: Meteorological data collection and processing

Block 1 of CGMS-Maroc constitutes an essential component in the overall functioning of the system, ensuring the collection, processing, and integration of meteorological data necessary for monitoring agro-climatic conditions and forecasting cereal yields in Morocco. This block, hosted within the GDM's infrastructure, is the pillar of the climate data processing chain.

Block 1 relies on two main data sources: observations from GDM's ground meteorological stations and ERA5 (ECMWF ReAnalysis 5th generation[3]) meteorological reanalyzes produced by the

[3] ERA5 data is available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels

European Centre for Medium-Range Weather Forecasts (ECMWF). The combination of these two sources allows for complete spatial coverage and a detailed characterization of meteorological conditions throughout the Moroccan territory.

Although observations from synoptic stations are accurate, they suffer from limited and uneven spatial coverage. To overcome this limitation, Block 1 integrates ERA5 reanalysis data, which provide a consistent and spatially continuous estimation of key meteorological variables (precipitation, temperatures) since 1981, with a spatial resolution of approximately 31 km.

One of the major challenges of Block 1 is to harmonize these two data sources and make them compatible with the CGMS-Maroc reference grid, which serves as a common foundation for all spatial analyses. This involves pre-processing, interpolation, and bias correction steps to optimally exploit the complementarity between in situ observations and reanalyzes.

The final product of Block 1 is a set of high-resolution spatialized daily meteorological data covering the entire Moroccan territory from 1981 to the present. These data constitute a crucial input for Block 2 of CGMS-Maroc, enabling the monitoring of the agricultural season and the estimation of cereal yields.

Beyond the mere provision of data, Block 1 incorporates continuous evaluation and validation processes to ensure the quality and reliability of the meteorological information used. Comparative analyses between corrected ERA5 data and station observations are regularly conducted to quantify contributions and identify areas for improvement.

This section II.1 offers a technical immersion into the workings of Block 1 of CGMS-Maroc, detailing the different stages of the processing chain, from the collection of raw data to the generation of final products integrated into the system. Particular attention will be given to spatial interpolation methods, bias correction techniques, and data evaluation and validation protocols.

This in-depth description of Block 1 will highlight its central role in the architecture of CGMS-Maroc and its decisive contribution to the quality and relevance of the information provided for monitoring and forecasting cereal yields in Morocco.

1.1. Collection of ERA5 meteorological reanalysis data

Block 1 of CGMS-Maroc integrates daily ERA5 meteorological reanalysis data, with a historical record starting from January 1, 1981. The ERA5 dataset is produced by the ECMWF and represents the state-of-the-art in climate reanalysis, offering a global, consistent, and high-resolution dataset.

Indeed, several recent studies have demonstrated the utility of meteorological reanalysis products for estimating precipitation in Morocco, despite certain biases that need to be corrected (Beck et al., 2017; Benkirane et al., 2023; Hanchane et al., 2023; Najmi et al., 2023; Tuel et al., 2023). For instance, Salih et al. (2022) showed the strong performance of the PERSIANN, CDR, and ERA5 satellite products in estimating annual precipitation in the Tensift basin of Morocco, particularly at low altitudes and during wet years. These satellite products proved to be in close agreement with ground observations from meteorological stations.

ERA5 reanalyzes are the result of a complex assimilation of meteorological observations from a multitude of sources, such as satellites, ground stations, ocean buoys, and airborne measurements. These observations are optimally combined with advanced climate models through a technique called "four-dimensional variational data assimilation" (4D-Var). This approach allows for the reconstruction of past meteorological conditions in a coherent and physically realistic manner, leveraging all available information.

The distinctive feature of ERA5 lies in its ability to provide a complete and homogeneous picture of the atmosphere, land surfaces, and oceans, continuously since 1979. The data are available at a spatial resolution of approximately 31 km (0.28125° horizontal resolution) and cover the entire globe with an hourly frequency. As an example, Figure 3 presents the precipitation map for January 19, 2024.

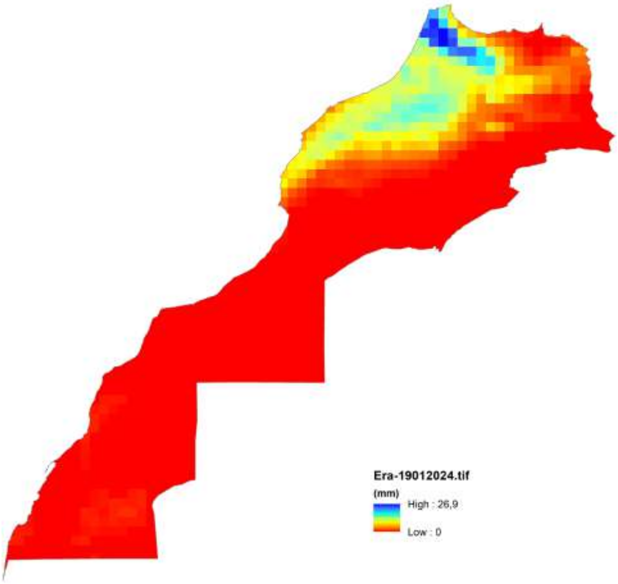

Figure 3 : ERA5 Meteorological reanalysis of precipitation for January 19, 2024.

Among the numerous variables available in ERA5, CGMS-Maroc focuses on two key parameters for agrometeorological monitoring: precipitation and temperatures (maximum and minimum). Precipitation is estimated by analyzing atmospheric moisture fields and the condensation and convection processes in the model. Temperatures, on the other hand, are obtained by combining surface observations with vertical temperature profiles derived from the atmospheric model.

The raw ERA5 data are collected in Block 1 of CGMS-Maroc directly from the ECMWF servers via the Copernicus Climate Data Store (CDS) application programming interface (API). This automated collection step allows for the regular retrieval of the latest reanalysis updates and the maintenance of an up-to-date climate database within the system.

The ERA5 data cover three parameters:

- **Maximum temperature at 2 meters since last post processing:** The maximum air temperature measured at 2 meters above the surface of the land, sea, or inland waters since the parameter was last archived in a particular forecast.
- **Minimum temperature at 2 meters since last post processing:** The minimum air temperature measured at 2 meters above the surface of the land, sea, or inland waters since the parameter was last archived in a particular forecast. The temperature measured at 2 meters is calculated by interpolating between the lowest model level and the Earth's surface, considering the atmospheric conditions. This parameter is expressed in Kelvin (K).
- **Total precipitation:** This parameter represents the accumulated liquid and frozen water, including rain and snow, that falls to the Earth's surface. It is the sum of large-scale precipitation and convective precipitation. Large-scale precipitation is generated by the cloud scheme in the ECMWF's Integrated Forecasting System (IFS)[4]. The cloud scheme represents the formation and dissipation of large-scale clouds and precipitation due to changes in atmospheric quantities (such as pressure, temperature, and humidity) directly

[4] https://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model

predicted by the IFS at spatial scales the size of the grid mesh or larger. Convective precipitation is generated by the convection scheme in the IFS, which represents convection at spatial scales smaller than the grid mesh. This parameter does not include fog, dew, or precipitation that evaporates in the atmosphere before reaching the Earth's surface. This parameter is accumulated over a particular time period that depends on the extracted data. For the reanalysis, the accumulation period is one hour ending at the valid date and time.

1.2. Extraction of the geographic area of Interest

After acquiring the raw ERA5 data on a global scale, the next crucial step involves extracting the relevant information specific to the geographic area of interest, which in this case is the Moroccan territory. This targeted extraction process serves two key purposes: it significantly reduces the volume of data that needs to be processed, and it allows for a more focused analysis of the region under study.

The extraction process relies on the precise geographic boundaries of Morocco, defined by its land and maritime borders. In the case of CGMS-Maroc, these boundaries are represented in the form of a shapefile, a commonly used format for storing vector geographic data. The shapefile contains the coordinates of Morocco's borders in a given geographic reference system, such as WGS84 (World Geodetic System 1984).

During the extraction phase, attention is given to maintaining the spatial consistency and integrity of the data. Quality control measures are implemented to verify that the selected ERA5 grid points provide a comprehensive and seamless coverage of the entire Moroccan territory, as defined by the boundary shapefile. It is also important to ensure compatibility between the geographic reference systems used by the ERA5 data and the shapefile to avoid any spatial discrepancies or misalignments.

The use of a shapefile to represent the geographic boundaries of Morocco offers high precision and flexibility in the process of extracting ERA5 data. It allows for easy adaptation to potential changes in borders or specific needs in terms of the study area.

1.3. The reference grid

The reference grid is a fundamental element of the CGMS-Maroc system, providing a harmonized spatial framework for the integration of multi-source data. It serves as a common basis for the storage, processing, and display of meteorological (ERA5) and satellite (NDVI, LAI, SWI) information.

In the early stages of CGMS-Maroc's development, the grid was composed of uniform square cells with sides measuring 9 km (Allard et al., 2014). However, to better cater to the specific requirements of agricultural monitoring, the current grid configuration has undergone optimization. It now features cells of varying sizes, with a resolution of 4.5 km in agricultural areas and 9 km in other regions of the country (Figure 4). This adaptation enables more refined precision in the analyses of key agricultural zones while optimizing the system's computational efficiency and storage capacity.

Particular attention has been given to the selection of spatial resolution in agricultural areas. The aim was to strike a delicate balance between the need to capture the local variability of agrometeorological conditions and the constraints imposed by the processing capabilities of the CGMS-Maroc server. The 4.5 km cell size has emerged as an optimal compromise, ensuring reliable interpolation of ERA5 data (detailed in the following section) while maintaining feasible computation times.

The CGMS-Maroc reference grid encompasses a total of 16,819 cells, providing comprehensive coverage of the entire Moroccan territory. Each cell serves as an elementary unit for data management and analysis. This structured approach guarantees spatial consistency among the diverse information sources integrated into the system, facilitating their seamless fusion and joint exploitation.

A major advantage of the reference grid lies in its ability to serve as a support for the spatial aggregation of data at various administrative scales. The information contained within each cell can be aggregated to generate indicators at the commune, provincial, or national level. This flexibility is essential for adapting the analyses to the needs of different users and decision-makers.

Each cell within the grid is characterized by a set of attributes, including meteorological data (precipitation, temperatures) and satellite-derived indices (vegetation indices, soil moisture). Furthermore, the integration of an agricultural mask allows each cell to be defined by the proportion of cultivated land it contains. This information is critical for refining analyses by focusing on critical agricultural production areas.

Daily meteorological data from ground stations are interpolated onto the reference grid, considering various factors such as distance to stations, altitude, climatic barriers, proximity to the sea, and climatic similarities between sites (Figure 5). This interpolation allows for the estimation of meteorological parameter values for each cell, including in areas devoid of stations, thus ensuring complete spatial coverage.

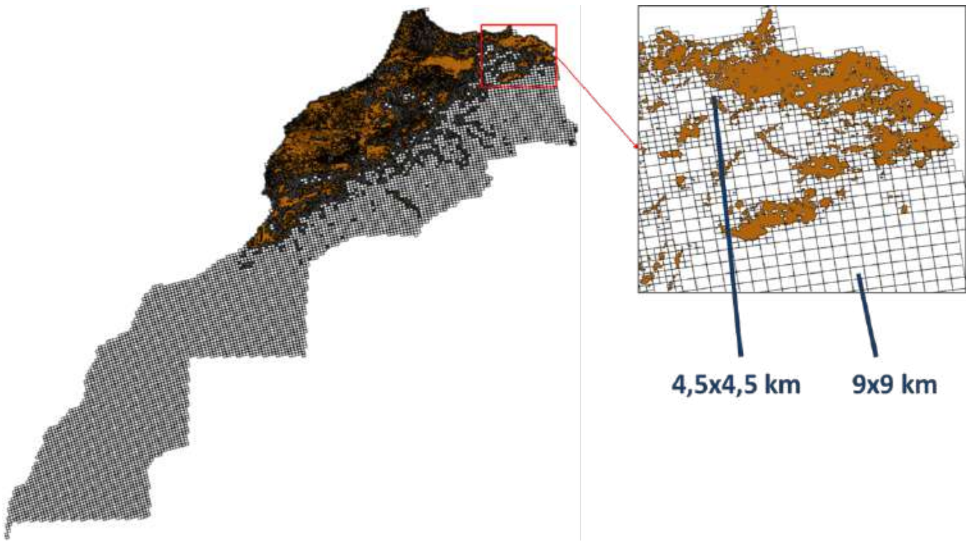

Figure 4: The CGMS-Maroc reference grid (agricultural lands are indicated in brown) (Balaghi et al., 2014).

1.4. Spatial interpolation of ERA5 data

The objective of interpolation is to generate spatially continuous, high-resolution daily meteorological fields from ERA5 data, enabling the monitoring of the agricultural campaign at any point within the Moroccan territory. To achieve this interpolation, the CGMS-Maroc system implements a geostatistical technique adapted to the specificities of reanalysis data.

ERA5 data is provided in the form of pixels organized in a regular grid covering the entire globe. Each pixel represents an area of approximately 31 km by 31 km and contains the values of various meteorological variables (precipitation, temperatures, etc.). However, this native spatial resolution is insufficient to capture the local variability of agrometeorological conditions. The interpolation aims to refine this resolution on the reference grid, reaching a cell size of 4.5 km in agricultural areas of interest and 9 km elsewhere.

The interpolation approach adopted for ERA5 data in CGMS-Maroc was originally implemented in 2011 as part of the E-AGRI project, designed to interpolate data from the 44 synoptic stations of the GDM. The method combines an Inverse Distance Weighting (IDW) technique, inspired by the seminal works of Beek et al. (1991) and van der Voet et al. (1994), with a thoughtful consideration of the effects of relief, climatic barriers, and distance from the sea.

The ERA5 data interpolation process unfolds in two main stages:

- First, for each cell of the CGMS-Maroc reference grid, the surrounding ERA5 pixels within a specified radius (typically 100 km) are identified. Each ERA5 pixel is assigned a weight based on its distance to the center of the target cell, adhering to the IDW principle. The closer a pixel is to the target cell, the higher its weight in the interpolation.
- Second, the value of the meteorological variable to be interpolated (e.g., precipitation or temperatures) is estimated at the center of each grid cell by calculating a weighted average of the values from the selected ERA5 pixels. To account for the effect of altitude, a correction is applied using a vertical gradient specific to each variable (for example, -0.65°C/100m for temperature).

To guide the interpolation algorithm and enhance the consideration of relief, several geographic information layers are used (Figure 5):

- A Digital Elevation Model (DEM) derived from GTOPO30[5] data at 30 arc-seconds resolution (~1 km) is used to characterize the altitude of each cell.
- A grid of distance to the sea is calculated for each cell using the AURELHY[6] (Analyse Utilisant le RELief pour l'Hydro-météorologie, see Appendix 3) method, implemented in the R programming language.
- The domain is partitioned into large homogeneous climatic zones serving as impassable barriers, defined based on the work of Knippertz et al. (2003) using topographic and meteorological criteria.

The interpolation protocol is applied independently for each meteorological variable of interest, including precipitation and maximum and minimum temperatures. The resulting high-resolution daily fields are then integrated into the CGMS-Maroc database for use in subsequent steps within Block 2 of the system, for yield modeling and forecasting.

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[5] USGS EROS Archive - Digital Elevation - Global 30 Arc-Second Elevation (GTOPO30) https://doi.org/10.5066/F7DF6PQS

[6] The AURELHY method uses relief to improve precipitation mapping. The method is based on the following three points: (1) Automatic recognition of the statistical relationship between precipitation and the surrounding relief; (2) Optimal use of this statistical relationship at points where no measured value is available; (3) Generation of a regional precipitation map, integrating the effects of relief.

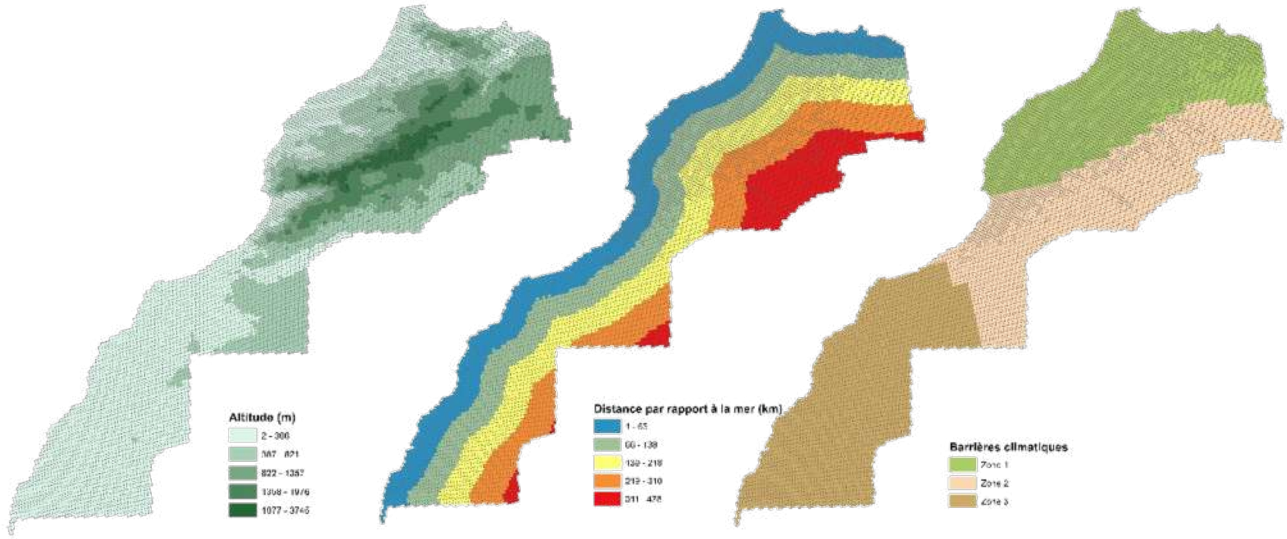

Figure 5 : The attributes allowing spatial interpolation of ERA5 data: Altitude (left), distance from the sea (center), and climatic barriers (right).

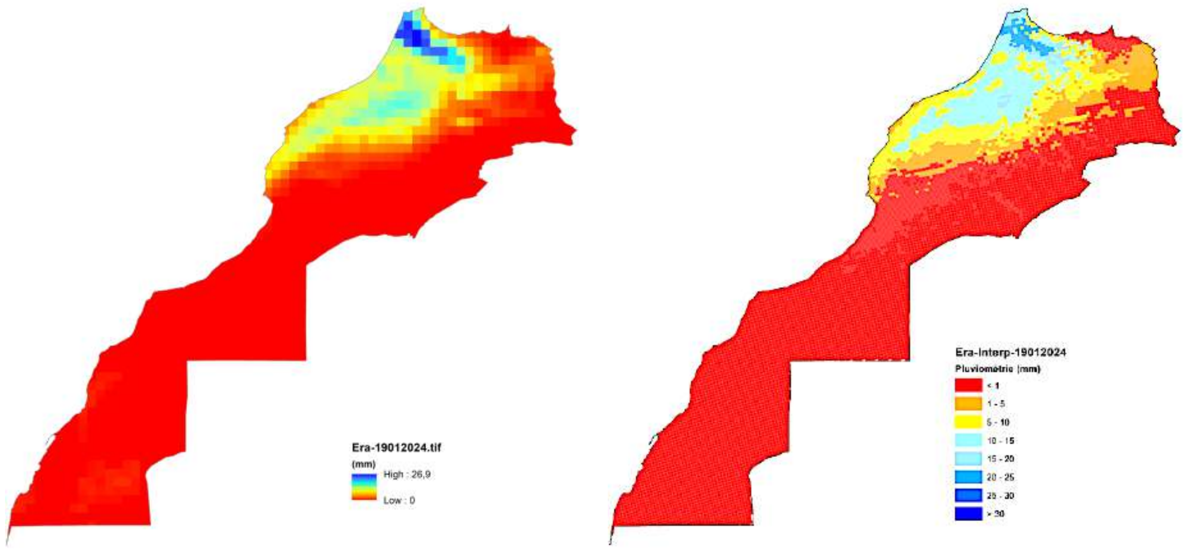

Figure 6 : ERA5 meteorological reanalysis of precipitation for the day of January 19, 2024. Native image (left) and interpolated on the reference grid (right).

Evaluation of Interpolated ERA5 Data

A comprehensive comparative analysis was conducted between precipitation data from the ERA5 reanalysis, interpolated on the CGMS-Maroc reference grid, and observations from the 44 synoptic stations managed by the GDM. This study focused on annual rainfall totals over a six-year period, spanning from 2016 to 2021 (Figure 7). The primary objective of this evaluation was to demonstrate the relevance and value of the operational integration of ERA5 data into CGMS-Maroc, aiming to fill the gaps in the spatial coverage of ground stations and enhance the representativeness of the rainfall fields used for agro-climatic monitoring.

It is important to note that Ifrane station, located at an altitude of 1,800 meters above sea level and in an area with complex relief, was deliberately excluded from the analysis. Indeed, reanalysis products like ERA5, as well as satellite estimates such as CHIRPS, encounter difficulties in accurately capturing precipitation in mountainous or highly rugged terrain. However, as will be detailed in the following section, specific correction methods have been developed to mitigate these local biases and ensure better representativeness of ERA5 fields, even in these unfavorable topographic contexts.

To assess the agreement between ERA5 and observations, a correspondence table was developed, enabling the comparison of annual rainfall totals measured at each station with the values of geographically co-located ERA5 grid cells. This approach facilitated a direct and quantitative comparison of the two datasets, providing valuable insights into their concordance.

The results of the analysis reveal a significant correlation between the annual precipitation totals derived from ERA5 and those recorded by the stations, with coefficients of determination (R^2) consistently exceeding 0.79. The scatterplots representing the paired values generally align with the 1:1 line (identity line), indicating that ERA5 reliably captures the interannual variability of precipitation without marked systematic bias. However, some discrepancies are observed for exceptionally rainy years, particularly in the northern regions of the country, where ERA5 tends to underestimate heavy rainfall events. Conversely, in arid zones, ERA5 exhibits a tendency to overestimate precipitation totals.

These discrepancies can be attributed to the native spatial resolution of ERA5 (31 km), which may not adequately resolve the local processes influencing the distribution of intense precipitation. However, it is important to emphasize that these biases remain limited in scope and do not substantially undermine the overall added value of reanalyzes for monitoring rainfall conditions at the country scale. This is especially true given the low density and sparse distribution of GDM stations in southern and eastern Morocco, which makes it challenging to ascertain whether the ERA5 product accurately estimates rainfall in these areas based on ground observations alone.

Figure 8 provides a compelling visual comparison of the cumulative rainfall distribution across Morocco during the 2018-2019 agricultural season (September 1, 2018, to May 31, 2019), as derived from two different data sources: the Interpolated ERA5 data (left) and the interpolation of observations from GDM synoptic stations (right). A visual analysis of these maps highlights the clear superiority of ERA5 in finely depicting the spatial distribution of precipitation across the country. The map generated from ERA5 data showcases a detailed and coherent spatial pattern of precipitation. The intricate interplay between Morocco's complex topography and atmospheric dynamics is vividly captured, with the major mountain ranges such as the Middle Atlas, High Atlas, Anti-Atlas, and Rif standing out as distinct zones of enhanced rainfall. The finer spatial resolution of ERA5 on the reference grid (4.5 km) allows for a more accurate representation of orographic effects, revealing local variations in precipitation that are often smoothed out in the interpolated station map.

Moreover, the interpolated ERA5 map faithfully reproduces the dominant north-south and west-east rainfall gradients across the country. The highest precipitation amounts are concentrated in the northern regions, particularly in the Rif and Middle Atlas Mountains, which are directly exposed to moisture-laden Atlantic disturbances. As we move southward and inland, a gradual decrease in rainfall is evident, transitioning into the arid expanses of the Saharan domain. The sharp delineation of these climatic zones underscores the ability of ERA5 to capture the heterogeneous nature of Morocco's precipitation regime.

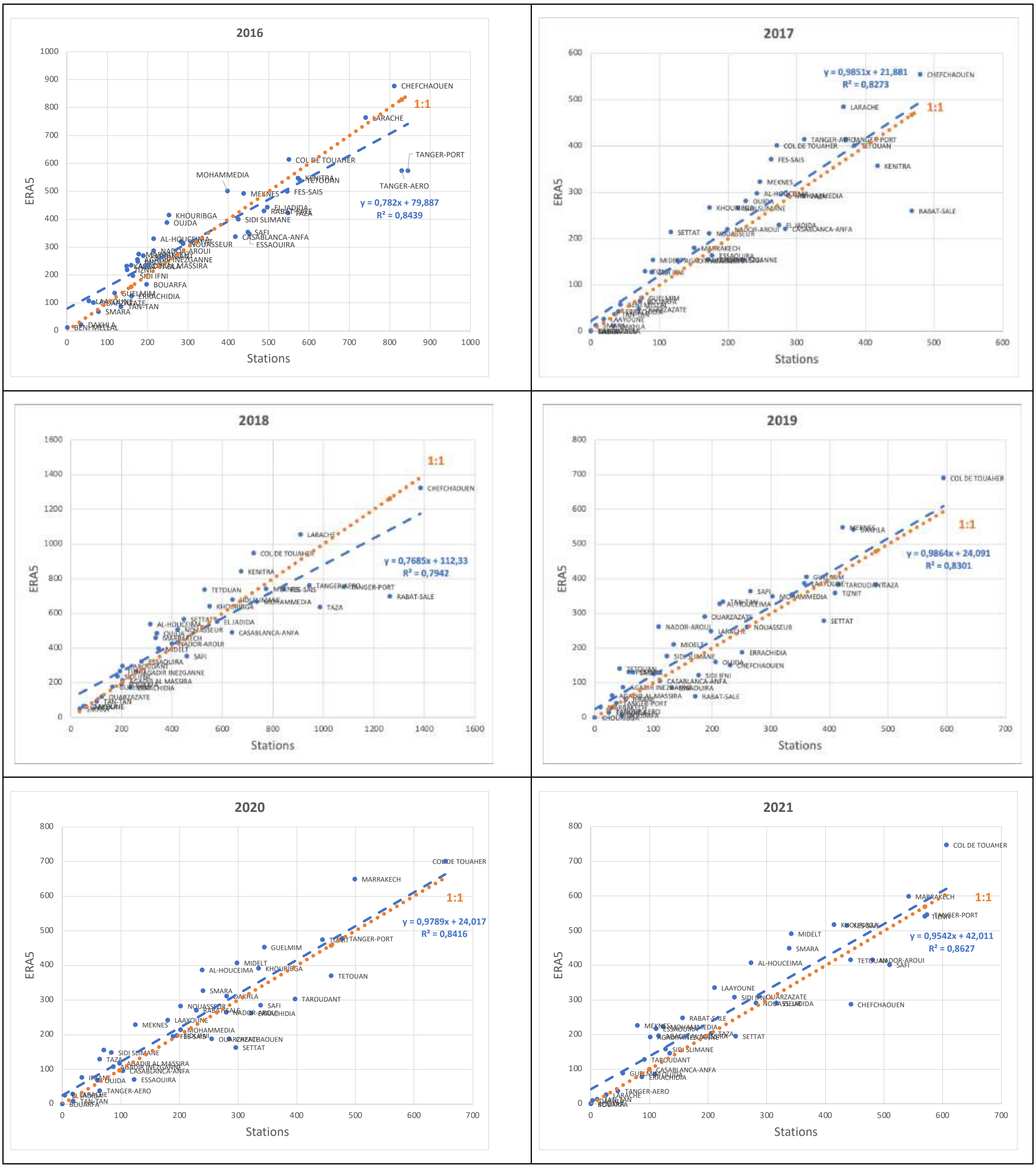

Figure 7 : Correlation between interpolated ERA5 data and data from the GDM synoptic stations.

In contrast, the interpolated station map struggles to resolve these fine-scale spatial features. The sparse and uneven distribution of the GDM synoptic stations results in an overly smoothed representation of the rainfall field. Critical topographic influences on precipitation are largely muted, leading to a blurred distinction between climatic zones and a lack of local detail. This limitation highlights the challenges of relying solely on ground-based observations for spatially continuous rainfall monitoring, especially in regions with complex terrain and limited station coverage.

The contrasting visual impression conveyed by these two maps underscores the immense value of integrating ERA5 reanalysis data into the CGMS-Maroc system. By leveraging the comprehensive spatial coverage and physical consistency of ERA5, the system can provide a more realistic and nuanced depiction of the country's precipitation landscape. This enhanced understanding of rainfall patterns is crucial for effective agricultural planning, water resource management, and climate risk assessment.

However, it is important to recognize that while ERA5 offers clear advantages over simple station interpolation, it may still exhibit systematic biases relative to the observed climatology of specific regions. To further refine the accuracy of the rainfall estimates, a local bias correction step using available in situ measurements is recommended (see section II.1.7). By combining the strengths of both ERA5 and ground-based observations, CGMS-Maroc can deliver the most reliable and actionable information for supporting decision-making in the agricultural sector.

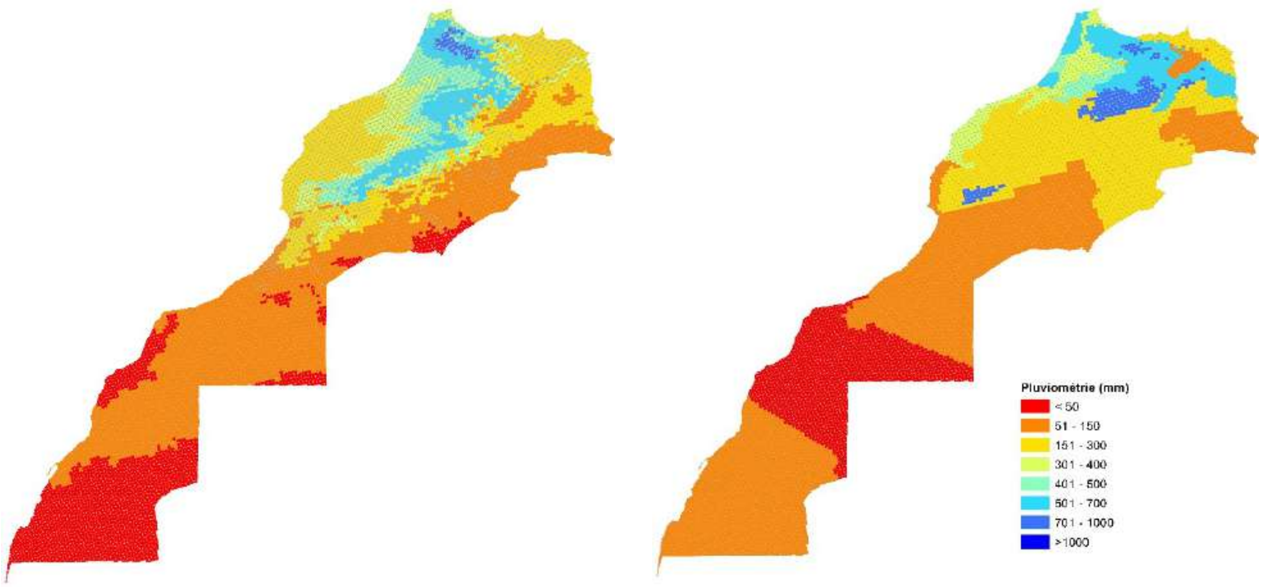

Figure 8: Total precipitation during the cropping season, from September 1, 2018, to May 31, 2019. Interpolated ERA5 data on the left and interpolated data from synoptic stations on the right.

Figure 9 presents a compelling comparison of average temperature maps for the 2018-2019 cropping season in Morocco, derived from interpolated ERA5 data and interpolated synoptic station data. Upon examining the two maps, a remarkable consistency is observed in the spatial patterns and gradients of temperature depicted by both data sources. The ERA5-based map and the synoptic station-based map exhibit a high degree of agreement, closely capturing the key geographical factors that influence temperature distribution across the country.

Both maps clearly illustrate the cooling effect of altitude, with lower temperatures prominently visible in the mountainous regions of Morocco, such as the Atlas Mountains. The complex interplay between topography and temperature is well-represented, highlighting the temperature gradients induced by elevation changes. Moreover, the maps effectively capture the influence of continentality on temperature patterns, with a noticeable warming trend observed as we move from the coastal areas towards the interior of the country. The local effects of oceanic influences along the coastal fringes are also discernible, particularly in the western and northern regions of Morocco.

The overall spatial resolution and level of detail exhibited by the ERA5-based map and the synoptic station-based map are comparable, suggesting that temperature fields can be effectively mapped using a moderately dense network of ground-based observations. The interpolation of temperature data from synoptic stations yields results that are consistent with the more comprehensive and physically-based ERA5 reanalysis.

The similarity in temperature patterns between the two maps can be attributed to the less spatially variable nature of temperature compared to precipitation. Temperature is closely related to stable geographic factors such as altitude, latitude, and distance from the sea, resulting in more regular and progressive spatial structures. In contrast, precipitation is more influenced by local and intermittent atmospheric processes, leading to greater spatial variability and complexity.

Given the strong agreement between ERA5 reanalysis and synoptic station observations in representing the spatial distribution of average temperatures, the contribution of ERA5 for temperature monitoring within CGMS-Maroc is less decisive than for precipitation. Observations alone are generally sufficient to produce realistic thermal fields, as even a moderately dense network of stations allows for satisfactory mapping of temperatures through simple interpolation techniques.

Nonetheless, the adoption of ERA5 temperatures in CGMS-Maroc remains valuable for ensuring the overall consistency and homogeneity of the atmospheric fields used in the system. While the gain in terms of spatial resolution or precision may not be substantial, integrating ERA5 temperature data helps maintain a coherent and standardized approach across all meteorological variables.

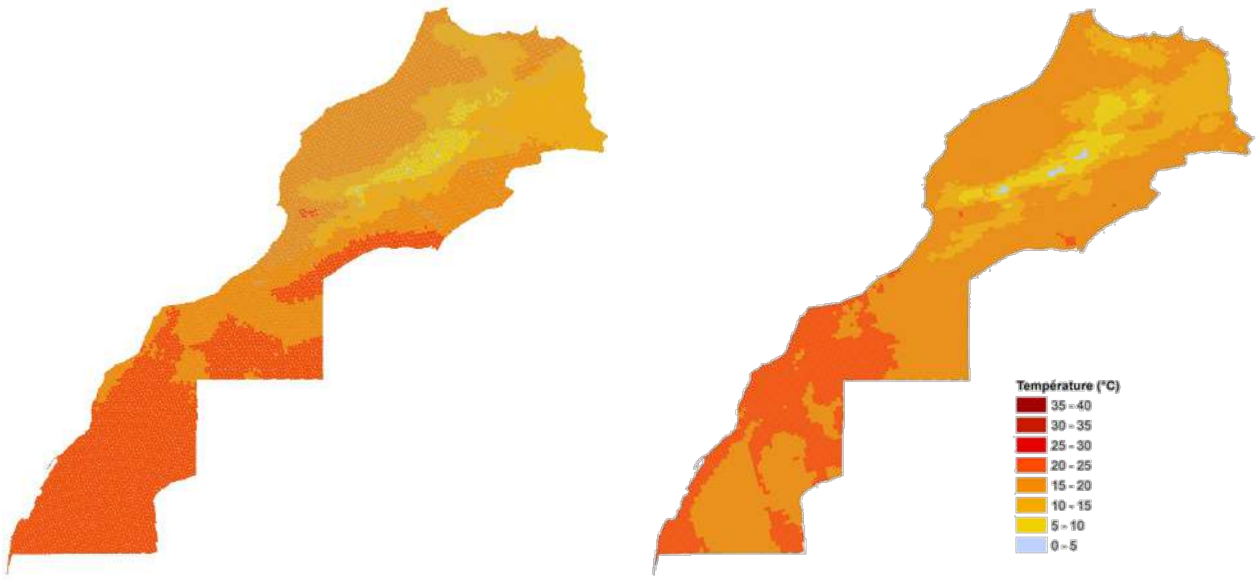

Figure 9 : Average temperatures during the agricultural season, from September 1, 2018, to May 31, 2019. Interpolated ERA5 data on the left and interpolated data from synoptic stations on the right.

In conclusion, this analysis highlights the differentiated contribution of ERA5 reanalysis depending on the meteorological variables. For precipitation, largely dependent on local relief effects and exhibiting high spatial variability, ERA5 offers a clear added value compared to the interpolation of conventional observations alone. For temperatures, with more spatially regular and predictable behavior, the gain is less significant, but the integration of ERA5 ensures overall consistency of atmospheric fields.

In any case, a local statistical correction using historical station series remains desirable to remove any biases and adapt the reanalysis to Moroccan climatic specificities. It is therefore a hybrid approach, combining the comprehensive coverage and resolution of reanalysis with the grounding in field realities of in situ observations, that will ultimately allow for the finest and most reliable agrometeorological characterization for the yield forecasting needs of CGMS-Maroc.

1.5. Collection and processing of observed meteorological data

In Block 1, the system also collects and processes daily observed meteorological data, such as rainfall, temperatures, wind speed, sunshine duration, and humidity, from a network of 44 GDM surface synoptic stations (Figure 10, see list in Appendix 1). This data has been available in the system's database since 1981. To ensure the reliability and consistency of the information, the raw data undergoes rigorous quality control, in accordance with the standards established by the World Meteorological Organization (WMO). This process aims to identify and eliminate any erroneous or questionable values that may result from sensor malfunctions or transmission errors. Beyond the directly measured parameters, Block 1 also incorporates the calculation of specific agronomic variables, such as vapor pressure, global radiation, and reference evapotranspiration.

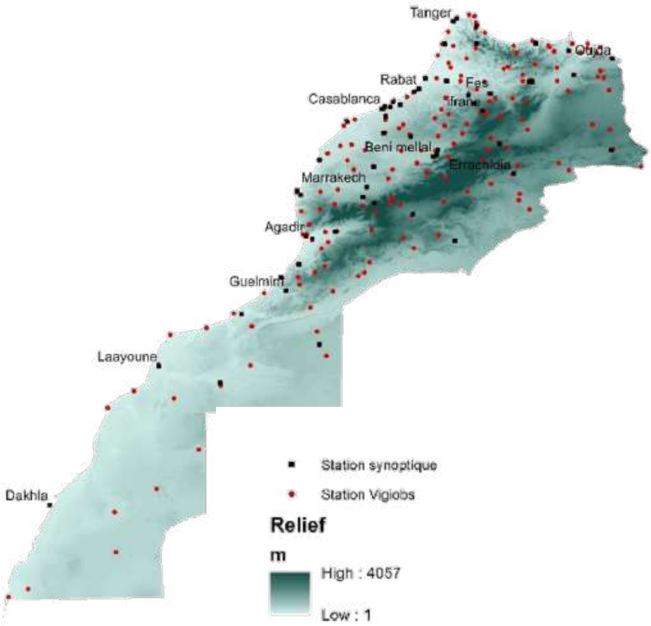

Figure 10 : Network of the 194 GDM meteorological stations (synoptic network in blue and VigiObs network in red).

These climatological data are then inserted into the METDATA table of the CGMS-Maroc system database (Table 1) for near-real-time processing (Allard et al., 2014). METDATA is populated by a combination of two meteorological messages sent by the GDM weather stations via its communication system. These messages are decoded to extract the required meteorological parameters, including precipitation, temperatures, sunshine duration, wind speed at 10m, dew point temperature, and cloud cover.

Table 1 : METADATA table of CGMS-MAROC containing the meteorological data from the GDM.

Variable	Description	Unit
DAY	Date	DATE
MAXIMUM_TEMPERATURE	Daily maximum temperature	°C
MINIMUM_TEMPERATURE	Daily minimum temperature	°C
VAPOUR_PRESSURE	Average daily vapor pressure	HPA
WINDSPEED	Average daily wind speed at 10 m	m/s
RAINFALL	Daily precipitation total	mm
SUNSHINE	Daily sunshine duration	H
CLOUD_DAYTIME_TOTAL	Average daily cloud cover	oktas
RAD_MEA	Daily global radiation	$KJ.m^{-2}.d^{-1}$

1.5.1. Calculation of average daily vapor pressure

The average daily vapor pressure (Ea) is a crucial variable in the calculation of reference evapotranspiration using the Penman-Monteith method. Although not directly measured by synoptic stations, it can be derived from the dew point temperature (Tdew) when available. In cases where Tdew is not recorded, Ea is estimated by assuming that the minimum temperature closely approximates Tdew in coastal areas. However, this approximation (Tmin ~ Tdew) is not valid for inland stations. To address this issue, an empirical correction is applied using linear regression between estimated Ea and observed Ea, ensuring more accurate values for inland locations.

1.5.2. Calculation of global radiation

Measuring global radiation poses a significant challenge due to the scarcity of direct observations. In such cases, global radiation must be estimated using indirect variables such as sunshine duration, cloud cover, and/or temperature. Three methods are commonly employed for this purpose: Ångström, Supit, and Hargreaves. An alternative approach involves obtaining global radiation data from the DSSF (Down-welling Short-wave Surface Flux) product for each meteorological station within CGMS-Maroc. This method leverages the archives of the Meteosat Second Generation time series, offering a specific calibration for each synoptic station. These DSSF values are then used to refine the global radiation models integrated into CGMS-Maroc, such as Ångström, Supit, and Hargreaves, enhancing their accuracy and reliability.

To overcome the limited availability of global radiation estimates, data has been extracted from the archives of first and second-generation Meteosat satellites. This compilation provides a comprehensive set of global radiation estimates spanning from 1983 to the present day. The validation of these estimates, derived from Meteosat Second Generation (MSG) data, has confirmed their reliability and suitability for use in CGMS-Maroc.

To streamline the analysis process, Alterra (De Wit et al., 2014) developed two Python scripts as part of the E-AGRI project. These scripts, which have been adopted by the GDM, are used to calculate the Ångström and Hargreaves coefficients. The scripts require a "RADIATION CALIBRATION DATA" table, structured as follows:

- **Wmo_no:** weather station number
- **Day:** date of observation
- **Sunshine:** measured sunshine duration
- **Temp_min:** observed minimum temperature
- **Temp_max:** observed maximum temperature
- **Global_radiation:** measured global radiation.

The results generated by these scripts are stored in a database and serve as the basis for estimating global radiation for subsequent use within CGMS-Maroc (see Appendix 2). This approach ensures that the system has access to reliable and consistent global radiation data, even in the absence of direct measurements, enabling more accurate modeling and analysis of agricultural processes.

1.5.3. Calculation of reference evapotranspiration

The daily meteorological data received from the GDM synoptic stations does not include reference evapotranspiration (ET0), a crucial parameter for estimating crop water requirements. To overcome this limitation, CGMS-Maroc calculates ET0 using the Penman formula (Penman, 1948), which considers various meteorological factors influencing evaporation.

The Penman formula is expressed as:

ET0 = (Δ/(Δ + γ)) * (Rn - G) + (γ/(Δ + γ)) * (6.43 * (1 + 0.536 * u2)) * (es - ea)

where:

- ET0 is the reference evapotranspiration (mm/day)
- Δ is the slope of the vapor pressure curve (kPa/°C)
- γ is the psychrometric constant (kPa/°C)
- Rn is the net radiation (MJ/m²/day)
- G is the soil heat flux (MJ/m²/day)
- u2 is the wind speed at 2 meters above the ground (m/s)
- es is the saturation vapor pressure (kPa)
- ea is the actual vapor pressure (kPa)

The formula considers the energy balance (Rn - G) and the aerodynamic term (es - ea) to estimate the evaporation demand. The energy balance term represents the available energy for evaporation, while the aerodynamic term accounts for the drying power of the air, influenced by wind speed and vapor pressure deficit.

To apply the Penman formula, CGMS-Maroc uses specific albedo values for different surface types: 0.05 for open water evaporation (E0), 0.15 for wet bare soil evaporation (ES0), and 0.20 for reference crop evapotranspiration (ET0). These albedo values determine the fraction of incoming solar radiation that is reflected by the surface.

Furthermore, the formula considers surface roughness, which affects the aerodynamic resistance to evaporation. For crop canopies (ET0), a surface roughness value of 1.0 is used, representing a standardized grass reference crop with a height of 0.12 m. For a free water surface and wet bare soil (E0, ES0), a lower surface roughness value of 0.5 is adopted, reflecting the smoother surface characteristics.

1.5.4. Quality of the national meteorological station network

The integration of ERA5 reanalysis data has substantially improved the spatial coverage and reliability of the precipitation and temperature data used by CGMS-Maroc. However, the system still relies on the GDM's network of meteorological stations for the calculation of reference evapotranspiration, a crucial parameter for drought monitoring and crop yield forecasting. The uneven spatial distribution of these stations across the country may affect the accurate estimation of evapotranspiration.

In 2017, researchers from the ACCAGRIMAG project (Alaouri et al., 2017) conducted a study to assess the suitability of the GDM's synoptic station network for cereal yield forecasting. They focused on rainfall, the most critical factor for rainfed crop yields in Morocco. Using a "leave-one-out" cross-validation method, they removed one station at a time and used the remaining stations to estimate the total precipitation at the excluded station. This allowed them to evaluate the network's ability to capture the spatial variability of rainfall. The results revealed significant differences (<-20% or >+20%) between the actual and interpolated precipitation values in nearly 700 districts (called "communes"). These findings highlighted the need to expand the station network, particularly in arid, mountainous, and rugged areas, as well as in southern and eastern Morocco, where coverage is limited.

To address this issue, the GDM expanded the network to a total of 194 stations in 2014, known as the VigiObs network (Figure 10). Despite this expansion, the average density of one station per 3,550 km2 still falls far short of the World Meteorological Organization (WMO) recommendations. According to these guidelines, Morocco would ideally require a network that is five times denser to achieve optimal coverage. This translates to more than 1,000 stations strategically distributed throughout the agricultural territory, with a density of one station for every 100 to 250 km² in mountainous areas and one station for every 600 to 900 km² in the plains (Table 2). Establishing such an extensive network would undoubtedly involve substantial financial investments and pose significant logistical challenges.

Table 2: Minimum number of automatic meteorological stations required in each geographical area to meet the need for accurate meteorological information for agriculture in Morocco (Source: Atlas of Moroccan Agriculture[7], 2009).

Zone	Area (Km^2)	Number
Mountains	112,000	560
Semi-arid and humid plains	111,170	445
High plateaus	47,620	48
Pre-Sahara and Sahara	439,210	0
TOTAL	**710,850**	**1,052**

1.6. Interpolating meteorological data from synoptic stations

To address the limitations of the low-density GDM meteorological station network and generate continuous spatial data fields, CGMS-Maroc uses the Inverse Distance Weighting (IDW) method, which is also used for the interpolation of ERA5 reanalysis data. The interpolation results are stored in the GRID_WEATHER table of the CGMS-Maroc database, providing daily meteorological variables for the entire country from January 1, 1987, to the present.

However, the IDW method has shown limitations in capturing the spatial variability of precipitation, particularly in regions with sparse station coverage. Figure 11 illustrates the total rainfall for the cropping season from September 2019 to June 2020, as spatialized by CGMS-Maroc using observed data from the 44 GDM synoptic stations. The map reveals that the interpolation struggles to represent the strong local precipitation gradients related to topography and site-specific effects, especially in the mountainous areas of the Atlas Mountains and the arid regions in the south and east of the country. These limitations are most apparent in areas with the lowest density of GDM stations, where the interpolation results in a smoothed and less detailed representation of the precipitation patterns.

The limited ability of the IDW method to capture the spatial heterogeneity of precipitation in these regions can be attributed to several factors. First, the complex terrain and orographic effects in the mountainous areas create local variations in precipitation that are not adequately captured by the sparse station network. Second, the arid regions in the south and east of Morocco experience highly localized and sporadic rainfall events that are difficult to interpolate accurately using the available station data. The IDW method, which relies on the assumption of spatial autocorrelation, may not be well-suited for these regions where precipitation patterns are highly discontinuous and influenced by local factors.

While more sophisticated interpolation techniques, such as kriging, could potentially improve the representation of precipitation patterns, their effectiveness may be limited by the low station density. Kriging relies on the spatial structure of the data to make predictions, and the sparse network may not provide sufficient information to capture the complex spatial variability of precipitation accurately.

[7] https://www.agriculture.gov.ma/sites/default/files/ATLASsynthese.pdf

To address these limitations, CGMS-Maroc has explored alternative data sources and approaches. The integration of freely available satellite rainfall data, despite their moderate spatial resolution and potential estimation errors, offers new opportunities to improve the spatial representation of precipitation. These satellite-based products provide continuous coverage and can capture the general patterns of precipitation, particularly in regions where station data is scarce.

Moreover, CGMS-Maroc has shifted towards using ERA5 meteorological reanalysis data, which is corrected using ground station observations. This combined approach leverages the strengths of both data sources - the spatial continuity and consistency of the reanalysis data and the accuracy of the ground measurements. By merging these two sources of information, CGMS-Maroc aims to significantly improve the mapping of precipitation across the country, leading to more accurate rainfall estimates and enhancing the overall reliability of the system as a decision support tool for agricultural planning and risk management.

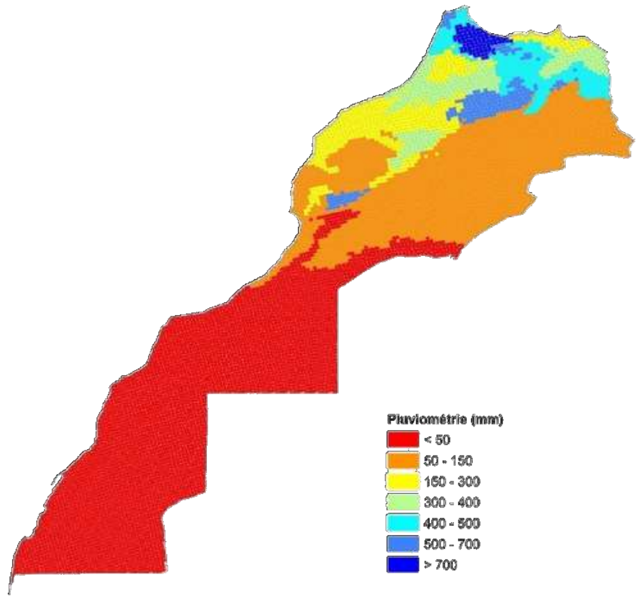

Figure 11 : Spatialization of total rainfall for the cropping season, spanning September 2019 through June 2020, conducted by CGMS-Maroc using observed data from GDM synoptic stations.

1.7. Correction of ERA5 reanalysis data

The CGMS-Maroc system employs a correction method to reduce discrepancies between the interpolated ERA5 precipitation data and observations from synoptic stations, aiming to obtain more accurate and reliable estimates of precipitation at the local scale.

The correction method involves the development of a specific ratio to adjust the ERA5 precipitation values. This ratio is derived from a base precipitation field, which is constructed using the "random forests" method and precipitation archives. By considering local climatic particularities, this approach allows for the adjustment of precipitation estimates from the reanalysis to better align with the actual conditions observed by meteorological stations.

The process utilizes average climatological data for the period 1981-2010, which is spatialized using the archives of 44 GDM meteorological stations and processed by the AURELHY method. AURELHY is renowned for its ability to integrate the effects of relief on the spatial distribution of precipitation and generate high-resolution maps.

To account for the climatic diversity of Moroccan regions, the base field is further customized by the random forests algorithm according to the season and uniform climatic zone, as defined by the De Martonne index (Figure 12 and Appendix 1). This approach ensures that the resulting precipitation estimates accurately reflect local climatic conditions and capture the spatial and temporal variability across the country, in agreement with station observations.

The random forests algorithm is then used to predict the mean monthly precipitation for the areas of the CGMS-Maroc reference grid that do not have direct measurements, using the spatial data of geographical and climatic characteristics. This method generates base precipitation fields covering the six homogeneous climatic zones identified in Morocco, minimizing discrepancies with station observations.

The daily ERA5 precipitation interpolated onto each cell of the CGMS-Maroc reference grid for the period 1981-2023 is adjusted using the monthly mean precipitation estimated by the random forests model for each corresponding cell. This correction allows for the generation of adjusted ERA5 daily precipitation data series, which are then subjected to an evaluation using observations from GDM synoptic stations. The objective is to ensure that the corrected ERA5 data is as close as possible to the observed values, thus reducing biases and errors.

1.7.1. Creation of a reference precipitation field from ground measurements

The base field for precipitation in the CGMS-Maroc system is developed using the random forests algorithm, which generates estimates of the monthly mean precipitation totals at the reference grid cells. This process relies on average climatological data for the period 1981-2010 (Figure 12), which is spatialized using the archives of 44 GDM meteorological stations and processed by the AURELHY method.

To account for the climatic diversity of Moroccan regions, the base field is further customized by the random forests algorithm according to the seasons and homogeneous climatic zones, as defined by the De Martonne index (Figure 12 and Appendix 1). This approach ensures that the resulting precipitation estimates accurately reflect local climatic conditions and capture the spatio-temporal variability across the country.

The variables considered by the Random Forests algorithm include:

- Geographical characteristics (longitude, latitude, altitude, distance from the sea), which have an impact on the distribution of precipitation.
- Classifications into uniform climatic zones.
- The ratio of observed annual precipitation averages to those derived from ERA5 data for the reference period 1981-2010.
- Seasons (autumn, winter, spring, summer).
- Observed monthly precipitation totals compared to those from ERA5.

To facilitate the effective application of the random forests algorithm, the meteorological station data is divided into two sets: a training set (70% of the data) and a test set (30% of the data). The algorithm is then trained to establish models that relate the monthly precipitation means to the relevant geographical and climatic characteristics, focusing on the specific zones and seasons corresponding to the collected data.

Once trained, the random forests algorithm is used to predict the monthly precipitation means for the cells of the CGMS-Maroc reference grid that lack direct measurements. This prediction is based on the spatial data of geographical and climatic characteristics. The method generates background precipitation fields covering the six homogeneous climatic zones identified in Morocco. Analysis of the algorithm reveals that altitude and the ratio between the observed annual precipitation averages and those estimated by ERA5 are the two main factors, contributing to more than 90% of the accuracy of the model's monthly precipitation predictions.

To further refine the predictions for each climatic zone and season, an in-depth study of the hyperparameters of the random forests model was conducted. This optimization involved a comprehensive analysis of possible hyperparameter combinations, such as the maximum depth of trees, the minimum number of samples required for a leaf node, the minimum number of samples needed to split a node, and the total number of trees composing the forest. An iterative cross-validation process was implemented to test the effectiveness of different hyperparameter configurations, aiming to strike an optimal balance between model complexity and generalization ability.

The effectiveness of the random forests algorithm is validated by comparing its predictions to the actual precipitation data of the test set using key statistical indicators such as the correlation coefficient, bias, and mean squared error. The results demonstrate that the algorithm's predictions exhibit a remarkably high correlation coefficient, ranging from 0.8 to 0.91 during cross-validation, indicating the model's high accuracy compared to actual rain gauge measurements.

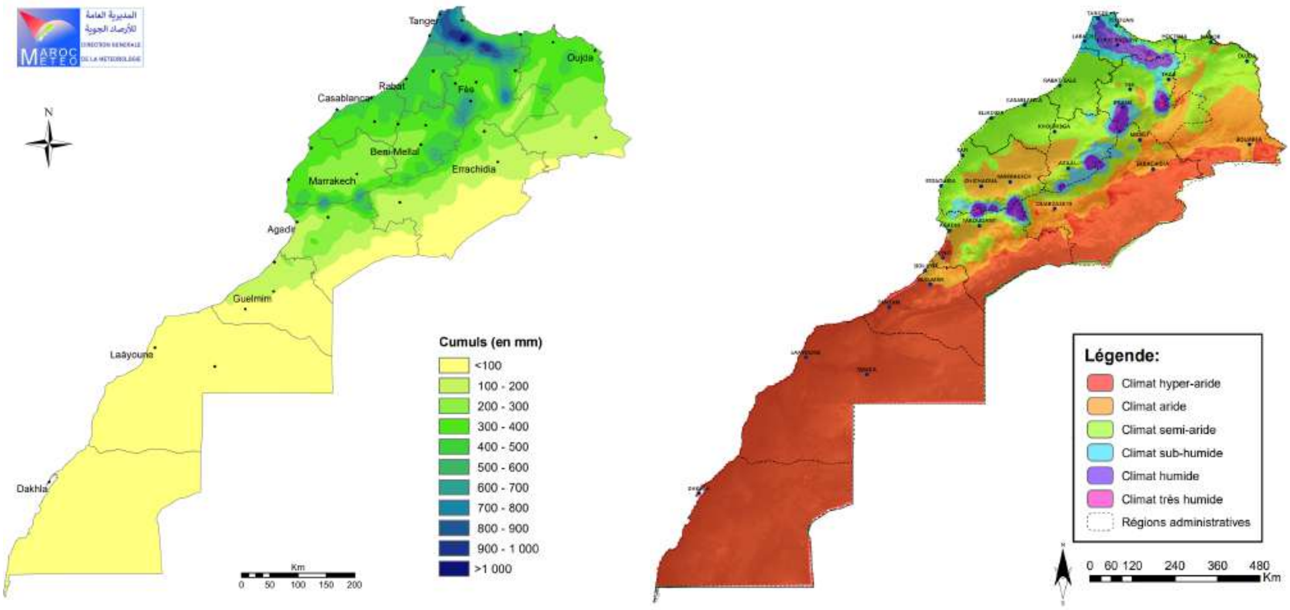

Figure 12 : Average total rainfall for the cropping season in Morocco, analyzed using the AURELHY method (left) and climatic zoning according to De Martonne index (right), for the period 1981-2010 (source: GDM).

1.7.2. Correction of daily ERA5 precipitation

The daily ERA5 precipitation data interpolated onto each cell of the CGMS-Maroc reference grid for the period 1981-2023 undergoes an adjustment process using the monthly mean precipitation estimates derived from the random forests model for each corresponding cell. The correction is applied using the following formula for each grid cell and each day j of the studied period, where i ranges from 1 to 16819, representing the total number of grid cells:

$$P_{EraCor,j,i} = P_{Era,j,i} \times \frac{P_{RF,m,i}}{P_{Era,m,i}} \qquad i = (1,2,\dots,16819)$$

- $P_{EraCor,j,i}$ is the corrected daily ERA5 precipitation for day j and grid cell i,
- $P_{Era,j,i}$ is the interpolated daily ERA5 precipitation for day j and grid cell i,
- $P_{RF,m,i}$ is the average monthly precipitation estimated by the random forest model for month m and grid cell i, based on observation data and associated geographical and climatic characteristics for the period 1981-2022,
- $P_{Era,m,i}$ is the average monthly ERA5 precipitation for month m and grid cell i over the same period.

This correction method has enabled the generation of adjusted ERA5 daily precipitation data series for the entire period of 1981-2024 on the CGMS-Maroc reference grid. To ensure the robustness of the corrected data, a rigorous evaluation was conducted using observations from

GDM meteorological stations for the period 2010-2022. This period was intentionally excluded during the model development phase to serve as an external validation dataset.

A comprehensive comparative analysis was performed to assess the agreement between the adjusted ERA5 data and observations from GDM synoptic stations. The analysis focused on the average monthly precipitation totals over this extended period, aiming to evaluate the accuracy and operational usefulness of the corrected ERA5 data within the specific context of the CGMS-Maroc system. The objective was to assess the effectiveness of the applied corrections and explore potential improvements compared to existing interpolation methods, which may be limited by deficiencies in surface rainfall measurements.

To facilitate this evaluation, a correspondence table was prepared to examine the correlations between the annual precipitation totals measured by the stations and those estimated for the corresponding cells of the ERA5 and corrected ERA5 grid. The results demonstrated a significant improvement, with the correlation coefficients for annual precipitation totals between ERA5 and station measurements.

Figure 13 provides a visual representation of the significant improvement in the correlation between ERA5 precipitation data and station observations after applying the correction method. The scatter plots compare the average total annual rainfall derived from ERA5, corrected ERA5, and observations at meteorological stations for the period 2010-2022. The plot on the left shows the relationship between the original interpolated ERA5 data and station observations, while the plot on the right illustrates the relationship between the corrected and interpolated ERA5 data and station observations. The notable increase in the correlation coefficient from 0.65 to 0.93 after the correction is evident. The improved alignment suggests that the corrected ERA5 data better captures the spatial and temporal variability of precipitation across Morocco, enhancing its reliability for use in the CGMS-Maroc system. The scatter plots also reveal that the correction method performs well across a wide range of precipitation amounts, from low to high values, indicating its robustness in representing different precipitation regimes. This visual analysis complements the numerical results and strengthens the confidence in the correction method's ability to improve the accuracy and representativeness of the ERA5 precipitation data for agricultural monitoring and decision support in Morocco.

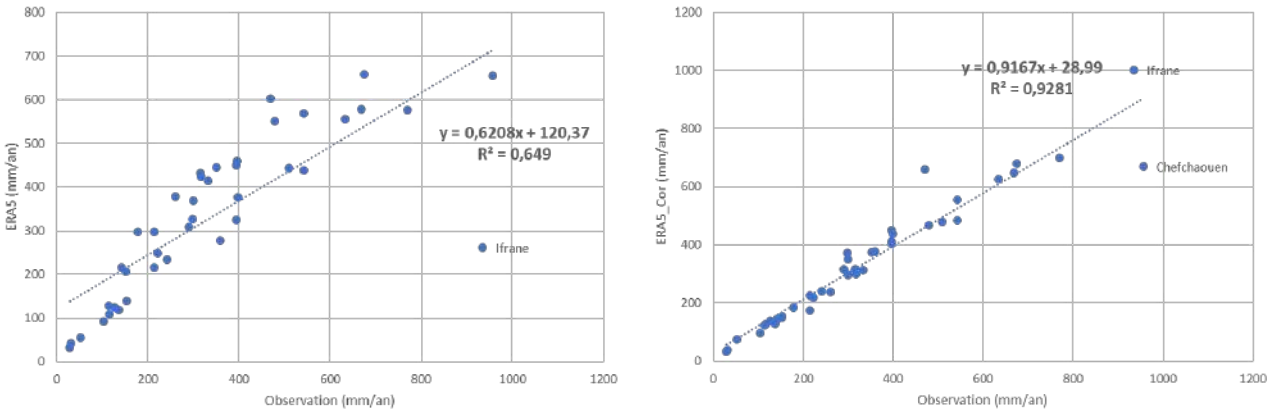

Figure 13 : Correlation of observed average total annual rainfall from GDM meteorological stations (average 2010-2022) with interpolated ERA5 data (left) and with interpolated and corrected ERA5 data (right).

To further assess the robustness and effectiveness of the correction method, in-depth analyses were conducted covering comparisons on monthly (Table 3), seasonal (Table 4), and zonal (Table 5) scales. These analyses aim to capture the climatic diversity of Morocco and provide a comprehensive evaluation of the corrected ERA5 data across different temporal and spatial domains. By examining the performance of the correction method at these various scales, the study seeks to establish the reliability and applicability of the adjusted ERA5 data for use in the CGMS-Maroc system, ultimately supporting improved agricultural monitoring and decision-making processes.

a. Monthly analysis

The corrections made to the ERA5 data have significantly strengthened the correspondence with actual monthly observations, as evidenced by the analyses presented in Table 3. The results demonstrate a reduction in bias and a decrease in the average difference between ERA5 estimates and effective measurements, marking a clear improvement in data accuracy. Moreover, the root mean square error (RMSE) saw a generalized decrease across all months, reflecting increased coherence between the adjusted data and observations. This improvement is particularly remarkable during the rainy season, where, despite a potential increase in bias and RMSE attributable to increased precipitation variability and intensity, the adjustments prove their effectiveness.

The post-correction correlation coefficients reveal enhanced harmony with real data, with notable increases from 0.85 to 0.90 for January, illustrating improved conformity with field observations. Additionally, the observed reductions in both bias and RMSE confirm improved accuracy and strengthened congruence of the corrected data compared to observed measurements. These results highlight the effectiveness of the correction method in capturing the monthly rainfall patterns and variability across Morocco.

Table 3: Correlation between total monthly rainfall from ERA5, interpolated and corrected ERA5, and observations at meteorological stations by month (2010-2022).

Month	Interpolated ERA5			interpolated and corrected ERA5		
	Coeff. Correlation	Bias	RMSE	Coeff. Correlation	Bias	RMSE
January	0.85	-5.49	28.54	0.90	-0.90	22.54
February	0.81	-1.93	24.46	0.86	0.87	21.48
March	0.80	-0.45	26.06	0.84	-1.32	23.63
April	0.76	1.69	20.51	0.82	-0.08	17.56
May	0.76	3.64	16.21	0.78	0.56	14.68
June	0.70	2.24	7.48	0.72	-0.36	5.97
July	0.44	1.16	4.03	0.50	0.17	3.05
August	0.51	0.86	5.46	0.56	-0.05	4.95
September	0.68	2.17	10.65	0.70	0.58	9.48
October	0.77	0.52	19.20	0.78	0.28	19.03
November	0.85	-4.84	27.72	0.88	1.13	24.97
December	0.85	-7.75	32.58	0.88	-1.71	27.27

b. Seasonal analysis

The correction method has yielded remarkable progress in the accuracy of seasonal interpolated ERA5 data, as shown in Table 4. This improvement is particularly evident during the winter months (December, January, and February), where a significant reduction in bias and an increase in the correlation coefficient indicate a strengthened adequacy between corrected predictions and actual measurements. The enhancements extend to all seasons, manifesting through increases in correlation coefficients and decreases in bias and root mean square error (RMSE). These adjustments have better aligned the corrected ERA5 data with concrete observations, making seasonal estimates more faithful to the observed reality.

The results in Table 4 demonstrate the effectiveness of the correction method in capturing the seasonal rainfall patterns across Morocco. The improved correspondence between the corrected ERA5 data and observations highlights the method's ability to account for the seasonal variability of precipitation, which is crucial for agricultural planning and water resource management.

Table 4: Correlation between total monthly rainfall from interpolated ERA5, interpolated and corrected ERA5, and observations at meteorological stations by season (2010-2022).

Season	Interpolated ERA5			Interpolated and corrrected ERA5		
	Coeff. Correlation	Bias	RMSE	Coeff. Correlation	Bias	RMSE
SON	0.84	-0.60	20.18	0.86	0.65	18.75
DJF	0.84	-5.02	28.68	0.88	-0.56	23.88
MAM	0.78	1.67	21.20	0.83	-0.26	18.88
JJA	0.63	1.43	5.90	0.66	-0.09	4.87

SON: September, October, and November; DJF: December, January, and February; MAM: March, April, and May; JJA: June, July, and August.

c. Zonal analysis

The examination of the corrections applied according to different climatic zones, as presented in Table 5, highlights notable progress in the accuracy of rainfall estimates. This improvement is particularly evident in the humid zone, where the bias has been significantly mitigated. The progression is uniformly observed across all zones, including arid and semi-arid regions, which are traditionally difficult to quantify due to their sporadic and often limited precipitation. The adjustments have led to universal improvement, characterized by a significant increase in correlation coefficients and a marked decrease in bias and root mean square error (RMSE), illustrating the effectiveness of these corrections in refining rainfall predictions and aligning them with Morocco's specific climatic characteristics.

The results in Table 5 demonstrate the ability of the correction method to capture the spatial variability of precipitation across the different climatic zones of Morocco. The improved accuracy and reliability of the corrected ERA5 data in representing the rainfall patterns in each zone highlight the method's potential to support region-specific agricultural decision-making and risk assessment.

Table 5: Correlation between total monthly rainfall from interpolated ERA5, interpolated and corrected ERA5, and observations at meteorological stations by climatic zone (2010-2022).

Zone	Interpolated ERA5			Interpolated and corrected ERA5		
	Coeff. Correlation	Bias	RMSE	Coeff. Correlation	Bias	RMSE
Humid	0.66	-23.94	64.05	0.74	-4.85	51.20
Subhumid	0.91	-3.77	23.42	0.91	-1.15	21.68
Semi-arid	0.88	1.30	15.80	0.89	0.88	14.97
Arid	0.86	2.21	10.33	0.87	-0.21	9.53
Hyper arid	0.76	-0.09	5.95	0.74	0.21	6.61

The evaluations presented in Table 3, Table 4, and Table 5 collectively attest to the major improvement in the reliability of the adjusted ERA5 data, validating their applicability and relevance to Morocco's diverse climatic conditions. The enhanced accuracy and correspondence with observed measurements across different temporal and spatial scales demonstrate the robustness and effectiveness of the correction method.

Figure 14 provides a compelling visual representation of the significant effect of the correction applied to the ERA5 data. The graphs reveal notable improvements across all examined localities, with the corrected ERA5 data (ERA_COR) impressively aligning with actual observations (OBS). This alignment is particularly evident during periods of maximum precipitation, highlighting a considerable improvement in accuracy. The adjustments enable the corrected data to accurately reflect intra-annual variability, faithfully reproducing the characteristic precipitation cycles of various Moroccan climates.

It is worth noting that the improvement of ERA5 is particularly significant at the Ifrane station, located at an elevation of 1,800 meters above sea level. This station, situated in a mountainous region, often poses challenges for accurate precipitation estimates due to its complex topography and orographic effects. The correction method's ability to enhance the accuracy of ERA5 data at this high-altitude station demonstrates its robustness and effectiveness in capturing the spatial variability of precipitation, even in challenging terrains.

This enhanced concordance with real observations, including at the Ifrane station, illustrates the effectiveness of the undertaken corrections and reinforces the reliability of ERA5 data for climatic and hydrological studies in the Moroccan context.

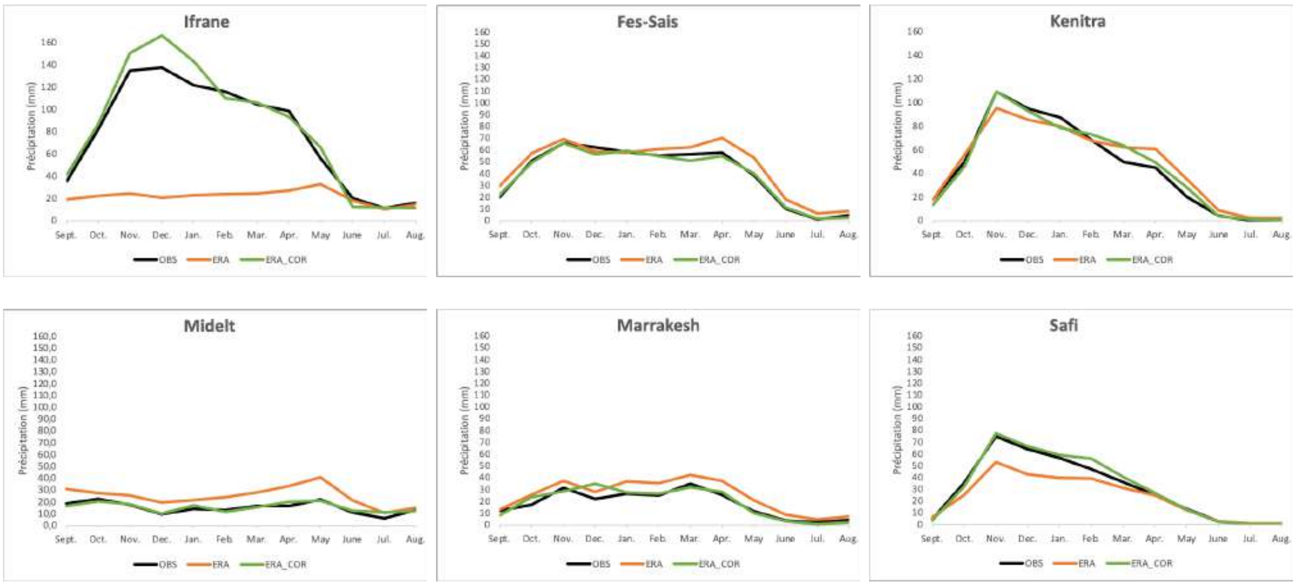

Figure 14 : Seasonal cycle of total monthly rainfall according to meteorological station observations (black line), interpolated ERA5 data (orange line), and interpolated and corrected ERA5 data (green line).

d. Spatial analysis of precipitation in Morocco: From interpolated observations to interpolated and corrected ERA5 data

The spatial analysis of precipitation in Morocco, comparing interpolated observations and corrected ERA5 data, highlights a significant improvement in the accuracy and detail of rainfall mapping across the country. Figure 15 and Figure 16 provide compelling examples of this enhancement, showcasing the benefits of the correction method for both annual and daily precipitation estimates.

Figure 15 presents a comparison of the total precipitation for the agricultural season from September 1, 2017, to May 31, 2018, using three different data sources: interpolated data from GDM synoptic stations, interpolated ERA5 data, and interpolated and corrected ERA5 data. The map based on interpolated GDM station data (left) exhibits a coarse and smoothed representation of the precipitation distribution, lacking the necessary spatial detail to capture local variations. This limitation stems from the sparse network of stations and the inherent constraints of the interpolation method in representing rainfall patterns between observation points.

In contrast, the map derived from interpolated ERA5 data (center) demonstrates a notable improvement in spatial resolution, providing a more refined delineation of the different climatic zones across Morocco. However, upon closer inspection, it becomes apparent that the interpolated ERA5 data tends to underestimate precipitation amounts, particularly in the mountainous regions of the Atlas Mountains. This underestimation can be attributed to the global nature of the ERA5 reanalysis and its limited ability to fully capture the complex topographic and orographic effects that influence precipitation in these areas.

The map generated using interpolated and corrected ERA5 data (right) showcases a remarkable advancement in both the spatial detail and the quantitative accuracy of the precipitation estimates. The correction method has effectively leveraged local topographic and climatic factors to produce a more realistic and nuanced representation of the rainfall distribution across Morocco. The corrected ERA5 map captures the higher precipitation amounts in the northern and mountainous regions, while accurately depicting the gradients towards the drier southern and eastern areas. The spatial patterns in the corrected ERA5 map exhibit a strong correspondence with the known climatic characteristics of Morocco, validating the effectiveness of the correction method in enhancing the spatial representation of precipitation.

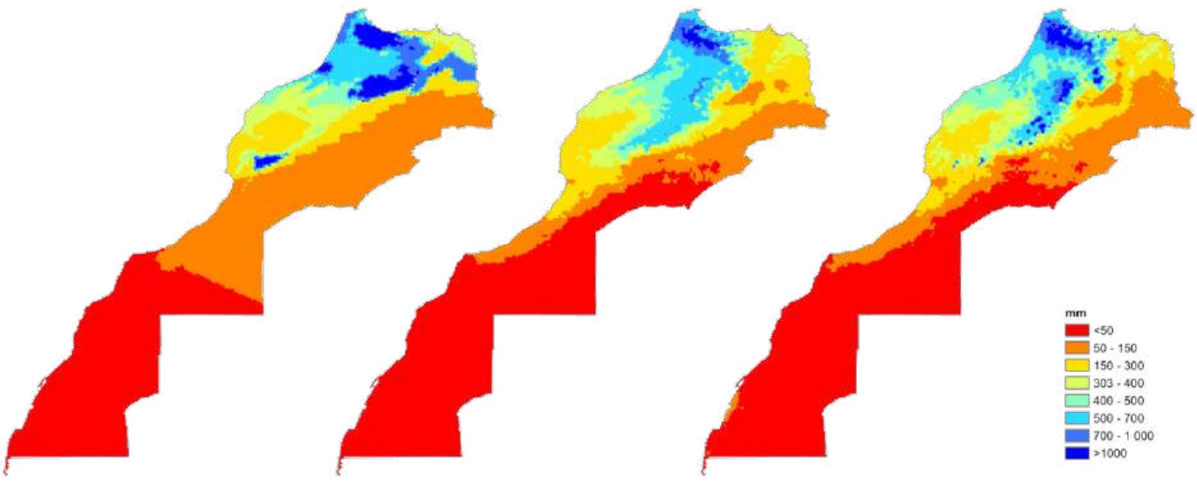

Figure 15 : Precipitation mapping using interpolated data from GDM synoptic stations (left), interpolated ERA5 (center), and interpolated and corrected ERA5 (right). Example of total precipitation from September 1, 2017, to May 31, 2018.

Figure 16 focuses on a specific day, December 1, 2023, and compares the daily precipitation estimates from the same three data sources. This figure provides a more granular perspective on the improvements achieved by the correction method. The map based on interpolated GDM station data (left) suffers from the same limitations as in Figure 15, with a coarse and generalized representation of the daily precipitation distribution. The sparse station network hinders the accurate capture of local rainfall variations, resulting in a smoothed and less informative map.

The map derived from interpolated ERA5 data (center) offers a higher spatial resolution and captures more detailed patterns of daily precipitation. However, upon closer examination, it becomes evident that the interpolated ERA5 data underestimates the rainfall amounts in certain regions, particularly in areas with complex terrain. This underestimation can be attributed to the limitations of the global reanalysis in resolving local-scale atmospheric processes and orographic effects that influence daily precipitation patterns.

The map produced using interpolated and corrected ERA5 data (right) demonstrates a substantial improvement in both the spatial detail and the quantitative accuracy of the daily precipitation estimates. The correction method has successfully incorporated local factors, resulting in a more realistic representation of the daily rainfall distribution. The corrected ERA5 map captures the fine-scale variations in precipitation, accurately depicting the higher amounts in the mountainous regions and the gradients towards the drier areas. The spatial patterns in the corrected ERA5 map are consistent with the expected daily precipitation characteristics based on the prevailing atmospheric conditions and topographic influences.

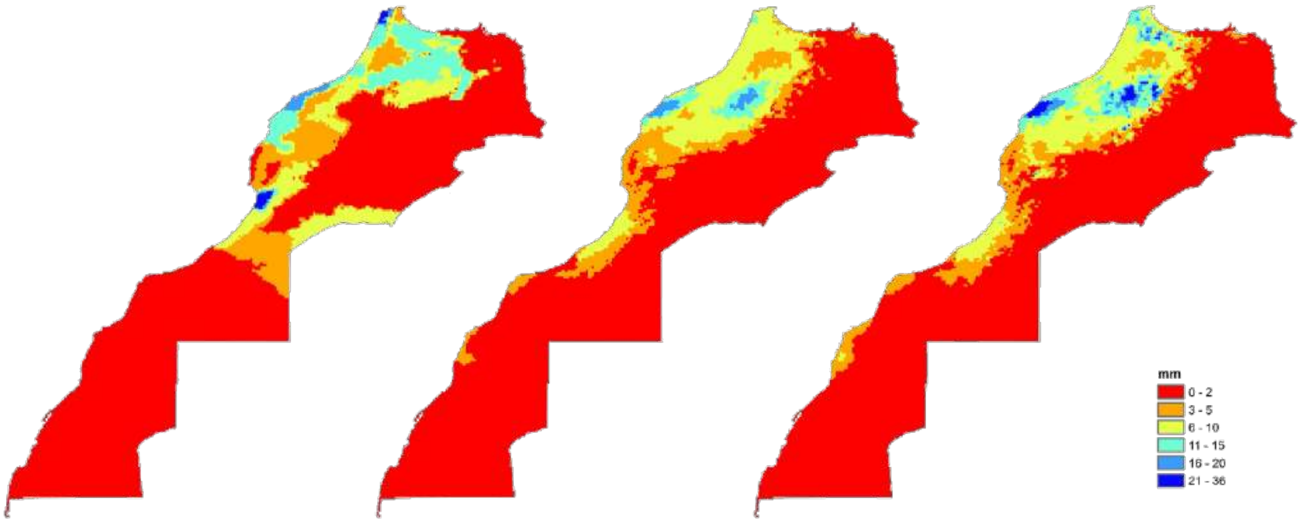

Figure 16 : Precipitation mapping using interpolated data from GDM synoptic stations (left), interpolated ERA5 (center), and interpolated and corrected ERA5 (right). Example of daily precipitation total for December 1, 2023.

The in-depth analysis of Figure 15 and Figure 16 underscores the significant enhancements achieved by the correction of ERA5 data for spatial precipitation mapping in Morocco. The interpolated and corrected ERA5 data offers a marked improvement in both the spatial resolution and the quantitative accuracy of the precipitation estimates, capturing the local variations and gradients that are crucial for understanding the impact of rainfall on agricultural activities at a finer scale.

The integration of this corrected data into the CGMS-Maroc system represents a substantial advancement in the system's capacity to provide reliable and high-resolution precipitation information for agricultural decision-making and climate risk assessment. The improved spatial detail and accuracy of the corrected ERA5 data enable a more precise characterization of the rainfall distribution across different climatic zones and topographic features, enhancing the system's ability to support targeted agricultural interventions and adaptation strategies.

Moreover, the corrected ERA5 data's ability to capture daily precipitation patterns with enhanced accuracy opens new possibilities for short-term forecasting and operational decision-making. The improved daily precipitation estimates can inform irrigation scheduling, crop management practices, and early warning systems for extreme weather events, ultimately contributing to more resilient and productive agricultural systems in Morocco.

2. Block 2: Data integration and analysis for yield forecasting

Block 2 of CGMS-Maroc serves as the core of the system, where multi-source data collected and processed by Block 1 converge to generate high-value information on the state of cereal crops and predict their yields. Hosted on a public server, this block performs crucial functions, including the integration of meteorological and satellite data, predictive modeling, and the development of the crop mask.

One of the primary challenges for Block 2 is the collection and harmonization of relevant remote sensing data for monitoring cereal growth. Two types of indices are particularly valuable: vegetation indices (NDVI, LAI), which provide insights into the vigor and development of vegetation cover, and the SWI, which captures the water status of agricultural lands. These satellite data, inherently spatially distributed but at varying resolutions, are projected onto the CGMS-Maroc reference grid to ensure coherent integration with other information sources coming from Block 1.

Another critical aspect is the development of a cereal crop mask through the classification of high-resolution satellite images. This mask enables the spatial filtering of meteorological data and vegetation indices, retaining only relevant information pertaining to crop areas. It plays a vital role in avoiding confusion with other types of land use and enhancing the accuracy of cereal monitoring and forecasting.

Block 2 also incorporates agricultural statistics derived from field surveys conducted by the Directorate of Strategy and Statistics (DSS) of the Ministry of Agriculture, Maritime Fisheries, Rural Development, and Water and Forests. These surveys provide reference observations on cereal yields at provincial scales, which are essential for calibrating and validating the prediction models developed within CGMS-Maroc.

To forecast cereal yields, three complementary approaches are employed: similarity analysis, which identifies past years with climatic profiles closely resembling the current campaign; multiple linear regressions, which statistically estimate yields based on agro-climatic indices; and machine learning algorithms, particularly random forests, which detect complex and nonlinear patterns in the data. This combination of methods enables the generation of robust predictions by exploring the relationships between climate and yield from various perspectives.

Lastly, Block 2 features a rich and user-friendly interface for visualizing the results of analyses through interactive cartographic representations. This data visualization tool facilitates an intuitive exploration of monitoring indicators and yield forecasts at different spatial and temporal scales, making the information produced by CGMS-Maroc more accessible and actionable for decision-makers and field actors.

Section II.2 provides an in-depth exploration of the processes and methods that underlie the analytical capabilities of Block 2 of CGMS-Maroc. Each stage of the processing chain will be thoroughly examined, encompassing the integration of satellite data, the development of crop masks, and the prediction of yields. Special attention will be given to the modeling approaches utilized and the advantages of the visualization interface. By doing so, we will shed light on how Block 2 transforms the data flow from Block 1 into directly actionable information for effective agricultural risk management and the anticipation of cereal production levels in Morocco. This detailed analysis will highlight the crucial role of Block 2 in harnessing the power of multi-source data to support informed decision-making and enhance the resilience of the Moroccan agricultural sector in the face of climate variability and change.

2.1. Collection of satellite data: Vegetation and Soil Water Indices

CGMS-Maroc retrieves NDVI and LAI vegetation indices, as well as the Soil Water Index, from the Copernicus platform[8]. These indices serve as essential inputs for monitoring vegetation dynamics and predicting crop yields.

2.1.1. Vegetation indices

The vegetation indices employed in CGMS-Maroc, namely NDVI and LAI, are obtained from the Copernicus Land Monitoring Service (Figure 17, Figure 18). These indices are widely used both globally and in Morocco to track vegetation dynamics and forecast crop yields. The literature presents dozens of different vegetation indices, but only a small subset is commonly utilized in practice. These indices can be expressed as simple formulas (e.g., simple difference or simple ratio) or more complex equations. They are categorized into families based on whether they account for factors external to the vegetation cover, such as atmospheric influence, spectral contribution of soils, vegetation water content, etc.

a. Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is one of the most widely used vegetation indices worldwide. It is calculated using reflectances in the red and near-infrared bands of the electromagnetic spectrum, according to the following formula:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

where NIR represents the reflectance in the near-infrared band and Red represents the reflectance in the red band.

NDVI values range from -1 to +1. A high NDVI value (close to +1) indicates a high density of vegetation, while a low value (close to -1) suggests a low density of vegetation or an absence of vegetation.

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[8] https://www.copernicus.eu/

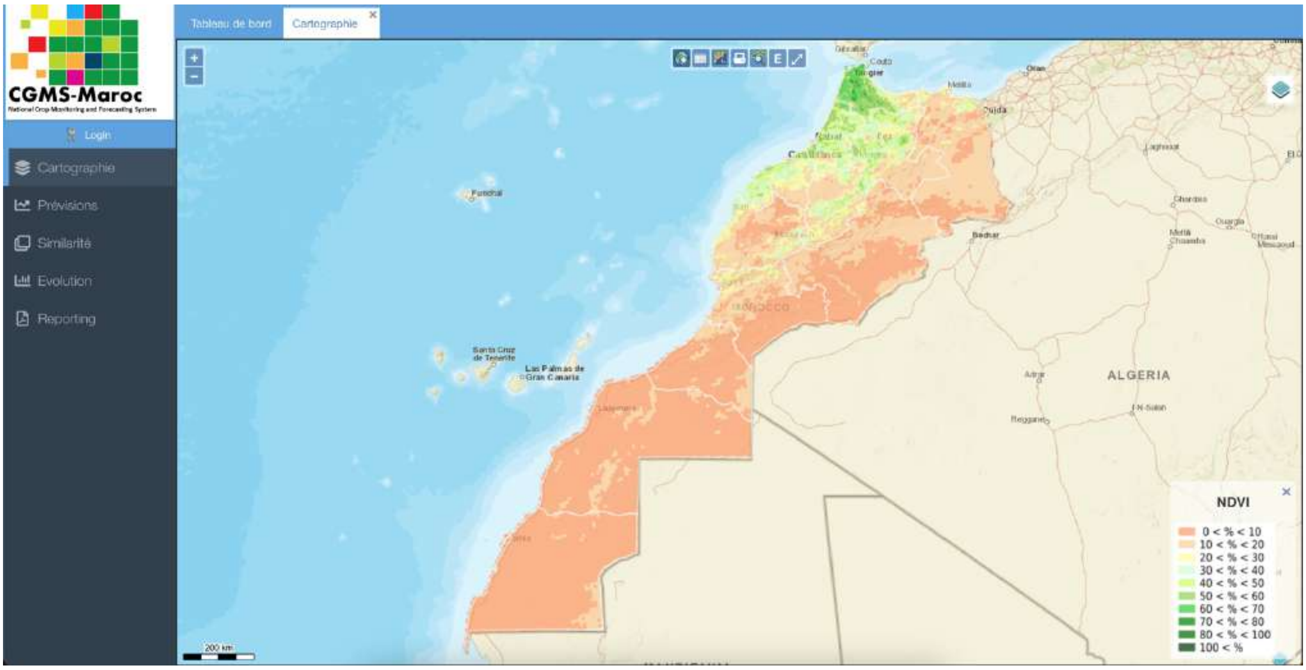


Figure 17 : Mapping of the average NDVI from January to March 2024 at the scale of the reference grid.

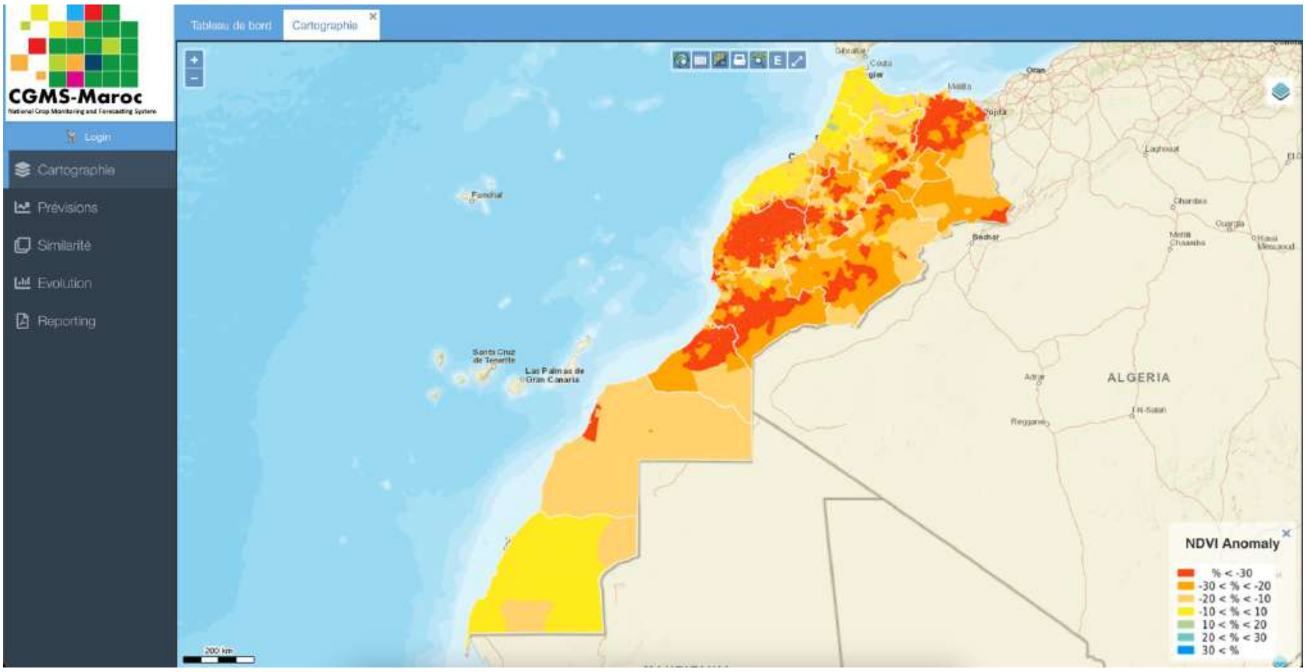


Figure 18 : Mapping of the NDVI deviation from the long-term average, for the period from January 1 to March 31, 2023, at the district scale.

b. Leaf Area Index

The Leaf Area Index (LAI) is a crucial environmental variable that governs the exchange of energy, mass, and momentum fluxes between the Earth's surface and the atmosphere. It plays a pivotal role in the interception of solar energy for photosynthesis while defining the surface area available for gas and water exchanges between the plant and the atmosphere. LAI, expressed as the total leaf area of the canopy per unit ground surface, varies from 0 (bare soil) to more than 10 (dense forest). This index holds significant importance in various models, including those related to ecosystem productivity, global climate, hydrology, ecology, and many others.

In the context of space remote sensing, LAI is defined as half of the total leaf area of the canopy per unit ground surface, primarily in relation to light interception. The projected leaf surface often serves as the central criterion for radiation interception and is influenced by the distribution of leaf angles.

The integration of NDVI, LAI, and the Soil Water Index into CGMS-Maroc enables a comprehensive assessment of vegetation health, growth, and water status. These indices provide valuable insights into crop development, water availability, and potential yield, allowing for informed decision-making in agricultural management and risk assessment. By leveraging the Copernicus platform, CGMS-Maroc ensures access to high-quality and up-to-date satellite data, enhancing the system's ability to monitor and predict crop conditions accurately.

2.1.2. Soil Water Index

The Soil Water Index (SWI) is an innovative product provided by the Copernicus program, playing a central role in monitoring, and assessing soil moisture conditions on a global scale. This index finds critical applications in various domains, including agriculture, water resource management, and the study of ecosystem resilience in the face of climate change.

The SWI stands out for its ability to provide accurate and up-to-date information on the water content of the topsoil layer, down to a depth of 5 cm. To generate this index, data from multiple microwave sensors, such as Sentinel-1 and ASCAT, are combined and analyzed to estimate the volumetric percentage of water in the soil. The SWI is expressed as a percentage, with values ranging from 0% (completely dry soil) to 100% (water-saturated soil).

In Morocco, the SWI is available at a spatial resolution of approximately 12.5 km, enabling a detailed analysis of soil moisture conditions at the regional scale. Although this resolution is coarser than that available in Europe (1 km), it remains sufficiently detailed to provide relevant information at the scale of many Moroccan rural communes, whose average area is around 141 km².

One of the key advantages of the SWI lies in its high temporal frequency. With daily availability, this index offers near-real-time monitoring of soil moisture evolution. This feature is particularly valuable for promptly detecting drought episodes or the impacts of rainfall events, thus enabling increased responsiveness in crop and water resource management.

From a technical perspective, the algorithm underlying the SWI relies on a two-layer infiltration model, which describes the dynamic relationship between the surface soil moisture profile and its vertical evolution over time. This model assumes that the water content of the deeper layer is influenced by the moisture conditions in the surface layer, which in turn depend on the precipitation history.

The formula for calculating the SWI is as follows:

$$SWI(t_n) = \frac{\sum_i^n SSM(t_i) e^{-\frac{t_n - t_i}{T}}}{\sum_i^n e^{-\frac{t_n - t_i}{T}}} \quad for\, t_i \leq t_n$$

In this formula, where ti ≤ tn, with tn being the time of the current measurement observation and ti representing the time of the previous measurement observations (both given in Julian days), it is assumed that the water content of the deeper layer is controlled by the moisture conditions in the surface layer and thus by the precipitation history. The parameter T, called the characteristic time length, represents the time scale of soil moisture variations in units of time T = L/C, where L is the depth of the reservoir layer and C is a pseudo-diffusive constant representative of the region.

In essence, the parameter T indicates how quickly soil moisture changes in response to past precipitation. A smaller T value implies that the soil reacts more rapidly to recent precipitation, while a larger T value suggests that the soil retains the memory of past precipitation over an extended period.

The SWI's ability to capture the temporal dynamics of soil moisture at a high frequency makes it an invaluable tool for monitoring and predicting soil water availability. By integrating the SWI into the CGMS-Maroc system, decision-makers and agricultural stakeholders gain access to timely and reliable information on soil moisture conditions. This information can be leveraged to optimize irrigation scheduling, assess crop water requirements, and develop strategies for mitigating the impacts of drought or excessive rainfall.

Moreover, the SWI's spatial coverage and resolution allow for a comprehensive understanding of soil moisture patterns across different regions of Morocco. This spatial insight is crucial for identifying areas that are more susceptible to water stress or flooding, enabling targeted interventions and resource allocation.

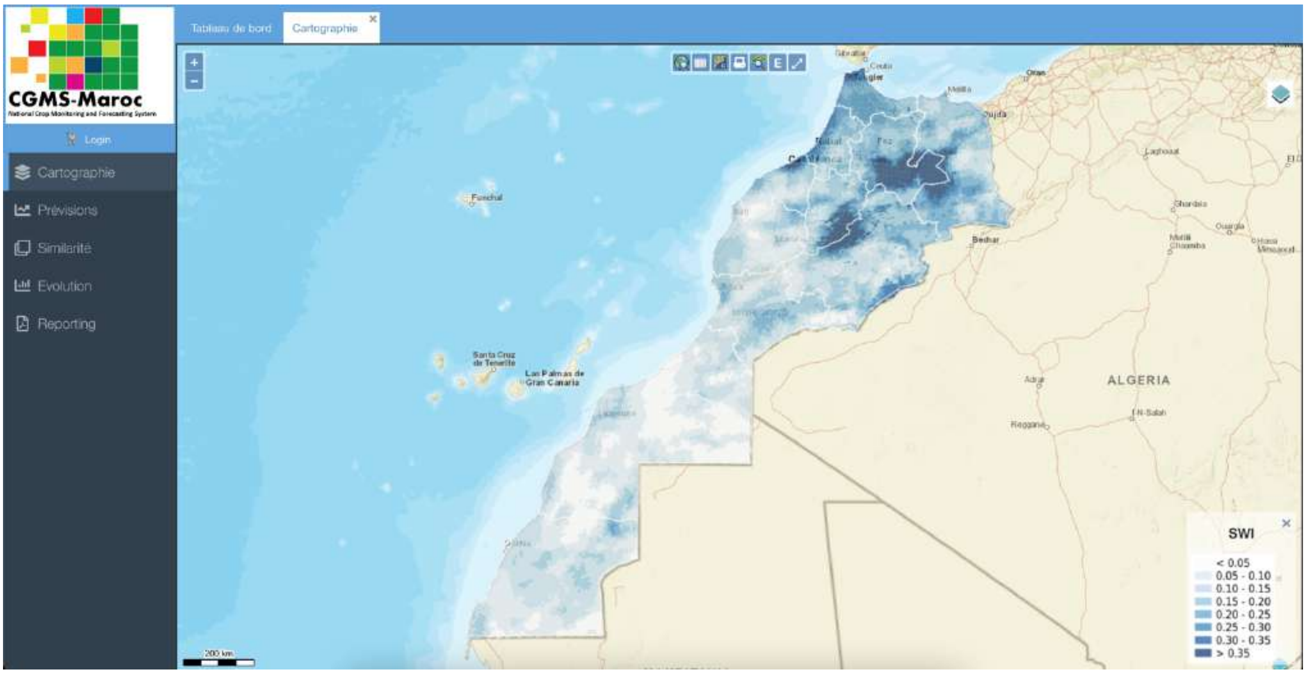


Figure 19 : Average Soil Water Index for the period from September 1, 2023, to March 1, 2024.

2.2. Harmonization of meteorological and satellite data on the CGMS-Maroc reference grid

Satellite data, such as NDVI, LAI, and SWI, are invaluable sources of information for monitoring crop conditions and agrometeorological parameters in the CGMS-Maroc system. To fully leverage the potential of this data, it is essential to integrate it seamlessly with other information sources within the system, particularly interpolated and corrected meteorological data from ERA5 reanalysis. This is where the process of harmonizing satellite data on the CGMS-Maroc reference grid comes into play.

The CGMS-Maroc reference grid, consisting of regular cells measuring 4.5 km in agricultural areas and 9 km elsewhere, serves as a common spatial framework for integrating various data sources. To adapt satellite images to this grid, CGMS-Maroc employs an approach similar to the "Zonal

Statistics" function in ArcGIS, a widely used tool in geomatics for extracting summary statistics from raster data using a vector layer of zones.

The harmonization process for satellite data involves several key steps. First, for each cell of the reference grid, the system identifies the pixels from the satellite images that overlap it, either fully or partially. Then, it calculates the weighted average value of the relevant pixels, considering their overlap area. Consequently, a pixel entirely contained within a cell will have a greater weight in the average calculation compared to a pixel that only partially overlaps the cell. This weighted averaging approach ensures that the contribution of each pixel to the final cell value is proportional to its overlap area, providing a more accurate representation of the satellite data at the cell level.

This approach effectively addresses the differences in spatial resolution between satellite images and the reference grid. It ensures that the value assigned to each cell accurately reflects the information contained in the overlapping pixels, even if those pixels do not perfectly align with the cell boundaries. By considering the spatial heterogeneity within each cell, the harmonization process captures the variability of the satellite data at a finer scale, enhancing the spatial accuracy of the derived indices.

Harmonizing satellite data is particularly crucial for low-resolution products, such as the SWI, whose pixels are larger (12.5 km) than the grid cells. In this case, considering the overlap area of each pixel is essential for obtaining a representative value at the cell level. The weighted averaging approach ensures that the SWI values are appropriately downscaled to match the resolution of the reference grid, enabling a more precise assessment of soil moisture conditions at the local scale.

Upon completion of the harmonization process, each cell of the reference grid is assigned a value for each satellite index (NDVI, LAI, SWI). These harmonized values, now integrated into the grid, can be used in combination with other system data, such as interpolated and corrected meteorological data from ERA5 reanalysis (Block 1), to monitor vegetation health and crop growth conditions. The integration of harmonized satellite data with ERA5 data enables a comprehensive analysis of the interactions between atmospheric conditions, vegetation dynamics, and soil moisture, providing a holistic view of the agrometeorological system.

The harmonization of ERA5 and satellite data on the CGMS-Maroc reference grid brings several key benefits. Firstly, it enables the seamless integration of multi-source data, facilitating a comprehensive analysis of crop conditions and agrometeorological parameters. By aligning all data with the reference grid, it becomes possible to analyze and visualize the spatial and temporal patterns of meteorological data, vegetation indices, and soil moisture at a consistent scale. This consistency allows for the exploration of complex relationships and feedback between atmospheric, vegetation, and soil variables, leading to a deeper understanding of the underlying processes driving crop growth and development.

Secondly, the harmonization process ensures the compatibility and interoperability of satellite data with other components of the CGMS-Maroc system. By adapting the satellite data to the reference grid, it can be readily combined with interpolated and corrected meteorological data from ERA5, crop growth models, and yield forecasting algorithms. This integration enhances the overall accuracy and reliability of the system's outputs, such as crop condition assessments and yield predictions. The harmonized data serves as a foundation for developing robust and spatially explicit models that capture the complex interactions between climate, soil, and vegetation, enabling more accurate simulations of crop growth and yield.

Moreover, the harmonized satellite data can be used to derive additional indicators and metrics that provide valuable insights into crop health, water stress, and productivity. For example, by analyzing the temporal evolution of NDVI and LAI values within each grid cell, it is possible to identify areas experiencing vegetation growth anomalies, phenological shifts, or potential crop failures. Similarly, the SWI can be used to assess soil moisture deficits and identify regions at risk of drought stress, enabling targeted interventions and adaptive management strategies.

The harmonization process also facilitates the integration of satellite data with ground-based observations, such as those from weather stations or field surveys. By aligning the satellite data with the reference grid, it becomes possible to validate and calibrate the derived indices using in-situ measurements, enhancing their accuracy and reliability. This integration of remote sensing and ground-based data enables the development of robust and locally adapted algorithms for estimating key agrometeorological variables, such as evapotranspiration, soil moisture, and crop yields.

2.3. Development of the cereal mask

The cereal mask plays a crucial role in the spatio-temporal filtering of meteorological data and vegetation indices within the CGMS-Maroc system. By focusing exclusively on cultivated areas, the mask enables the extraction of meteorological and satellite information that is directly relevant to cereal farming. This targeted approach significantly reduces spectral disturbances from other land use types, such as natural vegetation, water bodies, or infrastructure, which can introduce noise and uncertainties in the analysis. As a result, the statistical correlations between satellite-derived vegetation indices, moisture data, meteorological variables, and agricultural yields are considerably improved, leading to more accurate and reliable crop monitoring and yield forecasting.

Figure 20 showcases the rainfed agricultural areas mask (known as "bour" zones) developed specifically for CGMS-Maroc to optimize cereal yield forecasts. The spatial delineation of rainfed agricultural lands was achieved by combining two complementary information sources:

- The categorization of agricultural lands into 10 distinct land use classes, including villages, water bodies, forests, large cities, uncultivated areas, pastures, small towns, fruit plantations, irrigated lands, and rainfed lands. This detailed classification was derived using high-resolution SPOT 5 VHR satellite images with a spatial resolution of 2.5 meters, allowing for a precise identification of different land cover types.
- An agricultural land map, called "GlCropV2", specifically created by the Flemish Institute for Technological Research (VITO) as part of the E-AGRI project. This map provides a comprehensive overview of agricultural areas at a spatial resolution of 1 km, ensuring a consistent and reliable representation of croplands across the country.

The development of the cereal mask relies on the reasonable assumption that rainfed agricultural areas serve as a reliable proxy for the spatial distribution of cereal crops. This assumption is supported by the fact that cereals occupy the vast majority of rainfed agricultural lands in Morocco. The agricultural area in the country is limited to 8.7 million hectares, out of a total land area of 710,850 km2, with 81% of this area being cultivated under rainfed conditions. According to official statistics (MAPMDREF, 2018), the agricultural landscape is dominated by cereals, which cover 59% of the total agricultural land, followed by fruit plantations, primarily olive trees, occupying 16% (1.073 million hectares in 2019). In contrast, food legumes and fallow lands represent only a minor portion of the agricultural area, accounting for 3% and 12%, respectively. This land use pattern indicates a cropping system that is heavily focused on cereal production and relies on crop rotation practices.

To ensure a comprehensive coverage of all national agricultural lands, the cereal mask integrates information from both the DSS categorization and the GlCropV2 map. While the DSS categorization provides a highly detailed and accurate delineation of agricultural areas, it does not fully cover the entire country. To overcome this limitation, the GlCropV2 map, despite its lower spatial resolution, is used to complement the available information and fill any gaps in the DSS data. By combining these two sources, the resulting rainfed crop map offers a complete and reliable representation of the spatial extent of cereal cultivation in Morocco.

The development of the cereal mask is a critical step in the CGMS-Maroc system, as it enables the focused analysis of meteorological and satellite data over the areas that are most relevant for cereal production. By excluding non-agricultural land uses, the mask minimizes the influence of confounding factors and enhances the statistical relationships between the input variables and crop yields. This targeted approach improves the accuracy and reliability of crop monitoring, risk assessment, and yield forecasting, ultimately supporting informed decision-making and strategic planning in the agricultural sector.

Moreover, the cereal mask serves as a foundation for various downstream applications within the CGMS-Maroc system. It enables the extraction of crop-specific indicators, such as vegetation health indices, soil moisture estimates, and agrometeorological variables, which can be used to assess crop conditions, detect anomalies, and identify potential risks. By integrating the cereal mask with other components of the system, such as statistical yield forecasting algorithms, CGMS-Maroc can provide timely and actionable information to stakeholders, including farmers, agricultural extension services, and policy-makers.

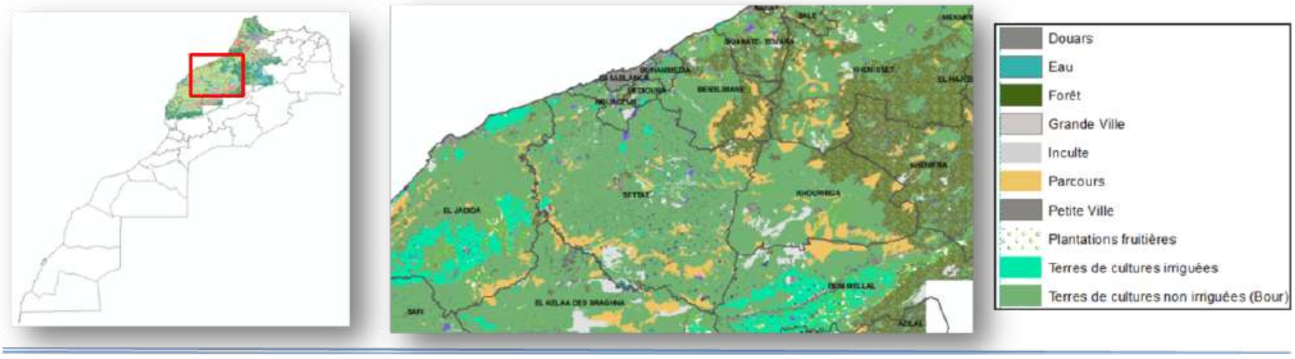
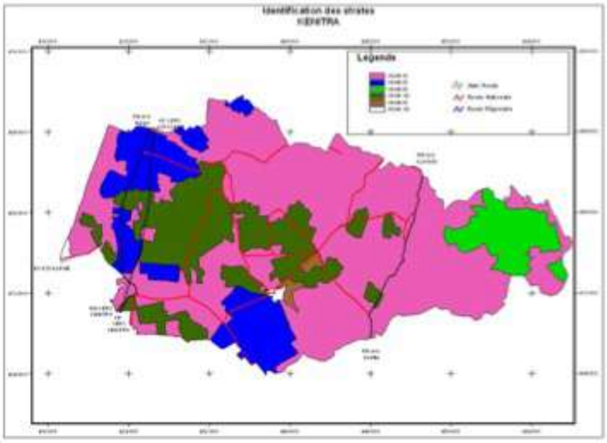


Figure 20 : Agricultural land cover (Balaghi et al., 2017).

2.4. Agricultural statistical data: Field surveys

The CGMS-Maroc system currently generates cereal yield forecasts at the provincial level using statistics available at the same spatial scale. The agricultural statistical data are collected according to a scientifically robust sampling frame, which is designed to ensure the reliability and representativeness of the collected information. Typically, a sampling frame remains valid for a period of 10 to 15 years, unless significant changes occur in the structure of the agricultural landscape. The development of an effective sampling frame requires careful optimization, balancing the implementation costs with the desired level of accuracy. Higher accuracy generally entails increased costs, while lower accuracy is more economically feasible. Expertise in this domain involves creating a sampling plan that minimizes the cost per sampling unit while maximizing the accuracy of the collected data.

In Morocco, as in many countries worldwide, including the United States, Europe, and Asia, agricultural statistics such as cultivated areas and production are commonly derived using a stratified area sampling approach. Stratified area sampling is a probabilistic sampling method in which the target population, in this case, agricultural production, is divided into non-overlapping subgroups or strata (e.g., non-irrigated crop stratum, arboricultural stratum, forest stratum, etc.) (Figure 21). These strata are often delineated using high-resolution satellite imagery, and sampling is subsequently conducted within each stratum to ensure that the sample adequately captures the diversity of the population subgroups.



Stratum number	Description
10	Rainfed land
20	Irrigated land
30	Fruit trees
40	Forest
50	rangeland and wasteland
60	Small city
70	Large city
80	Large village
90	wasteland
100	Water body

Figure 21 : Example of land stratification (Source[1] : DSS).

The DSS is responsible for this task since 1975. The DSS not only oversees the production of agricultural statistics but also manages the design and implementation of surveys, coordinates regional teams, and handles the analysis and dissemination of results. At the provincial level, statistical services are tasked with completing questionnaires related to their respective sample areas, as well as verifying and entering the collected data.

The scope of information managed and provided by the DSS is extensive, covering a wide range of agricultural aspects. It includes data on the production of major crops, the demographic profile of livestock (age, sex, and breed), foreign trade, and the production prices of key cereals, legumes, and olives. Additionally, the DSS maintains records of wholesale prices for major fruits and vegetables.

Regarding cereals specifically, the DSS offers data on the cultivated areas and yields of soft wheat, durum wheat, and barley across 40 provinces in Morocco, with historical records dating back to 1978. The provincial production figures are calculated by multiplying the estimated yield by the cultivated area, both of which are determined through sampling.

The area sampling process conducted by the DSS involves 3,000 Secondary Sampling Units (SSUs), also referred to as segments. The data collection takes place just before the harvest, typically between February 10 and March 30 of each agricultural season, which commences either in September or October, depending on the onset of the first rains. Since 2008, the methodology has evolved to incorporate modern techniques such as satellite remote sensing and Geographic Information Systems (GIS), resulting in improved accuracy of the estimates.

The homogeneous strata are further divided into sampling units, usually in two stages. First, Primary Sampling Units (PSUs) are delineated, and then a small sample of PSUs is selected for further subdivision into Secondary Sampling Units (SSUs). The size of the PSUs and SSUs is flexible and depends on the desired level of accuracy and the available survey resources. In the case of large rainfed crops (known as "Bour") in Morocco, the size of the SSUs is set at 30 hectares (Figure 23).

The stratified area sampling approach employed by the DSS in Morocco serves as a critical foundation for the CGMS-Maroc system. By providing reliable and representative agricultural statistics at the provincial level, it enables the system to generate accurate cereal yield forecasts and support informed decision-making in the agricultural sector. The integration of modern technologies, such as satellite remote sensing and GIS, has further enhanced the precision and efficiency of the sampling process, ensuring that the collected data accurately reflects the reality on the ground.

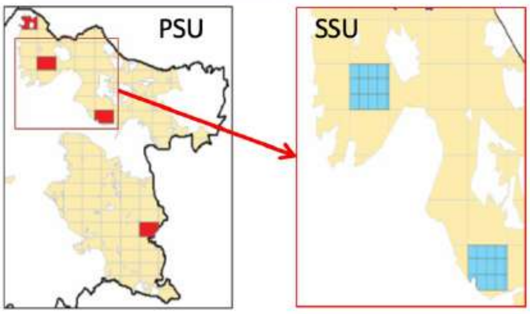
Moreover, the long-term historical data maintained by the DSS, dating back to 1978, allows for the analysis of trends and patterns in cereal production over time. This historical perspective is invaluable for understanding the impact of various factors, such as climate variability, technological advancements, and policy interventions, on the productivity and resilience of the Moroccan agricultural system.

Size of the Primary Sampling Units (PSU)

Stratum ID	Area of the PSU (hectares)
10, 20 and 30	500 < < 1000
40 and 50	2000 < < 4000
60	20 < < 40
70	10 < < 20
80	40 < < 80

Size of the Secondary sampling Units (SSU)

Stratum ID	Size of the SSU (hectare)
10	30
20	30
30	30
40	200
50	200
60	2
70	1
80	4



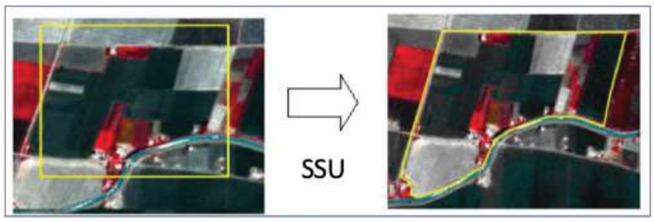


Figure 22 : Primary and secondary sampling units at the provincial level in Morocco (Source[1] : DSS).

2.5. Yield forecasting methodologies

Before the development of the CGMS-Maroc system, cereal yield forecasting was performed using a standalone statistical tool called the CGMS Statistical Tool (CST). This tool was originally designed in 1994 by Wageningen University (Hoek et al., 2009) in the Netherlands for the Joint Research Centre (JRC) of the European Commission, with the aim of forecasting crop yields at the European Union scale. As part of the E-AGRI project, the CST was adapted to the Moroccan context, allowing for the estimation of cereal yields based on three main data categories:

- **Simulations from WOFOST** (WOrld FOod STudies) simulation model, which was specifically calibrated for Moroccan conditions (Confalonieri et al., 2013; Bregaglio et al., 2015). These simulations generated indicators of crop growth and development, considering local environmental factors and management practices, used as cereal yield predictors.
- **Annual rainfall data**, collected from September onwards from GDM meteorological stations across the country.
- **Vegetation indices**, such as NDVI, derived from satellite imagery. These indices serve as proxies for the state and vigor of vegetation cover, providing insights into crop health and productivity.

The CST employed a specific Principal Component Analysis (PCA) technique, referred to as "scenario PCA", and multiple linear regression models[9] to generate yield forecasts. However, the linear regression module of the CST had certain limitations. It only allowed for the manual

[9] Statistical method modeling the relationship between a target variable and several explanatory variables.

selection of a restricted number of predictive variables, which constrained the flexibility and comprehensiveness of the forecasting process. Despite these limitations, the CST could produce forecasts at various spatial scales, ranging from the provincial level to agroecological zones and even at the national level. These forecasts were typically generated between the end of February and the end of April, providing valuable information for agricultural decision-making and policy planning.

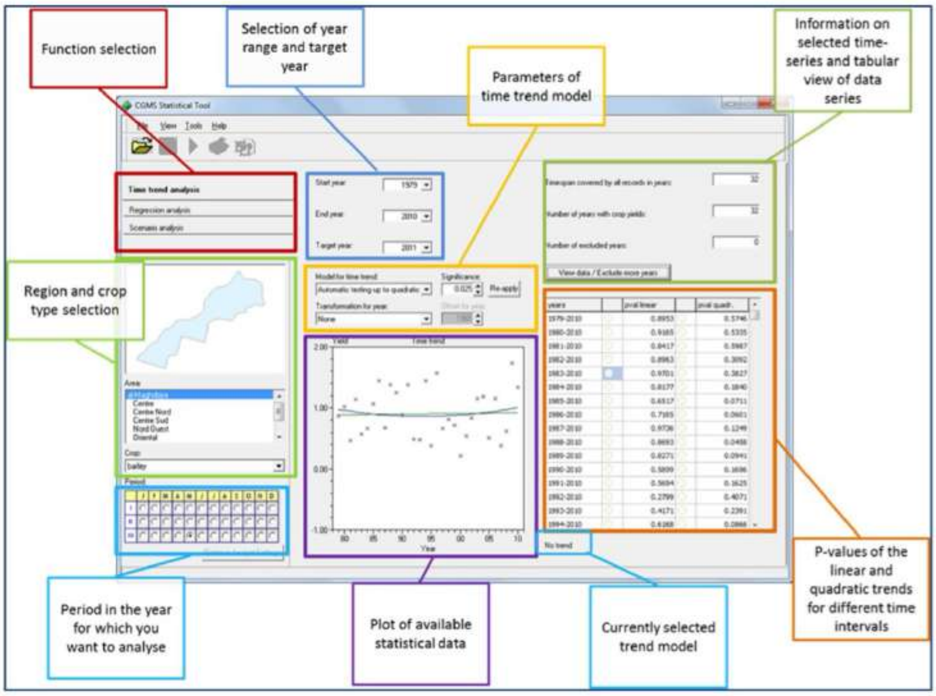


Figure 23 : The former CGMS Statistical Toolbox software for statistical analysis of cereal yield forecasting (Balaghi et al., 2012a).

The introduction of the CGMS-Maroc system marked a significant advancement compared to the CST. This new system seamlessly integrated and automated all the previously developed forecasting tools into a unified interface, streamlining the yield prediction process. More importantly, CGMS-Maroc expanded the realm of possibilities by incorporating state-of-the-art advancements in three complementary domains:

1. **Similarity analysis techniques:** These methods enable the identification of past cropping seasons with analogous conditions to the current growing season. By leveraging historical data and identifying similar patterns, these techniques provide a basis for yield forecasts.
2. **Multiple linear regressions:** These statistical models allow for the quantification of relationships between agro-climatic variables and cereal yields. By considering multiple predictors simultaneously, these regressions capture the complex interactions influencing yield variability.
3. **Machine learning algorithms:** CGMS-Maroc harnesses the power of machine learning, particularly using "Random Forests" and “Boosted Trees”. These algorithms can autonomously learn from historical data, uncovering intricate patterns and relationships that may not be apparent through traditional statistical methods.

The integration of these advanced methodologies in CGMS-Maroc has greatly enhanced the system's predictive capabilities. By leveraging similarity analysis, multiple linear regressions, and machine learning algorithms, CGMS-Maroc can generate more accurate and reliable yield forecasts, considering a wide range of agro-climatic factors and their complex interactions. This holistic approach enables the system to capture the nuances and variability of cereal yields in Morocco, providing valuable insights for agricultural stakeholders and decision-makers.

Moreover, the automation and streamlining of the forecasting process in CGMS-Maroc have significantly improved the efficiency and timeliness of yield predictions. The system can rapidly process large volumes of data from multiple sources, generating forecasts at various spatial scales and time horizons. This enhanced efficiency allows for more frequent updates and real-time monitoring of crop conditions, enabling proactive decision-making and risk management in the agricultural sector.

2.5.1. Modeling approach in CGMS-Maroc

The development of CGMS-Maroc employs an approach that focuses on using yield prediction models approaches that strike a balance between robustness and compatibility with the quality of available data. The primary goal is to establish explicit, verifiable, and adaptable models that can effectively capture the unique characteristics of cereal agriculture in Morocco.

The process of developing cereal yield prediction models in CGMS-Maroc is guided by five fundamental principles:

- **Relevance:** Thoroughly understanding the needs and requirements of users within the Ministry of Agriculture to ensure that the developed models are well-suited to the Moroccan context.
- **Parsimony:** Prioritizing simplicity in model design, gradually introducing additional complexity only when clearly warranted and justified. Initiating the modeling process with small but high-quality datasets.
- **Robustness:** Implementing strict quality control measures on the data used for model training and validation. Proactively identifying and addressing errors, uncertainties, and outliers to ensure the reliability of the models.
- **Pragmatism:** Acknowledging the inherent limitations of available data and adopting a pragmatic approach when defining the scope and capabilities of the models. Prioritizing the accurate representation of agro-climatic processes over the pursuit of statistical perfection.
- **Adaptability:** Continuously refining and updating models to reflect advancements in knowledge and evolving agricultural practices. Maintaining a diverse and representative dataset that captures real-world conditions to ensure the models remain relevant and applicable.

2.5.2. A diversified approach to yield prediction

CGMS-Maroc uses a multifaceted methodology for predicting cereal yields, leveraging a diverse array of techniques. This multilayered approach enables the generation of reliable forecasts while also assessing and quantifying the inherent uncertainties associated with them. Addressing uncertainty is crucial given the complexity of the system and the numerous sources of uncertainty stemming from data quality limitations and the necessary simplifications involved in modeling intricate natural phenomena.

1. **Similarity analysis:** This initial category involves exploring historical archives to identify past years that exhibit conditions similar to the current year. While this method can provide valuable insights, its effectiveness is dependent on the quality and completeness of historical data and the assumption that the relationships between variables remain consistent over time.

2. **Modeling agro-climatic relationships:** Two distinct approaches are employed to model the interactions between agro-climatic variables and cereal yields:
    a. **Classical statistical regressions:** Techniques such as multiple linear regression provide a transparent framework for modeling the relationships between variables and yields. These methods are known for their robustness, although they may occasionally oversimplify the complexity of real-world interactions.
    b. **Machine learning algorithms:** Advanced techniques, including neural networks and random forests, possess the ability to identify nonlinear and complex patterns that often go undetected by traditional regression models. However, these algorithms can be sensitive to erroneous data and are prone to overfitting, potentially overreacting to anomalies in the data and resulting in excessively complex models.

Utilizing this diverse range of models is crucial for evaluating the robustness of the cereal yield forecasts generated by CGMS-Maroc. The strength of this approach lies in its ability to generate multiple prediction scenarios, encompassing a wide spectrum of potential uncertainties. When the results from these different models converge, it enhances confidence in the obtained forecasts. Conversely, significant discrepancies between models highlight areas of uncertainty that require careful consideration. By employing a plurality of approaches, decision-makers are provided with a comprehensive understanding of the uncertainties involved, allowing them to naturally integrate this information into the decision-making process. This is a critical aspect of anticipating agricultural yields with a reasonable degree of confidence.

a. Similarity analysis: A Method based on past experience to forecast cereal yields

Similarity analysis seeks to identify historical cropping seasons that closely mirror the current one, concentrating on key factors such as rainfall (Balaghi et al., 2012a). This method operates on the premise that similar climatic conditions are likely to produce similar crop yields.

The efficacy of similarity analysis depends greatly on the richness and length of the historical data available. A diverse and extensive time series increases the likelihood of identifying seasons that closely match the current conditions, enhancing the accuracy and reliability of the analysis. Conversely, a shorter or less varied time series may limit the ability to find relevant historical examples, thus weakening the predictive power of the analysis. To overcome this limitation, it is essential to maintain a comprehensive, regularly updated database of historical cropping seasons that captures a wide range of climatic variability. Expanding the range of potential analogues through regular updates and the inclusion of new data points can significantly improve the robustness of similarity analysis. Additionally, employing multiple agro-climatic indices and considering finer spatial and temporal patterns can increase the likelihood of finding appropriate historical matches. If no close analogues are found, alternative methods like crop modeling or statistical techniques might be necessary to supplement or substitute for similarity analysis.

However, applying past yields directly to current conditions without considering technological advancements overlooks the impact of agricultural progress. Adjusting yields from similar past seasons to account for technological improvements is essential, especially given the considerable variability in annual precipitation in Morocco, which complicates the identification of consistent trends in rainfed crop yields (Balaghi et al., 2012a). Data from 2001 to 2022 show notable improvements in yields, aligned with the "Green Morocco Plan" (2008-2020). For example, wheat yields increased by about 4 quintals per hectare, and barley yields by nearly 2 quintals per hectare (Figure 24). These technological advancements are crucial for recalibrating yields in similar seasons, allowing the analysis to not only reflect climatic similarities but also incorporate a forward-looking agronomic perspective. This integration enhances the predictive accuracy of the analysis, enriching the forecasts produced by systems like CGMS-Maroc.

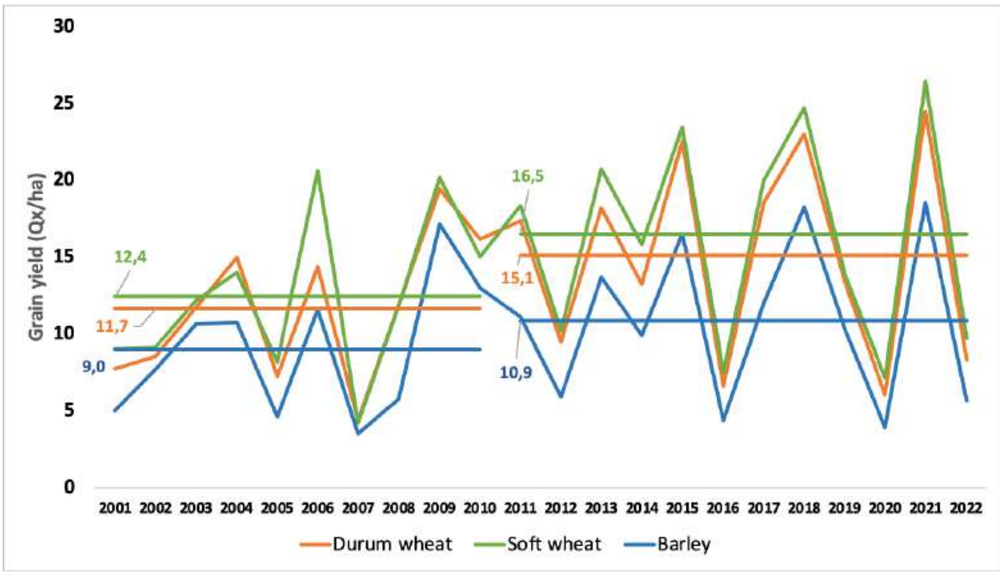


Figure 24 : Evolution of grain cereal yields in rainfed areas from 2001 to 2022 at the national level.

Moreover, similarity analysis provides valuable insights into the current cropping season by leveraging experiences from past seasons with similar conditions. Analysts, equipped with robust agronomic and meteorological expertise, play a critical role in interpreting the potential outcomes of the current season based on these historical analogues. By comparing the current season with its historical counterparts, analysts gain a deeper understanding of the factors influencing crop growth and development. This knowledge helps assess the likely impact of current conditions on yield potential, considering the unique mix of climatic variables and their interactions.

Furthermore, the insights derived from similarity analysis can inform proactive decision-making and risk management strategies, allowing stakeholders to optimize crop management, adapt to evolving conditions, and mitigate potential risks. This may involve adjustments in irrigation schedules, pest and disease control measures, or modifications to harvest plans based on anticipated outcomes from the analysis.

For instance, a similarity analysis for the 2022-2023 cropping season conducted for the province of Benslimane (Figure 25) reveals that the 2013-2014 season exhibits the greatest similarity in terms of rainfall, followed by the 2006-2007 season and others, with the most distant being the 2015-2016 season. The yields observed during the 2013-2014 season serve as a direct reference for the 2022-2023 season, without the need for adjustments due to the lack of significant technological progress at the scale of the province from 2011-2022. These yield figures are then used to calculate the expected production for the current season by multiplying them by the area currently under cultivation.

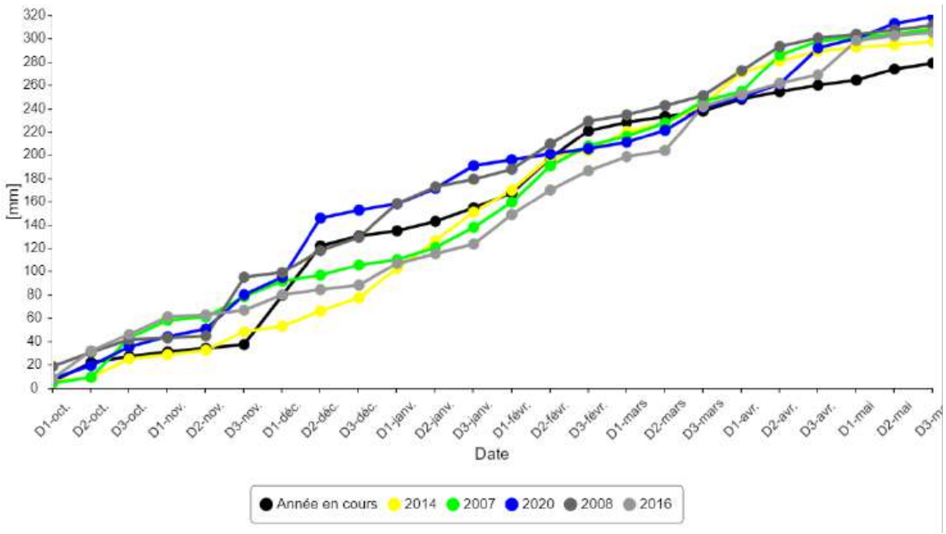


Figure 25 : Similarity analysis in CGMS-Maroc, based on total rainfall from October 1, 2013, to April 15, 2014, at the scale of Benslimane province.

b. Models depicting the relationships between agro-climatic variables and cereal yields

CGMS-Maroc employs predictive modeling of cereal yields, customized to regional agro-climatic conditions. These models, which utilize either statistical regressions or machine learning techniques, are designed at the provincial level to account for local variations and enhance the precision of yield forecasts.

Cereal growth cycle analysis

To optimize the correlation between agro-climatic variables and cereal yields, the explanatory variables—sourced from meteorological data or satellite imagery—are specifically calculated for the phenological cycle of cereals. Due to the lack of comprehensive phenological data at the national level, the growth cycles are estimated using a remote sensing technique developed by NASA (Li et al., 2014).

This method utilizes time-series data from MODIS vegetation indices to construct a theoretical profile of the EVI2 (two-band enhanced vegetation index) for each pixel. This is achieved using the MCD12Q2 Land Cover Dynamics maps. Key phenological stages such as emergence, maturity, and harvest are identified by characteristic transitions in the EVI2 profile, marked at 15%, 50%, and 90% of the profile's amplitude (Table 6). This process ensures a precise alignment of growth stages with observed vegetation dynamics, enhancing the accuracy of yield forecasts.

$$EVI2 = 2.5 * ((NIR - Red)/(NIR + 2.4 * Red + 1))$$

Table 6: Estimation of phenological stages dates based on the EVI2 index profile.

Stage	Description	Date
Greenup	Emergence	When EVI2 first crossed 15% of the amplitude of the EVI2 segment
MidGreenup	50% of crop development peak	When EVI2 first crossed 50% of the amplitude of the EVI2 segment
Maturity	Maturity	When EVI2 first crossed 90% of the amplitude of the EVI2 segment
Peak	Peak of crop development	When EVI2 reached the maximum amplitude of the EVI2 segment
Senescence	Senescence	When EVI2 last crossed 90% of the amplitude of the EVI2 segment
MidGreendown	50% of crop decline	When EVI2 last crossed 50% of the amplitude of the EVI2 segment
Dormancy	Harvest	When EVI2 last crossed 15% of the amplitude of the EVI2 segment

To optimize the extraction of satellite indices that correlate most closely with yield, six distinct phenological periods (P0 to P5) are identified (Figure 26):

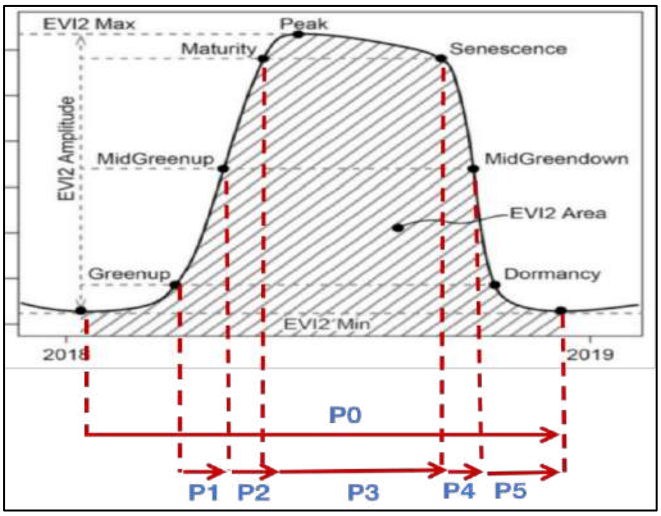


Figure 26: Theoretical profile of the EVI2 index, indicating the different phenological stages of crops and index extraction periods (P0 to P5). Adapted from Gray et al., 2019.

P0: Complete cycle — from emergence to harvest.

P1: Emergence to mid-growth — initial growth phase.

P2: Mid-growth to maturity — development phase.

P3: Maturity to senescence — ripening phase.

P4: Senescence to mid-decline — early post-maturity phase.

P5: Mid-decline to harvest — final phase before harvesting.

This method provides objective estimates of key dates in the cereal growth cycle for each Spatial Unit, optimizing yield correlations within CGMS-Maroc. It presents a straightforward, automated, and adaptable approach, although it has some limitations. By enhancing the understanding of crop phenology in Morocco, this method aids in selecting relevant satellite indices for accurate yield prediction.

Linear regression: Explicit modeling of variable-yield relationships

In addition to similarity analysis, CGMS-Maroc utilizes multiple linear regression (MLR) models to predict yields of major cereals (durum wheat, soft wheat, and barley) for each province. These models are developed by leveraging:

- Historical data on observed yields, scaled to administrative province.
- Aggregated indices calculated at the same scale from meteorological factors (such as precipitation and temperatures) and ET0, as well as agro-climatic indices derived from satellite imagery (including NDVI, LAI, and SWI).

The multiple linear regression approach statistically links historical yield fluctuations with variations in key agro-climatic factors and indices, facilitating the forecasting of cereal yields at provincial level.

Model development process

The development of multiple linear regression (MLR) models in CGMS-Maroc follows a structured approach:

1. **Calculation of Indices:** For each cereal and each province, a series of potential indices is derived from meteorological and satellite data, tailored to the phases of the identified cereal growth cycle.
2. **Creation of Correspondence Tables:** For each cereal and province with at least eight years of observed yield data, to ensure statistical robustness, tables are created to link the observed yields with indices aggregated at the provincial level.
3. **Model Development:** For each cereal and province, a sequential process of model construction is adopted:
    a. Random exclusion: 20% of the agricultural seasons are randomly excluded from the dataset (N) of available seasons.
    b. Stepwise selection: The "Stepwise" method is applied to the remaining 80% of cropping seasons to identify a linear regression model, retaining only the most correlated and non-redundant indices. Models are selected based on the highest coefficient of determination[10] (R-squared), noting that a high R-squared alone does not guarantee predictive accuracy (Balaghi et al., 2012a), necessitating cross-validation.
    c. Cross-validation: Implement a cross-validation methodology by recalculating the model parameters from step 3.b for N-1 cropping seasons, omitting one season at each iteration (Balaghi et al., 2008). The root mean square error (RMSE) is calculated, measuring the model's predictive accuracy.
    d. Model selection: After 10 iterations of steps 3.a to 3.c, 10 predictive models are generated. The model with the lowest RMSE is selected as the definitive model.

This methodology ensures the development of robust MLR models for each cereal and province. These models undergo systematic evaluation based on criteria including the coefficient of determination (R^2), RMSE, and relative error percentage, among others.

Advantages and limitations of MLR Models in CGMS-Maroc

The development of MLR models offers several benefits. Firstly, the explicit nature of these models provides clear insights into the relationships between agro-climatic predictors and cereal yields, helping to identify key factors influencing yield variability. This supports targeted interventions and informed policy decisions. Additionally, the use of historical yield data and aggregated indices at the provincial scale ensures that the models reflect local agro-climatic realities.

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[10] Measure of the variance explained by a statistical model.

However, it's crucial to recognize the limitations of linear regression models. While they provide simplicity and interpretability, they may not capture complex non-linear relationships between variables and yields. Furthermore, the performance of these models heavily depends on the quality and representativeness of the input data. Incomplete or biased data can compromise model performance and predictive accuracy.

To mitigate these issues, CGMS-Maroc implements a comprehensive model evaluation and validation process. Cross-validation helps assess the models' robustness and generalizability, reducing overfitting risks. Systematic performance evaluations using multiple criteria ensure that the selected models are reliable and provide accurate yield forecasts.

CGMS-Maroc continually updates and refines the MLR models as new data becomes available. Incorporating additional seasons of observed yield data and improved agro-climatic indices enhances the models' predictive capabilities.

Quality assurance for robust modeling

The robustness of MLR modeling is crucial for ensuring accurate and reliable yield forecasts within the CGMS-Maroc system. To achieve this, a comprehensive quality assurance framework has been established, evaluating, and enhancing MLR modeling robustness based on meteorological and satellite data at the national level (Table 7). This framework covers a broad spectrum of processes, including data collection, preprocessing, variable selection, model building, adherence to modeling assumptions, performance evaluation, sensitivity analysis, model updating, documentation, and peer review. Systematically addressing each of these areas, the framework aims to maintain the highest standards of quality and reliability in the modeling process.

To quantitatively assess the effectiveness of the framework, a set of key performance indicators (KPIs) has been defined. These KPIs offer objective metrics for evaluating the robustness of the modeling process across different stages. For instance, data accuracy and completeness, along with handling of missing data, are indicators for assessing data collection quality. Outlier detection rate and data standardization accuracy are KPIs for data preprocessing effectiveness. Accuracy in variable selection, predictor significance, and correlation analysis results gauge the variable selection process. Model accuracy metrics, such as R-squared and adjusted R-squared, along with residual analysis results and validation accuracy, are employed to assess the model building stage. By monitoring and analyzing these KPIs, CGMS-Maroc can pinpoint improvement areas and implement necessary enhancements to increase modeling robustness.

Additionally, the framework includes programming considerations to ensure each aspect is implemented using efficient, scalable, and maintainable programming techniques. For example, during the data collection stage, the framework advocates for efficient data retrieval and processing algorithms, automation of data collection procedures, and effective management of large data volumes. In data preprocessing, it recommends automated data cleaning, consistent data standardization, and optimization of preprocessing algorithms for computational efficiency. These programming considerations ensure that the quality assurance framework is not only conceptually robust but also practically implementable with advanced programming practices.

Adhering to this comprehensive quality assurance framework enables CGMS-Maroc to maintain the robustness and reliability of the MLR modeling process for cereal yield prediction. This structured approach facilitates thorough evaluation and continual enhancement of data quality, variable selection, model building, and performance assessment. The integration of key performance indicators enables quantitative monitoring and ongoing improvement of the modeling process. Moreover, programming considerations ensure that the implementation of quality assurance measures is efficient and sustainable from a computational perspective.

The benefits of this framework extend beyond the immediate applications within the CGMS-Maroc system. By establishing a rigorous, standardized approach to modeling quality assurance, the framework not only enhances the reliability and credibility of the yield forecasts produced but also fosters increased confidence among decision-makers, stakeholders, and end-users. These groups can rely on the accuracy and robustness of the predictions, enabling informed decision-making based on CGMS-Maroc's outputs. Additionally, this framework serves as a model for best practices in crop yield modeling and agricultural decision support systems, encouraging the adoption of robust quality assurance practices in wider agricultural modeling efforts.

Table 7: Quality assurance framework for robust statistical crop yields modeling.

Aspect	Description	Key Performance Indicators	Programming considerations
Data collection	Ensure the collection of accurate and reliable meteorological and satellite data from reputable sources. Use standardized protocols for data collection to maintain consistency. Verify data quality, including accuracy, precision, and completeness. Handle missing data appropriately (e.g., interpolation, data imputation).	Data accuracy and precision, data completeness, missing data handling.	Implement efficient data retrieval and processing algorithms. Automate data collection procedures. Efficiently handle large volumes of data.
Data preprocessing	Perform thorough data preprocessing steps, including data cleaning, outlier detection, and removal or correction. Standardize data to a consistent scale to eliminate potential biases due to different units of measurement.	Outlier detection rate, data standardization accuracy.	Develop code for automated data cleaning and outlier detection. Implement data standardization functions to ensure consistent scaling. Optimize preprocessing algorithms for computational efficiency.
Variable selection	Conduct a thorough analysis of variables to select the most relevant predictors for modeling cereal yields. Consider both meteorological and satellite variables based on their biological relevance, statistical significance, and correlation with cereal yield. Utilize domain knowledge and statistical techniques (stepwise regression) for variable selection.	Variable selection accuracy, predictor significance, correlation analysis results.	Implement automated variable selection algorithms. Develop functions for calculating statistical significance and correlation coefficients. Optimize variable selection procedures for speed and accuracy.
Model building	Employ appropriate modeling techniques (multiple regression, etc.) to construct the cereal yield prediction model. Validate the model using suitable techniques such as cross-validation, holdout validation, or bootstrapping. Assess model fit quality, including measures such as R-squared, adjusted R-squared, and residual analysis.	Model accuracy (R^2, adjusted R^2), residual analysis results, validation accuracy	Develop functions or classes for model construction and evaluation. Optimize model fitting algorithms for efficiency. Implement validation techniques using programming libraries or custom code.
Modeling assumptions	Verify the assumptions of the chosen modeling technique (linearity,	Assumption verification results,	Implement functions to test model assumptions and

	independence, homoscedasticity, etc.) and address violations using appropriate transformations or robust modeling techniques if necessary.	transformation accuracy.	detect violations. Develop code to transform variables and handle non-linear relationships. Use robust modeling algorithms when assumptions are not met.
Model prformance	Evaluate the model's performance by assessing its predictive accuracy and precision. Use measures such as Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), and Pearson's correlation coefficient (r) between predicted and observed cereal yields. Compare the model's performance to other benchmark models or historical data.	RMSE, Coefficient of correlation, Performance Comparison with reference models.	Implement functions to calculate performance measures. Develop code for comparison with benchmark models. Optimize calculations for computational efficiency.
Sensitivity analysis	Perform sensitivity analysis to assess the model's robustness and identify influential predictors. Vary input variables within plausible ranges and observe the impact on model output. Identify potential sources of uncertainty and quantify their effect on model predictions.	Sensitivity analysis results, predictor influence assessment, uncertainty quantification.	Develop functions or scripts for sensitivity analysis. Automate the variation of input variables and observation of model outputs. Implement methods for uncertainty quantification (Monte Carlo simulations, etc.).
Model updating	Regularly update the model by incorporating new data and refining the variable selection and model building process. Perform model validation and recalibration to ensure it remains accurate and reliable over time. Monitor changes in data sources and adjust preprocessing steps accordingly.	Update frequency, model validation accuracy, recalibration success rate.	Create scripts or workflows for automated model updating. Implement procedures for integrating new data and retraining the model. Develop functions for model validation and recalibration.
Documentation	Maintain detailed documentation of all analysis steps, including data sources, preprocessing procedures, variable selection criteria, model specifications, and evaluation measures. Document any assumptions made during the analysis. Clearly report the limitations and uncertainties associated with the model.	Documentation completeness, clarity of assumptions and limitations.	Include comments and annotations in the code for better understanding. Document data processing and analysis scripts. Prepare clear and comprehensive reports summarizing programming steps and results.

Integrating machine learning for enhanced cereal yield forecasts in CGMS-Maroc

CGMS-Maroc enhances its cereal yield forecasting by incorporating machine learning algorithms alongside traditional statistical methods. Machine learning, a subset of artificial intelligence, develops algorithms that learn from data autonomously, without explicit programming. These algorithms process extensive datasets to discern patterns, formulate mathematical models, and reveal intricate statistical relationships. Once trained, they can apply these insights to make predictions or decisions based on new, unseen data.

Among various machine learning techniques, random forests stand out due to their robustness and versatility (Breiman, 2001). This ensemble learning method combines multiple decision trees, each trained on a random data subset with a random selection of features. This approach not only minimizes overfitting but also enhances the model's accuracy and generalization capability by averaging the predictions from numerous trees.

In CGMS-Maroc, random forests complement traditional methods like multiple linear regressions and similarity analysis, offering a robust alternative capable of capturing complex, nonlinear dependencies. Unlike linear models, which require precise variable selection and are limited to linear relationships, random forests excel in identifying subtle patterns and interactions that might elude simpler models. This capability is crucial given the complexity of factors influencing cereal yields. However, the adaptability of random forests comes with reduced interpretability compared to linear models, where the impact of each variable is more straightforward to discern (Table 8).

A pivotal study by Bouras et al. (2021) demonstrated the effectiveness of random forests for predicting cereal yields early in the season across Morocco's provinces. Leveraging diverse data sources, including satellite imagery and meteorological data, random forests outperformed linear regression models, underscoring their superior capacity to model the intricate dynamics of crop growth and yield formation.

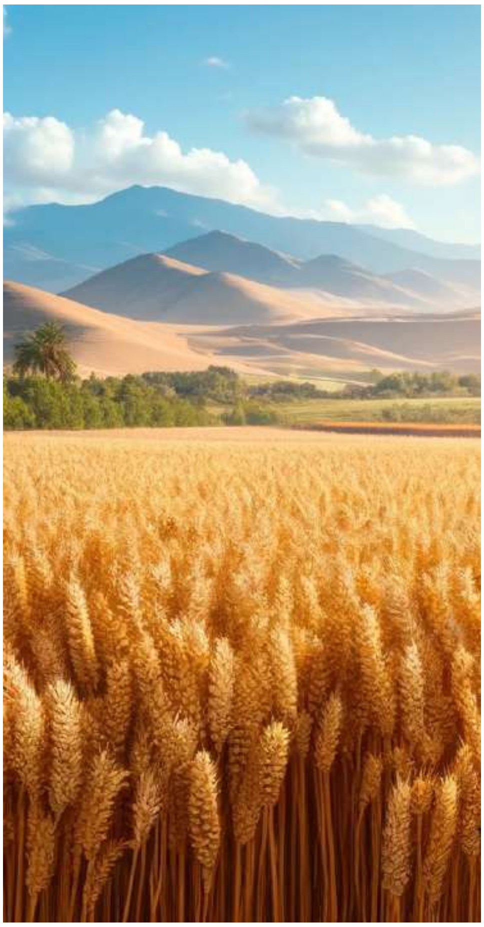
Table 8: Comparative analysis: Linear Regression vs. Random Forests.

Criterion	Linear Regression	Random Forests
Assumptions	Linear relationship between predictive variables and target variable	No assumptions about the form of the relationship
Nonlinearity	Can only model linear relationships	Can capture complex nonlinear relationships
Number of variables	Suitable for a limited number of predictive variables to avoid overfitting	Can handle a very large number of predictive variables
Outliers	Sensitive to outliers that can distort the model	Robust due to aggregation over many trees
Interpretability	Coefficients are easily interpretable	Difficult to interpret variable importance
Regularization	High risk of overfitting	Intrinsically regularized, no overfitting
Implementation	Simple algorithm to implement	Requires significant computational power
Prediction	Good performance on simple linear problems	Excellent performance on a wide range of problems

The successful deployment of random forests within CGMS-Maroc highlights the transformative potential of machine learning in agricultural forecasting. This approach not only improves the accuracy and timeliness of yield predictions but also equips decision-makers with deeper insights into the complex interplay of environmental factors affecting crop growth.

As CGMS-Maroc continues to evolve, integrating new data sources and advanced modeling techniques, the role of machine learning algorithms like random forests is poised to expand. Their capacity to assimilate extensive data and adapt to variable conditions makes them particularly suited to the dynamic and multifaceted nature of agricultural systems. By marrying machine learning's analytical strength with agricultural expertise, CGMS-Maroc aims to enhance the reliability, accuracy, and applicability of its forecasts, supporting sustainable agricultural practices and ensuring food security in Morocco.

2.6. Yield forecasts



The predictive capabilities of CGMS-Maroc for forecasting cereal yields at provincial and national levels have been evaluated against officially observed yields for soft wheat, durum wheat, and barley across 22 agricultural seasons, from 2000-2001 to 2021-2022 (Figure 27). Yield predictions were generated using a combination of linear regression models and advanced machine learning techniques, namely Random Forests and Extra Trees.

These models utilized satellite predictors including vegetation indices (NDVI, LAI), ERA5 precipitation and temperature data, interpolated reference evapotranspiration (ET0), and the SWI.

2.6.1. Model performance and comparison

Figure 27 visually compares observed and predicted cereal yields at the national level, using regression models, Random Forests, and Extra Trees. The graphs illustrate the models' performance over the 22 seasons, highlighting their capability to capture interannual yield variability. The blue shaded area indicates uncertainty limits derived from different modeling approaches, providing insights into prediction reliability.

Random Forests and Extra Trees generally achieve higher accuracy in predicting cereal yields compared to linear regression models. These machine learning algorithms align more closely with observed values, effectively capturing production peaks and troughs. Their superior performance is attributed to their ability to model complex non-linear relationships between environmental factors and crop productivity.

However, during seasons marked by extreme weather conditions, such as severe droughts or excessive rainfall, machine learning models sometimes perform less robustly than linear regression. This suggests that the rarity of such extreme events in the training dataset may limit the generalizability of machine learning algorithms. As the dataset grows and includes more exceptional data, the performance of these models is expected to improve.

2.6.2. Integration of machine learning

The integration of machine learning techniques into CGMS-Maroc has led to significant improvements over traditional linear regression approaches. However, residual prediction errors may still occur due to inconsistencies in cereal statistics or unmeasured factors at these spatial scales, such as sowing dates, cultivation practices, and crop varieties.

Significant enhancements in prediction accuracy have also been achieved by incorporating corrected ERA5 reanalysis data for precipitation and temperature, outperforming models based solely on synoptic station data. This highlights the value of ERA5 satellite products, especially in regions with sparse or inadequate station coverage.

2.6.3. Advanced model insights

An in-depth analysis at the provincial level reveals the importance of several predictive variables, ranked by their significance: ERA5-derived precipitation, LAI, ERA5 minimum and maximum temperatures, NDVI, and SWI.

2.6.4. External validation and future direction

External validation through comparison with the EU's Joint Research Center's crop growth monitoring system (JRC) corroborates the robustness and reliability of CGMS-Maroc's predictions. However, both systems occasionally struggle to forecast yields accurately during anomalous weather seasons, highlighting the ongoing challenge of modeling unprecedented climatic impacts on crop growth.

Figure 27 not only serves as a compelling visual tool for assessing the performance of CGMS-Maroc's models but also emphasizes the importance of integrating both traditional and advanced modeling techniques to provide accurate, reliable yield predictions. As CGMS-Maroc continues to evolve, incorporating new data sources and modeling approaches, its predictive capabilities are expected to enhance, supporting more resilient and informed agricultural decision-making in Morocco.

2.6.5. The indispensable role of human analysts in yield prediction

While CGMS-Maroc's predictive capabilities are enhanced by sophisticated modeling techniques, it is imperative to emphasize the indispensable role of the human analyst in critically evaluating the generated yield prediction results. The agro-climatic indicators used in these models serve as imperfect proxies for the true state of the agricultural season. They cannot fully capture the myriad of local factors that influence crop growth and development, such as the prevalence of diseases, pests, and abiotic stresses. Moreover, both statistical models and machine learning algorithms have inherent limitations and depend heavily on the richness and quality of the datasets used for their calibration.

Consequently, analysts play a vital role in critically assessing the model outputs, contextualizing the yield predictions with the actual conditions observed in the field. Their expertise in agrometeorology, honed through years of experience across multiple cropping seasons, allows them to judiciously interpret the model results and evaluate their plausibility based on practical knowledge. This empirical validation of algorithmic predictions through human discernment is essential to ensure the accuracy and reliability of the forecasts disseminated by CGMS-Maroc to its end-users.

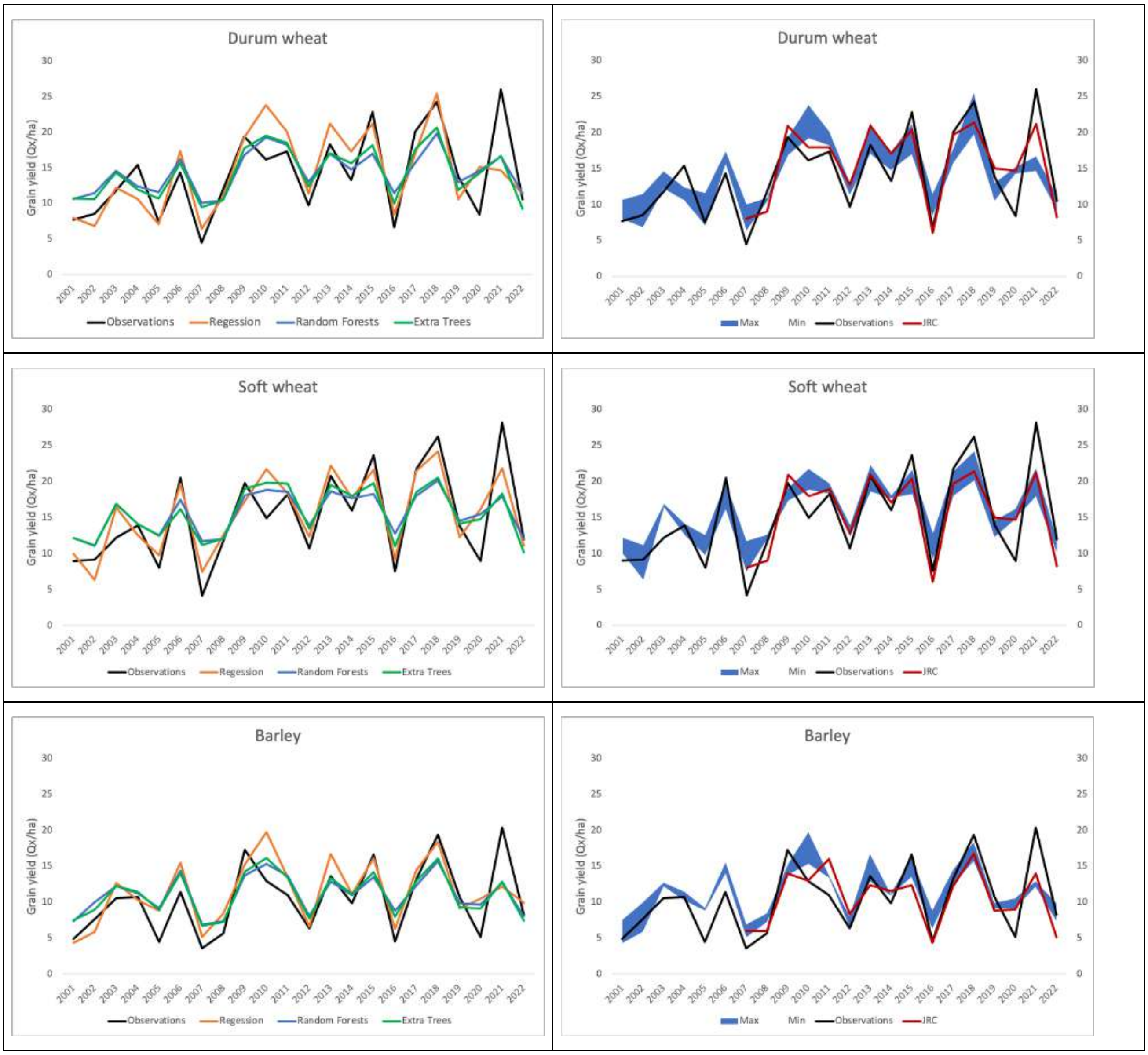


Figure 27 : Observed and predicted cereal yields using regression models, Random Forests, and Extra Trees at the national level.

2.7. Result visualization: The user interface

The initial user interface of CGMS-Maroc was developed as part of the E-AGRI project (Allard et al., 2013). It was an intuitive web-based mapping application (Figure 28) accessible through a web browser using a Flash Player plugin. Developed with Adobe Flex and LuigiOS, the interface supported advanced web applications featuring interactive maps.

Operational logic of the interface:

- **Model:** Contains data and functions for data access.
- **View:** Displays data in the form of maps and charts.
- **Controller:** Manages interactions between the model and the view.

The interface was designed to display raster data (like grids) and vector data (like administrative units), which were rendered by servers into images or maps for display. This combination of simplicity and advanced features enabled users to easily access and interpret data.

Since then, a new user interface has been developed to leverage the latest technological advancements and enhance user experience. Redesigned to be more ergonomic, intuitive, and friendly, this modern tool simplifies the visualization and analysis of agricultural data. It enhances user interaction through easy navigation, indicator selection, layering of information, and interpretation of maps and graphs. Utilizing current web technologies like HTML5, JavaScript, and CSS3, it offers improved responsiveness and advanced features. This overhaul was aimed at delivering an optimal user experience for CGMS-Maroc's end-users, significantly improving usability over the initial version.

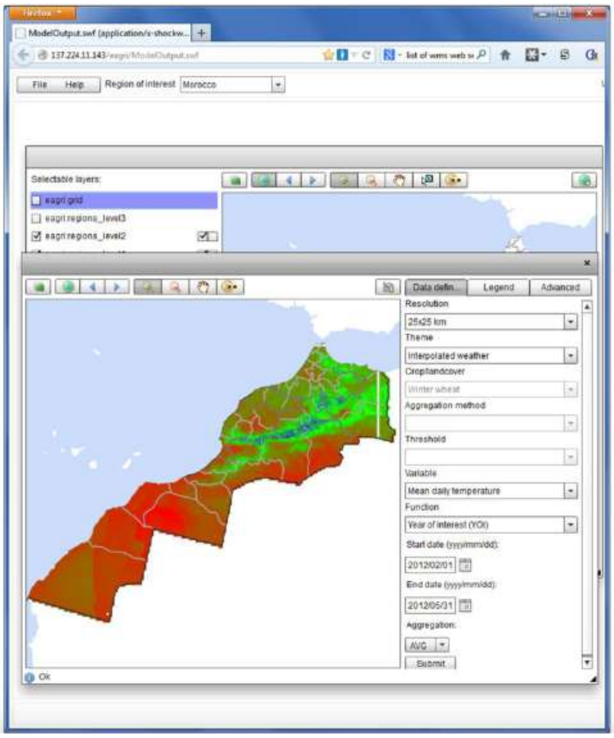


Figure 28 : First user interface of CGMS-Maroc displaying the average daily temperature in Morocco from February 1 to May 31, 2012.

The redesigned interface is organized into interconnected modular sections, navigated via an adaptive side menu tailored to user profiles and needs (Figure 29):

- **Section 1 - Administrative Selection:** Users can select the geographic level of analysis (national or regional) to activate visualizations in other sections.
- **Section 2 - Dashboard:** Features gauge charts and anomalies compared to a ten-year average, providing a quick overview. It includes historical campaign data for context, supplemented by a map and a timeline graph.
- **Section 3 - Rain and Temperature Indicators:** Displays current campaign's cumulative rainfall and average temperatures against decadal normals, making essential indicators readily available.
- **Section 4 - Indicator Selector:** A dropdown menu allows users to select indicators like precipitation, temperatures, NDVI, or SWI for detailed visualization on maps and charts.
- **Section 5 - Mapping:** An interactive map shows deviations of the selected indicator at the municipal level compared to the past ten years, with tooltips displaying precise values on hover.
- **Section 6 - Similarity Analysis:** Includes time-series graphs comparing current campaign progress to historical data from similar years in terms of rainfall.
- **Section 7 - Administration:** Dedicated to administrative functions and user management, including account creation/deletion, role/rights assignment, and activity logs.

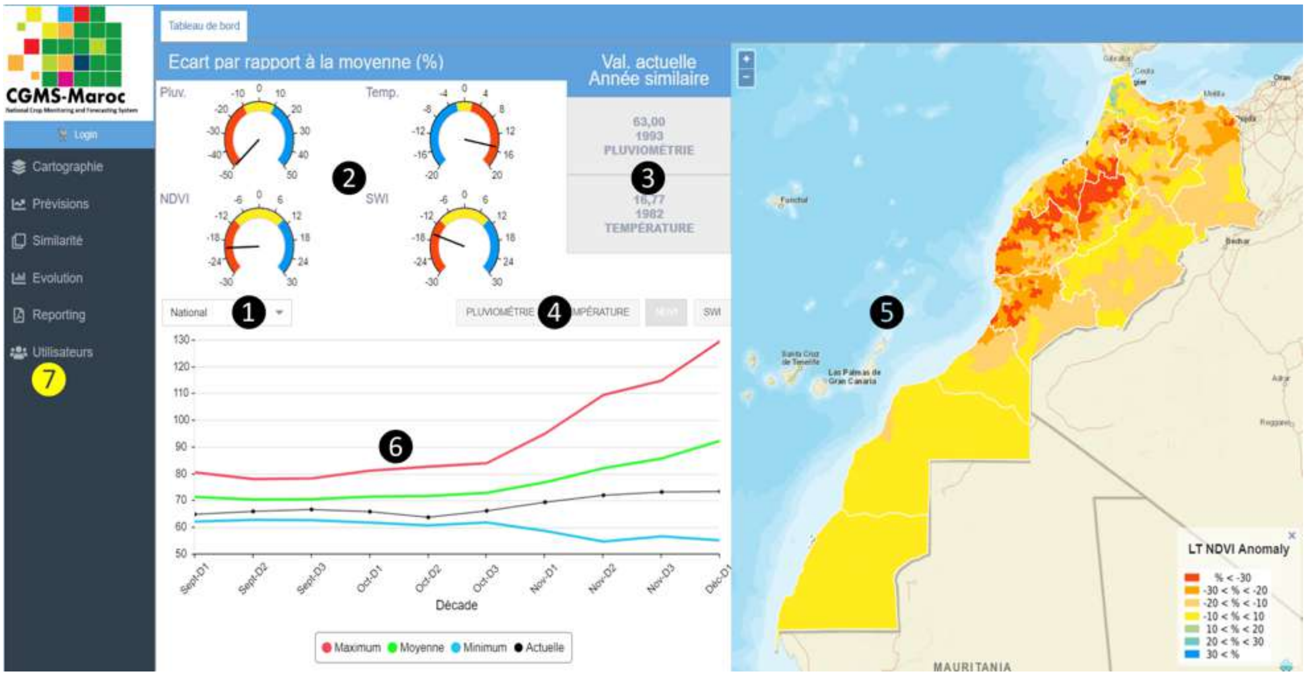


Figure 29 : New Interface of CGMS-Maroc.

Enhanced analytical capabilities of CGMS-Maroc

CGMS-Maroc now offers an extensive suite of features designed to assist analysts in gathering and interpreting vital information throughout the agricultural season. Its sophisticated mapping functionality provides detailed statistics on meteorological and satellite parameters, facilitating tailored analyses and precise yield forecasts for crops such as soft wheat, durum wheat, and barley. The similarity analysis feature improves forecasting accuracy by identifying historical seasons with comparable climatic conditions. Additionally, the intra-seasonal analysis capability enables real-time monitoring of meteorological and satellite data, offering valuable insights into crop development and environmental conditions.

Moreover, CGMS-Maroc's automated reporting system generates comprehensive reports that incorporate critical indicators at various administrative levels—from regional and provincial to rural communes—supporting informed agricultural decision-making. These reports, along with the system's enhanced data visualization tools, simplify complex data interpretation for decision-makers and other stakeholders, promoting well-informed agricultural policies and food security strategies. The integration of these advanced functionalities enriches data exploration, facilitates historical analysis, and provides robust support for real-time monitoring and decision-making, ultimately advancing agricultural operations across Morocco.

By presenting data in its native resolution or aggregating it to suit different administrative needs, CGMS-Maroc ensures flexibility in data analysis and visualization. Advanced processing features like seasonal similarity analysis, campaign duration monitoring, and thematic mapping allow for a deeper understanding of agricultural dynamics. Precipitation data, temperature readings, and vegetation indices are meticulously aggregated at the provincial level, excluding non-agricultural areas identified via remote sensing. This selective aggregation forms a solid foundation for statistical modeling, enhancing the reliability of yield predictions which are then visually represented through maps, charts, and reports. These synthesized visual products streamline the decision-making process, enabling stakeholders to implement effective agricultural policies and food security measures based on precise, easily accessible information.

2.7.1. Mapping functionality

CGMS-Maroc offers a mapping feature that presents statistics related to various meteorological and satellite parameters such as the current value, average, total, minimum, maximum, deviation from the long-term average, deviation from the previous season, and deviation from a specific season (Figure 30). These statistics can be displayed in a user-friendly manner and viewed at the scale of the interpolation grid or aggregated to an administrative scale such as the rural commune (district), province, or region. The mapping functionality also includes features that allow users to customize their analysis. Users can specify the period of interest, calculate, and display different statistics for the entire country or only for agricultural areas determined from the cereal mask. The cereal mask is a crucial tool that identifies areas under cereal production, enabling yield forecasts at a more granular level. Additionally, the mapping functionality provides standard features such as zooming in and out, focusing on a specific area, adding map backgrounds, querying a map element, etc. Users also have the option to download the mapped image in image format.

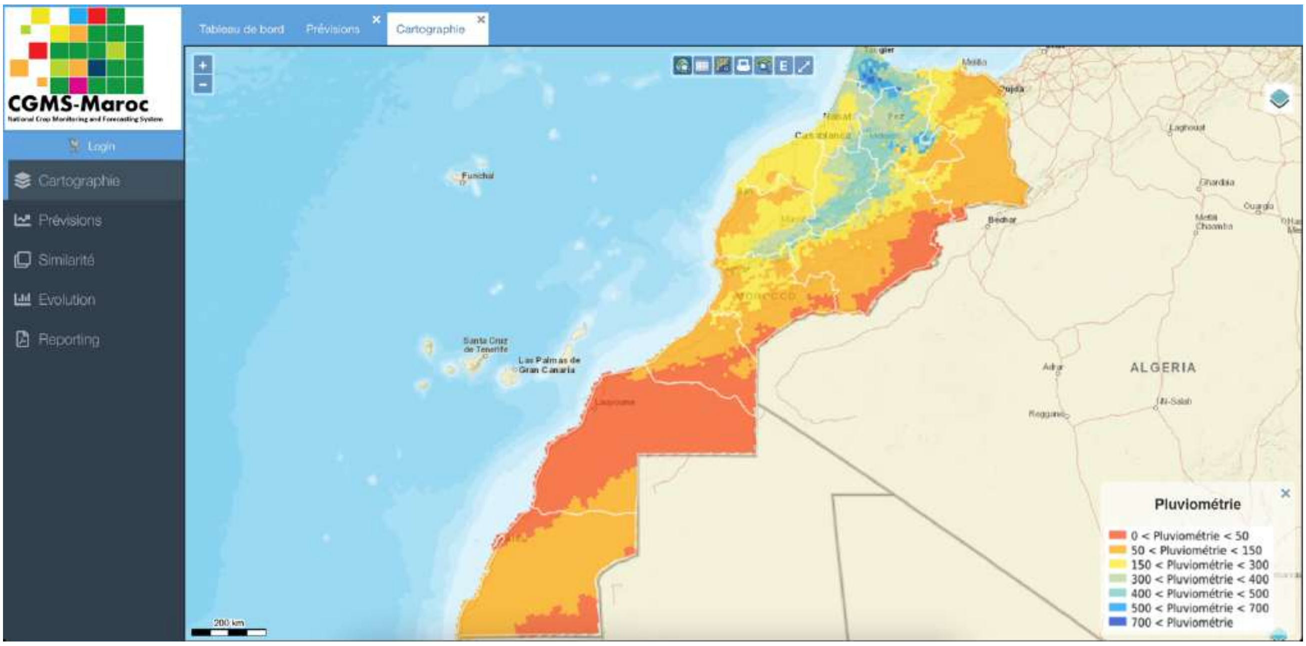


Figure 30 : Example of displaying rainfall from September 1, 2022, to May 31, 2023, using the mapping functionality of CGMS-Maroc.

2.7.2. Similarity analysis

CGMS-Maroc's similarity analysis feature, illustrated in Figure 31 for the 2022-2023 cropping season, serves as a critical tool for assessing the current season by comparing it with past seasons that exhibited similar agro-climatic conditions. This method involves calculating the Euclidean distance between key indicators such as cumulative rainfall from the current season against historical data.

The analysis specifically examines rainfall accumulated every ten days from October 1, 2022, to March 31, 2023. For each historical season, it calculates the average Euclidean distance across these 18 intervals, ranking the seasons by ascending distance to identify the closest match to the current campaign.

In addition to similarity analysis, CGMS-Maroc includes a comparison analysis feature (Figure 32) that focuses on a single variable, usually total rainfall. It allows for a direct comparison of this variable's final values across different agricultural seasons. For instance, the total rainfall from

October 1, 2022, to March 31, 2023, was 234 mm, closely matching the 232 mm from the 2001-2002 season and slightly less than the 247 mm recorded in the 2007-2008 season.

While comparison analysis provides straightforward insights, it lacks the ability to illustrate the temporal dynamics captured by similarity analysis within the season. This more comprehensive approach considers not just the final values but also the progression of conditions throughout the season. This can reveal significant differences in how similar total rainfall amounts are distributed over time, impacting crop growth and development in varied ways.

The method's versatility enables its application across a range of agrometeorological indicators, including SWI, rainfall, temperature, NDVI, and LAI. It is important to acknowledge that similarity analyses using different indicators may identify different seasons as the most similar. Therefore, agronomic expertise is essential to effectively interpret the results and choose the most appropriate indicator that aligns with the specific regional and crop characteristics.

CGMS-Maroc also enhances user experience by enabling downloads of both the analytical charts and the underlying numerical data (Figure 33), facilitating deeper engagement with the analysis.

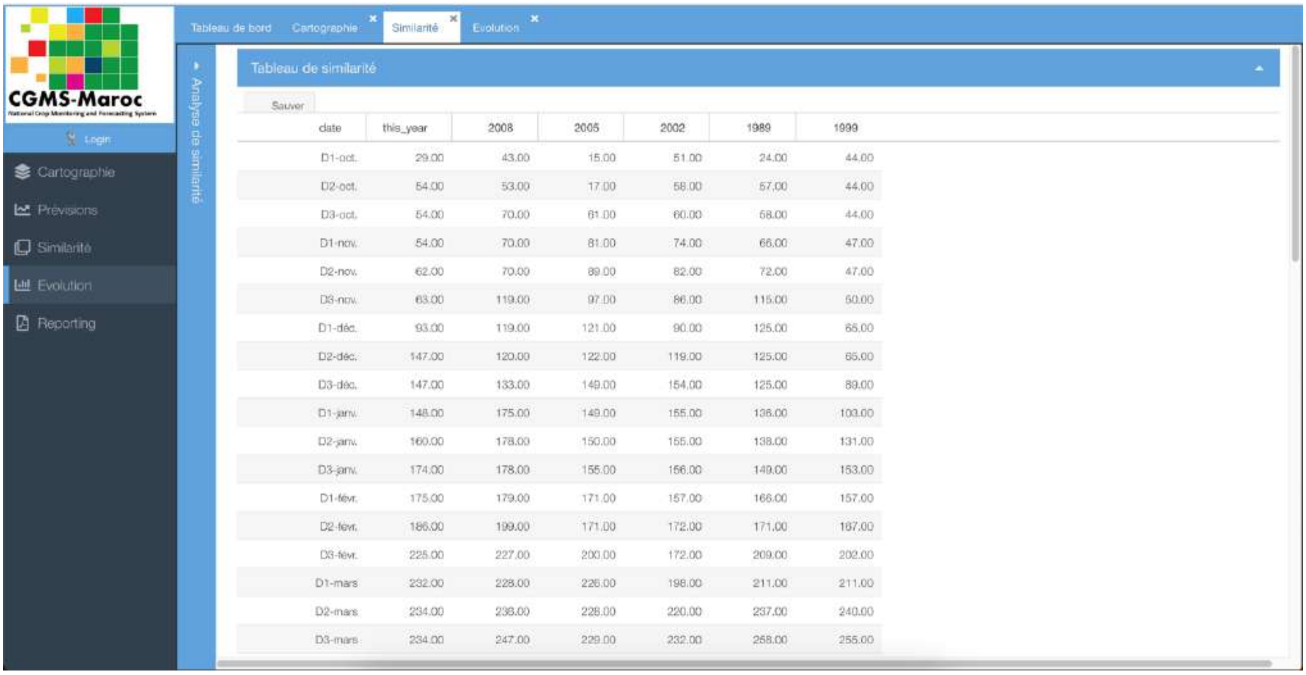
As CGMS-Maroc evolves, expanding the similarity analysis to incorporate multiple indicators could provide a more nuanced assessment of how similar or different seasons are. This multi-dimensional approach would necessitate a sophisticated weighting of each indicator, reflecting its relative importance informed by expert agronomic knowledge and specific local conditions.

Looking ahead, the similarity analysis feature is set to play a crucial role in supporting climate adaptation and risk management in agriculture. By identifying historical parallels to current and projected conditions, this tool empowers stakeholders to more effectively foresee and prepare for potential climate-related impacts on agricultural practices.

Furthermore, integrating similarity analysis with other CGMS-Maroc components like yield forecasting models could refine yield predictions and evaluate risks and opportunities associated with various agricultural practices and policies. This integration promises a holistic approach to agricultural decision-making, enhancing resilience and sustainability in response to climate variability and change.

Figure 31 : Similarity analysis of the 2022-2023 agricultural campaign based on cumulative rainfall from October 1, 2022, to March 31, 2023.

Figure 32 : Comparison analysis of the 2022-2023 agricultural campaign based on cumulative rainfall from October 1, 2022, to March 31, 2023.



date	this_year	2008	2005	2002	1989	1999
D1-oct.	29.00	43.00	15.00	51.00	24.00	44.00
D2-oct.	54.00	53.00	17.00	58.00	57.00	44.00
D3-oct.	54.00	70.00	61.00	60.00	58.00	44.00
D1-nov.	54.00	70.00	81.00	74.00	66.00	47.00
D2-nov.	62.00	70.00	89.00	82.00	72.00	47.00
D3-nov.	63.00	119.00	97.00	86.00	115.00	50.00
D1-déc.	93.00	119.00	121.00	90.00	125.00	65.00
D2-déc.	147.00	120.00	122.00	119.00	125.00	65.00
D3-déc.	147.00	133.00	149.00	154.00	125.00	89.00
D1-janv.	148.00	175.00	149.00	155.00	136.00	103.00
D2-janv.	160.00	178.00	150.00	155.00	138.00	131.00
D3-janv.	174.00	178.00	155.00	156.00	149.00	153.00
D1-févr.	175.00	179.00	171.00	157.00	166.00	157.00
D2-févr.	186.00	199.00	171.00	172.00	171.00	167.00
D3-févr.	225.00	227.00	200.00	172.00	209.00	202.00
D1-mars	232.00	228.00	226.00	198.00	211.00	211.00
D2-mars	234.00	238.00	228.00	220.00	237.00	240.00
D3-mars	234.00	247.00	229.00	232.00	258.00	255.00

Figure 33 : Display of similarity analysis values in CGMS-Maroc.

2.7.3. Intra-seasonal analysis

The intra-seasonal analysis functionality of CGMS-Maroc offers a dynamic tool for real-time monitoring of agrometeorological conditions throughout the cropping season. Utilizing key indicators such as rainfall, temperatures, SWI, NDVI, and LAI (Figure 34), this feature provides a detailed, comprehensive view of the season's progression.

Advantages of intra-seasonal analysis

One major advantage of intra-seasonal analysis is its ability to provide continuously updated information at a high temporal resolution—daily, decadal (10 days), or monthly. This granularity enables close tracking of changes in agrometeorological conditions and their potential impacts on crop development. Stakeholders can promptly detect deviations from expected patterns, such as rainfall deficits, heat waves, or water stress, facilitating timely and informed decision-making.

The user-friendly interface of CGMS-Maroc enhances the exploration and interpretation of intra-seasonal data. Users can select indicators relevant to their specific needs and visualize their evolution through interactive graphs and charts. This visual representation offers a clear and intuitive understanding of trends, anomalies, and critical thresholds for each parameter, aiding in the quick identification of potential issues or opportunities.

Spatial and temporal granularity

Another significant benefit of this functionality is its ability to leverage spatialized data, available at various geographical scales from rural communes to the national level, including provinces and regions. This spatial granularity allows for a refined analysis that considers local specificities such as microclimates, soil types, and cultural practices. Decision-makers can thus tailor their strategies and interventions to the unique conditions of each area, ensuring more effective and customized management approaches.

Integrating agronomic expertise

To maximize the effectiveness of intra-seasonal analysis, it's essential to integrate it with agronomic expertise and field knowledge. The indicators provided need to be contextualized with the specific characteristics of crops, phenological stages, and agronomic practices. This integrated approach fosters a more nuanced and accurate assessment, enabling better anticipation of potential impacts on yields, product quality, and resource management. By combining data-driven insights with expert knowledge, stakeholders can optimize agricultural practices and make more informed decisions.

Foundation for precision agriculture

Intra-seasonal analysis also underpins precision agriculture by enabling targeted and timely interventions. For example, early detection of water deficits can prompt the implementation of supplementary irrigation to ensure adequate moisture during critical growth phases. Similarly, identifying conditions conducive to pest outbreaks can guide timely phytosanitary interventions, minimizing crop damage and yield losses. This responsive management approach is crucial for optimizing crop performance, reducing input costs, and minimizing environmental impacts.

Contributing to climate-smart agriculture

Furthermore, the intra-seasonal analysis feature contributes to the advancement of climate-smart agriculture by providing actionable information for climate risk management. By closely monitoring agrometeorological conditions and their evolution, stakeholders can better understand the impacts of climate variability on crop growth. This insight is vital for developing adaptation strategies, such as adjusting planting dates, selecting drought-resistant crop varieties, or implementing water conservation techniques, enhancing the resilience of agricultural systems to climate challenges.

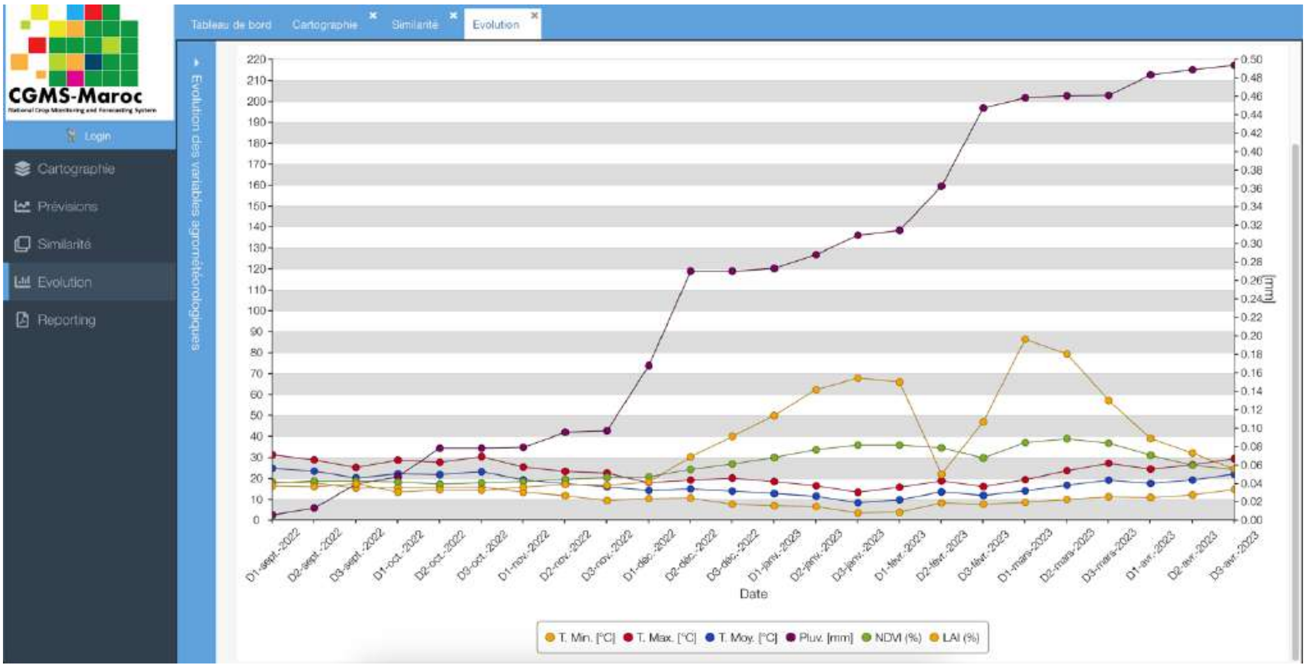


Figure 34 : Intra-seasonal analysis feature of CGMS-Maroc.

2.7.4. Automatic generation of yield Forecasts

CGMS-Maroc's crop yield prediction feature is one of its most innovative and critical aspects. Activated at the end of February, this functionality forecasts the yields of the three main autumn cereals—durum wheat, soft wheat, and barley—at the provincial level where cereal cultivation occurs (Figure 35).

CGMS-Maroc employs three main methods to generate yield predictions, each offering a unique perspective and leveraging different approaches to estimate production:

1. **Similarity analysis:** This method assesses the current season by comparing it with previous ones to identify yield trends based on similar agrometeorological conditions. It integrates historical data to establish a solid basis for predicting expected yields, using patterns and analogues from past seasons.
2. **Linear regression models:** Employing statistical techniques, this approach models the relationships between climatic indicators such as rainfall and temperature, SWI, and vegetation health indices (NDVI, LAI), to predict cereal yields. By quantifying the influence of these key agrometeorological factors, the models provide precise, data-driven forecasts based on current environmental conditions.
3. **Machine learning techniques:** Advanced algorithms analyze large datasets to detect complex, nonlinear relationships that traditional methods might not capture. Techniques like random forests or neural networks delve into the intricate interactions between numerous variables to provide nuanced forecasts that reflect the multifaceted nature of crop growth.

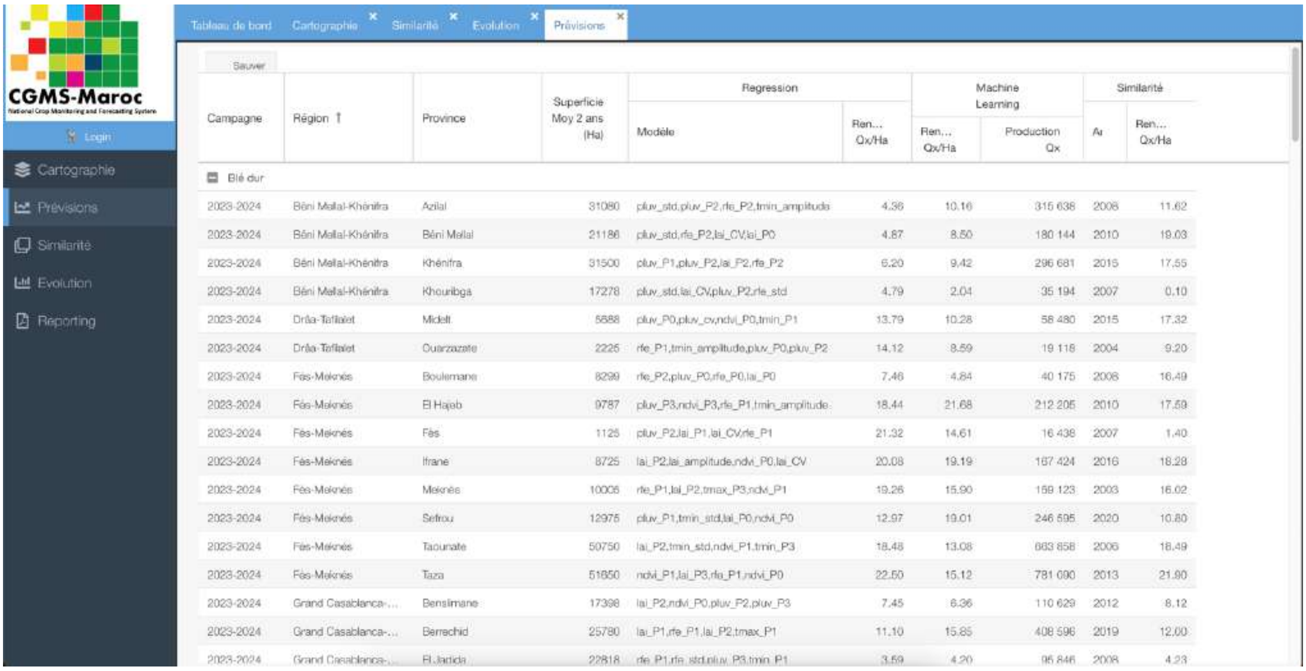
In addition to providing yield predictions at the provincial level, CGMS-Maroc offers the functionality to aggregate these forecasts at the national scale. This aggregation process involves weighting the provincial yields by the cultivated area of each province, ensuring that the national forecast reflects the spatial distribution and relative importance of cereal production across the country. This feature enables decision-makers to gain a comprehensive overview of the expected national cereal production, facilitating strategic planning and resource allocation at a broader scale.

A key strength of CGMS-Maroc's yield forecasting system is its ability to provide continuously updated predictions throughout the agricultural season. From March until the end of the season in June, yield forecasts are updated daily, incorporating the latest satellite data received in real-time. This dynamic approach ensures that the forecasts remain current and relevant, capturing the effects of evolving agrometeorological conditions on crop growth and development. By providing timely and accurate information, CGMS-Maroc empowers stakeholders to make proactive decisions and adapt their strategies in response to changing circumstances.

To guarantee the seamless availability of these yield forecasts, CGMS-Maroc has implemented an efficient overnight calculation strategy. The potentially time-consuming and computationally intensive calculations are scheduled to run during off-peak hours by the CGMS-Maroc Block 2 server. This optimized setup not only maximizes the utilization of available computing resources but also ensures that the results are readily accessible at the start of each day. By automating the data processing and analysis pipeline, CGMS-Maroc streamlines the delivery of actionable insights to users, enabling them to make informed decisions without delay.

The automatic generation of yield forecasts in CGMS-Maroc represents a significant advancement in the field of agricultural monitoring and decision support. By combining multiple methods, including similarity analysis, linear regressions, and machine learning techniques, the system provides a comprehensive and robust assessment of expected crop yields. The ability to update forecasts daily based on real-time satellite data ensures that the information remains relevant and responsive to changing conditions on the ground. Moreover, the aggregation of provincial forecasts to the national level offers a holistic view of the country's cereal production, facilitating strategic planning and policy-making.

As CGMS-Maroc continues to evolve and incorporate new data sources and analytical techniques, the yield forecasting functionality is expected to become even more sophisticated and accurate. The integration of additional variables, such as soil characteristics, crop management practices, and socio-economic factors, could further enhance the predictive power of the system. Furthermore, the potential integration of CGMS-Maroc with other decision support tools, such as crop simulation models or market information systems, could provide a more comprehensive and integrated platform for agricultural risk management and policy formulation.



Campagne	Région	Province	Superficie Moy 2 ans (Ha)	Regression: Modèle	Regression: Ren... Qx/Ha	Machine Learning: Ren... Qx/Ha	Machine Learning: Production Qx	Similarité: An	Similarité: Ren... Qx/Ha
2023-2024	Béni Mallal-Khénifra	Azilal	31080	pluv_std,pluv_P2,rfe_P2,tmin_amplitude	4.36	10.16	315 638	2008	11.62
2023-2024	Béni Mallal-Khénifra	Béni Mellal	21186	pluv_std,rfe_P2,lai_CV,lai_P0	4.87	8.50	180 144	2010	19.03
2023-2024	Béni Mellal-Khénifra	Khénifra	31500	pluv_P1,pluv_P2,lai_P2,rfe_P2	6.20	9.42	296 681	2015	17.55
2023-2024	Béni Mellal-Khénifra	Khouribga	17278	pluv_std,lai_CV,pluv_P2,rfe_std	4.79	2.04	35 194	2007	0.10
2023-2024	Drâa-Tafilalet	Midelt	5688	pluv_P0,pluv_cv,ndvi_P0,tmin_P1	13.79	10.28	58 480	2015	17.32
2023-2024	Drâa-Tafilalet	Ouarzazate	2225	rfe_P1,tmin_amplitude,pluv_P0,pluv_P2	14.12	8.59	19 118	2004	9.20
2023-2024	Fès-Meknès	Boulemane	8299	rfe_P2,pluv_P0,rfe_P0,lai_P0	7.46	4.84	40 175	2008	16.49
2023-2024	Fès-Meknès	El Hajeb	9787	pluv_P3,ndvi_P3,rfe_P1,tmin_amplitude	18.44	21.68	212 205	2010	17.59
2023-2024	Fès-Meknès	Fès	1125	pluv_P2,lai_P1,lai_CV,rfe_P1	21.32	14.61	16 438	2007	1.40
2023-2024	Fès-Meknès	Ifrane	8725	lai_P2,lai_amplitude,ndvi_P0,lai_CV	20.08	19.19	167 424	2016	18.28
2023-2024	Fès-Meknès	Meknès	10006	rfe_P1,lai_P2,tmax_P3,ndvi_P1	19.26	15.90	159 123	2003	16.02
2023-2024	Fès-Meknès	Sefrou	12975	pluv_P1,tmin_std,lai_P0,ndvi_P0	12.97	19.01	246 595	2020	10.80
2023-2024	Fès-Meknès	Taounate	50750	lai_P2,tmin_std,ndvi_P1,tmin_P3	18.48	13.08	663 858	2006	18.49
2023-2024	Fès-Meknès	Taza	51650	ndvi_P1,lai_P3,rfe_P1,ndvi_P0	22.50	15.12	781 090	2013	21.90
2023-2024	Grand Casablanca-...	Benslimane	17398	lai_P2,ndvi_P0,pluv_P2,pluv_P3	7.45	6.36	110 629	2012	8.12
2023-2024	Grand Casablanca-...	Berrechid	25780	lai_P1,rfe_P1,lai_P2,tmax_P1	11.10	15.85	408 596	2019	12.00
2023-2024	Grand Casablanca-...	El Jadida	22818	rfe_P1,rfe_std,pluv_P3,tmin_P1	3.59	4.20	95 846	2008	4.23

Figure 35 : Fonctionnalité de prévision de rendements des céréales (blé dur, blé tendre et orge) au niveau provincial.

2.7.5. Automated reports

CGMS-Maroc streamlines the creation of essential reports through a one-click automated reporting feature. This functionality delivers key seasonal indicators such as precipitation, temperature, and vegetation indices for each administrative region (Figure 36). Designed specifically to support regional agricultural departments, these reports provide a comprehensive overview of the agricultural season across each province or commune in the region.

The automated reports are tailored to facilitate the monitoring of agricultural and environmental conditions efficiently. They encompass crucial meteorological data and vegetation indices, which are vital for assessing the health and vitality of crops. The CGMS-Maroc interface enables users to generate these detailed reports effortlessly with just one click, significantly saving time and effort.

Once created, the reports are available in PDF format, ensuring they are easily distributable and accessible to all relevant stakeholders, promoting informed decision-making and effective communication across the agricultural sector.

Figure 36 : Automated reporting feature of CGMS-Maroc.

III. IT architecture of CGMS-Maroc

The functional architecture of CGMS-Maroc, as described in the previous section, relies on a robust IT infrastructure to ensure seamless data integration, processing, and dissemination. In this section, we will explore the IT architecture that underpins CGMS-Maroc, highlighting the key components and design principles that enable the system to perform efficiently and securely.

The IT architecture of CGMS-Maroc forms the technological backbone that enables the system to efficiently integrate diverse data flows, execute complex mathematical models, and provide results through user-friendly interfaces. This foundational architecture is vital for ensuring the system's performance, reliability, and scalability.

CGMS-Maroc's architecture is strategically divided into two distinct blocks to optimize both security and performance. The first block (Block 1) is dedicated to intensive meteorological data processing within a secure, controlled environment to maximize computational efficiency and maintain data integrity. The second block (Block 2) handles consultation and analysis functionalities, presented on a more accessible platform to facilitate user interaction and collaborative efforts.

However, the true strength of CGMS-Maroc lies in the seamless integration of these two blocks. Standardized exchange protocols and robust synchronization mechanisms ensure continuous and bidirectional data flows. This service-oriented architecture enhances interoperability and modularity, making it easy to update or add functional modules as the system evolves.

Scalability and resilience are key priorities in the design of CGMS-Maroc's IT architecture. The utilization of containerization and orchestration technologies enables fine-grained management of resource allocation, ensuring that the system can dynamically adapt to varying workloads. Furthermore, failover and replication mechanisms are implemented to guarantee high availability, even in the face of temporary failures or disruptions.

Security is a paramount concern, and CGMS-Maroc employs a multi-layered approach to safeguard the integrity and confidentiality of sensitive data. Firewalls, encrypted communications, role-based access control, and proactive monitoring of suspicious activities are just a few of the measures in place. The goal is to maintain a robust security posture while ensuring a high level of service availability for users.

From a software perspective, CGMS-Maroc leverages a blend of reliable open-source components and custom-developed modules. The adoption of open standards and interoperable formats facilitates seamless integration with third-party systems and allows for flexibility in adapting to evolving requirements. The adoption of a DevOps culture promotes close collaboration between developers and operations, streamlining agile and secure deployments.

The architecture's modular and extensible nature is crucial for accommodating future growth and technological advancements. It is primed to integrate new data sources, such as IoT devices and mobile applications, enhancing its monitoring capabilities. Furthermore, the architecture is well-equipped to incorporate sophisticated analysis techniques like AI and big data analytics, providing deep insights from the extensive data collected.

CGMS-Maroc's dissemination capabilities are as advanced as its analytical tools, with APIs and chatbots to extend accessibility and enhance user engagement. This ensures that stakeholders can easily access and utilize data and functionalities provided by the system.

This section delves into the IT architecture of CGMS-Maroc, highlighting the principles, components, and technological decisions that underpin its functionality. It provides a detailed view of the system's robust technical foundation, illustrating how it is equipped to address the complex challenges of agricultural decision-making under variable climate conditions.

1. Block 1: IT Infrastructure of the climate database

Block 1 of CGMS-Maroc is hosted on two dedicated servers situated within the GDM's state-of-the-art data center, specifically within the rack allocated to the National Climate Center (CNC). This data center forms the heart of the GDM's IT infrastructure, housing the critical hardware resources that power all its systems. Designed to provide a highly controlled and secure environment, the data center ensures optimal availability, performance, and redundancy of the hosted equipment.

In recent years, the GDM has undertaken a significant initiative to upgrade the technical and environmental capabilities of its data center. This modernization effort has yielded impressive results, achieving several key objectives:

- Compliance with the most stringent standards for modern data centers, attaining Tier III+++ certification in accordance with the TIA 942 standard.
- An availability rate approaching 100%, thanks to the implementation of advanced measures for securing and ensuring redundancy of critical installations.
- A comprehensive overhaul of the technical infrastructure, including upgrades to electrical systems, cooling mechanisms, fire detection sensors, and cabling networks.

The adoption of innovative and eco-friendly technologies, such as water mist-based fire suppression systems, free-cooling and aisle containment air conditioning solutions, and energy-efficient LED lighting.

To maintain the highest levels of security, all server racks[11] are equipped with locked doors, strictly controlling physical access to the hosted equipment. The servers benefit from a redundant power supply architecture and are interconnected via a high-speed fiber optic network, ensuring reliable and efficient data transmission. Precise temperature control is achieved using precision air conditioning units that circulate treated air through a raised floor system, maintaining optimal operating conditions for the servers.

The technical and operational implementation of Block 1 of CGMS-Maroc leverages this robust IT infrastructure, hosted within the secure confines of the GDM's data center. By relying on this state-of-the-art facility, the system ensures the availability, performance, and security of all the software and hardware components that underlie the critical meteorological data processing chain. This solid foundation instills confidence in the system's ability to deliver reliable and timely information, supporting effective decision-making in the face of climatic challenges.

1.1. Redundant hardware architecture

The heart of the CGMS-Maroc system is built upon a robust and redundant hardware architecture, featuring two identical IBM System x3650 physical servers. This redundancy ensures high availability and fault tolerance, minimizing the risk of system downtime. These servers are equipped with powerful multi-core Intel Xeon processors and 32 GB of RAM, providing ample computing power and memory capacity to handle the intensive daily data processing workloads.

To ensure data integrity and high-performance storage, the system employs disk arrays configured in RAID-5. This configuration offers a balance between fast data access and fault tolerance, protecting against data loss in the event of disk failures. Each server boasts a usable

[11] A server rack, also known as a server cabinet, is a physical structure designed to house electronic equipment, computers, and servers, as well as other network and telecommunication devices.

storage capacity of 584 GB, which can be easily expanded by adding hot-swappable disks without interrupting system operations.

Network connectivity is a critical aspect of the CGMS-Maroc infrastructure, and the servers are interconnected to the GDM's local network through redundant Gigabit Ethernet links. These high-speed links allow for full-duplex data transfer rates of 1 Gb/s, ensuring rapid and reliable communication between the servers and other system components. To further enhance system resilience, each server is powered by two separate electrical feeds, each backed up by an uninterruptible power supply (UPS). This redundant power configuration eliminates the risk of system downtime due to power outages or fluctuations.

Physical security is a top priority for the CGMS-Maroc infrastructure, and all equipment is housed in two dedicated racks. Access to these racks is strictly controlled through badge-based authentication, and video surveillance systems monitor the premises 24/7. To maintain optimal operating conditions for the servers, the data center employs an advanced air conditioning system that maintains a constant temperature by segregating cold and hot aisles. This efficient cooling setup ensures that the servers operate within their recommended temperature range, prolonging their lifespan and minimizing the risk of hardware failures.

1.2. Highly secure software environment

CGMS-Maroc places a strong emphasis on software security to protect the system and its data from unauthorized access and potential breaches. The servers run on the Red Hat Enterprise Linux version 6 operating system, which is widely recognized for its stability, performance, and security features. To further enhance security, the system configuration has been meticulously hardened following industry best practices. This hardening process involves implementing strict security policies, disabling unnecessary services, and applying the latest security patches to minimize the system's attack surface.

Access to the CGMS-Maroc servers is tightly controlled and requires users to pass through an authentication bastion using the secure SSH protocol[12]. Only authorized administrators with valid credentials are granted access to the servers, ensuring that sensitive data and system resources are protected from unauthorized users. All administrative sessions are logged and monitored, providing complete traceability and accountability.

To protect against malware and other cyber threats, the CGMS-Maroc servers are equipped with advanced antivirus software that is updated daily. This ensures that the system is protected against the latest known vulnerabilities and malicious software. In addition, an application firewall is deployed to filter incoming and outgoing network traffic, allowing only the necessary services for the proper functioning of CGMS-Maroc. This firewall acts as a barrier, preventing unauthorized access attempts and potential attacks.

Keeping the software components up to date is crucial for maintaining a secure environment. The CGMS-Maroc team diligently applies critical security updates to all software components on a weekly basis. This proactive approach ensures that any newly discovered vulnerabilities are promptly addressed, reducing the risk of exploitation by malicious actors.

At the heart of the CGMS-Maroc system lies a robust database managed by Oracle Database version 11g. The database schema has been carefully optimized to handle complex application queries efficiently, with response times consistently below 100 ms. This optimization ensures that users can access and analyze data quickly, enabling timely decision-making. The current data volume stored in the database is estimated at 80 GB, with an anticipated annual growth rate of

[12] The SSH protocol is a secure communication method designed for remotely accessing servers and computer systems, utilizing data encryption and user authentication to ensure safety.

15%. The system's scalable architecture allows for seamless expansion to accommodate this expected data growth.

To meet the specific requirements of CGMS-Maroc, custom software developments are carried out using the C++ programming language. The development team leverages proven libraries and follows industry best practices to ensure code quality and reliability. The source code is thoroughly documented to facilitate maintainability and future enhancements. Regular code reviews are conducted to identify and address any potential vulnerabilities or weaknesses in the codebase. To validate the integrity and functionality of the system, comprehensive unit and integration tests are performed before each production release. These tests help to identify any regressions or incompatibilities introduced by new features or bug fixes, ensuring a stable and reliable system.

1.3. Optimized supervision and operations

Effective supervision and operation of the CGMS-Maroc system are critical for ensuring its smooth functioning and promptly addressing any issues that may arise. To achieve this, the system employs the Centreon monitoring tool[13], which provides real-time monitoring of all infrastructure elements and business processes. Centreon consolidates system and application monitoring data, giving operators a holistic view of the system's health and performance.

The monitoring system is configured to raise alerts when predefined thresholds are exceeded for key metrics such as CPU usage, memory consumption, disk utilization, response times, and batch[14] job status. These alerts enable the operations team to proactively identify and address potential issues before they impact system availability or performance. To ensure rapid response to critical incidents, a 24/7 on-call duty is established for the operations team. In the event of a severity 1 incident, the team is committed to initiating intervention within a maximum of 4 hours. Additionally, vendor support is available to provide expert assistance when needed.

User support is an integral part of the CGMS-Maroc operations. A dedicated help desk is staffed during business hours to address user inquiries and issues. The help desk team is committed to responding to user requests within 2 hours, ensuring prompt assistance and minimizing any disruptions to user workflows.

To facilitate efficient operations and knowledge sharing, CGMS-Maroc maintains an online documentation portal. This portal serves as a centralized repository for all operational procedures, administrator manuals, acceptance test plans, and business continuity plans. By providing easy access to up-to-date documentation, the portal enables operators to quickly find the information they need to perform their tasks effectively. The portal also serves as a platform for tracking change requests and incident reports, promoting collaboration between the operations and development teams.

Effective governance is essential for aligning the technical roadmap of CGMS-Maroc with the evolving needs of its users. To achieve this, a monthly steering committee is convened, bringing together business and technical managers. The committee reviews key performance indicators related to the system's operational maintenance and discusses priorities for future enhancements. This collaborative approach ensures that the system's development aligns with user expectations and business requirements, fostering a continuous improvement mindset.

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[13] Centreon is a comprehensive IT infrastructure monitoring tool that offers real-time monitoring, performance tracking, and customizable features through a user-friendly interface, suitable for organizations of all sizes.

[14] Batch processing is a data processing method where instructions are executed as a group or 'batch' without user intervention.

Hosting the Block 1 servers within the GDM's data center offers significant advantages in terms of availability, security, and operational efficiency. By leveraging the GDM's state-of-the-art infrastructure, CGMS-Maroc benefits from a highly available and secure environment. The data center's robust physical security measures, redundant power and cooling systems, and advanced networking infrastructure ensure optimal operating conditions for the servers.

This hosting arrangement allows the CGMS-Maroc infrastructure team to focus on their core responsibilities, such as system administration, monitoring, and maintenance. The team can rely on the GDM's expertise and resources for data center management, freeing them to concentrate on optimizing the system's performance and supporting user needs. Additionally, the GDM's contractual service quality commitments provide assurance regarding the availability and reliability of the hosting environment.

Storing the CGMS-Maroc data within the national territory is a strategic decision that ensures compliance with data sovereignty requirements. By keeping the data on-premises, the system maintains full control over this critical asset, adhering to legal and regulatory obligations. This local hosting approach also offers the benefits of reduced latency and improved data access speed compared to remote or cloud-based solutions.

2. Block 2: Integration, analysis, and visualization of multi-source data

The IT architecture of Block 2 of CGMS-Maroc (Figure 37) is structured into six distinct but interconnected functional compartments, ensuring a clear separation of responsibilities while fostering collaboration across the entire system.

1. The first compartment, dedicated to Data Retrieval, automatically collects raw data from four main sources: daily meteorological and agrometeorological data from GDM, satellite data from Copernicus and Modis, and end-of-season agricultural statistics from DSS. Scheduled scripts query the APIs[15] and directories of these providers to feed the system with fresh data. This compartment ensures a constant flow of up-to-date information into the system, laying the foundation for accurate monitoring and forecasting.
2. The second compartment (Preprocessing) handles the preprocessing of the collected data. This crucial step aims to correct, filter, homogenize, and restructure the raw data to conform to the target data model. Specialized libraries like GDAL[16] are leveraged for processing geospatial data. The preprocessed data is then loaded into the central database. By standardizing and optimizing the data format, this compartment facilitates efficient storage, retrieval, and analysis in subsequent stages.
3. The third compartment is the Database Server, the true backbone of the system. Based on PostgreSQL and its spatial extension PostGIS[17], it has been finely tuned, notably through an overhaul of the indexes, to handle heavy queries. It structures the data into four types of tables: geographical reference data, raw data per grid cell, aggregates per administrative entity, and agricultural statistics. An API REST[18]/JSON[19] API allows for

[15] Application Programming Interface: a set of rules and protocols allowing different software to communicate with each other.

[16] Geospatial Data Abstraction Library: a software library for translating and processing vector and raster geospatial data.

[17] PostGIS: an extension to the PostgreSQL database management system for storing and processing spatial data.

[18] Representational State Transfer: a software architectural style for distributed hypermedia systems like the World Wide Web.

[19] JavaScript Object Notation: a lightweight text-based data format, derived from the notation of JavaScript objects, used for structured data interchange.

querying and updating this repository. The centralized and optimized database serves as a single source of truth, enabling seamless data integration and efficient querying.

4. The fourth compartment (Postprocessing) orchestrates the business and scientific treatments applied daily to the data. Implemented in Python, these workflows calculate indicators and statistics at various scales, execute agronomic models, and generate cartographic products. Starting from February 1st, predictive models based on machine learning estimate yields by combining historical data and current conditions. This compartment transforms the preprocessed data into actionable insights and forecasts, leveraging advanced computational techniques to support decision-making.
5. The fifth compartment groups the Server-side Apps. A Python business application is deployed there to expose computation services and APIs. It interfaces with MapServer to produce maps and geographic services compliant with OGC[20] standards. An Apache web server acts as a front-end to intercept client requests, route them to the business application, and return the responses after processing. This compartment ensures the seamless integration of data, computational models, and visualization services, providing a unified interface for client applications.
6. The sixth and final compartment is dedicated to Client-side Apps. A single-page web application[21] (SPA) serves as a user-friendly and ergonomic user interface. Developed with the JavaScript frameworks[22] ExtJS and OpenLayers, it offers rich interactive components such as dynamic mapping, data tables and charts, as well as export and printing tools. The interface communicates with the server via AJAX[23]/JSON calls for smooth client-side rendering. A responsive web portal serves as a single-entry point to the platform. This compartment delivers a powerful and intuitive user experience, enabling users to explore, analyze, and visualize the data and insights generated by the system.

The six compartments collaborate to orchestrate the data flow, from collection to delivery to the end-user. The service-oriented and modular architecture facilitates the scalability and evolvability of the platform through the simple addition of modules or resources.

[20] Open Geospatial Consortium: an international standards organization that develops and promotes open standards for geospatial data and services.

[21] A web application accessible via a single web page that allows for a more fluid user experience by avoiding page reloads.

[22] Framework: a cohesive set of structural software components that provide the foundational architecture and essential guidelines for building a software program.

[23] Asynchronous JavaScript and XML: a set of technologies used to build dynamic and interactive web applications.

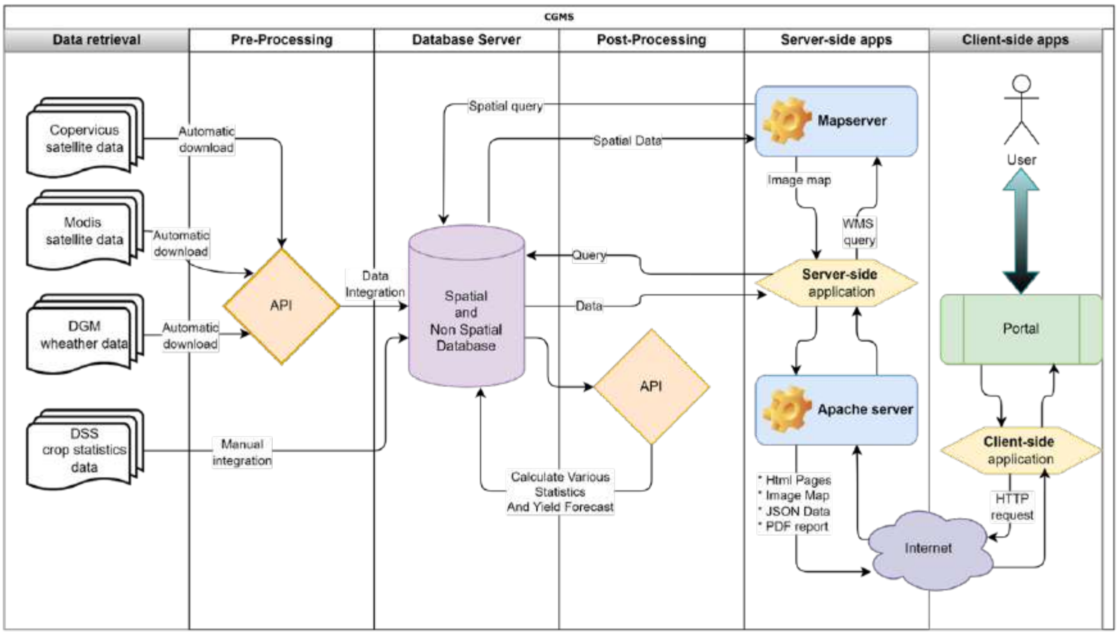

Figure 37 : IT architecture of Block 2 of CGMS-Maroc.

IV. Strategic roadmap: Future enhancements for CGMS-Maroc

Having thoroughly examined the functional and IT architecture of CGMS-Maroc, the focus now shifts to the system's future development. The subsequent section presents a comprehensive strategic roadmap designed to enhance CGMS-Maroc's capabilities, targeting crucial areas such as data quality, collaborative monitoring, and capacity building. This roadmap serves to ensure that the system maintains its position at the vanguard of agricultural decision support, continuously evolving to address the dynamic requirements of stakeholders and incorporating cutting-edge advancements in technology and methodology. By concentrating on these pivotal aspects, CGMS-Maroc will be well-equipped to deliver progressively accurate, timely, and actionable insights, ultimately optimizing agricultural practices and mitigating the impacts of climate change on Morocco's cereal production.

Global insights and inspirations for CGMS-Maroc

Numerous technological systems for monitoring and forecasting agricultural yields have emerged worldwide, constituting relevant references for CGMS-Maroc (Table 9). These include the European MARS[24] system, CropWatch[25] developed by the Chinese Academy of Sciences, the American USDA-FAS[26] tool, CRAFT[27] from CGIAR, and the Integrated Canadian Crop Yield Forecaster[28] (ICCYF).

These systems demonstrate the potential of modern technologies – machine learning, satellite remote sensing, numerical modeling - to improve yield monitoring and forecasting at different scales. Their integrated approach, merging various meteorological, agronomic, and satellite data, provides highly detailed information on crop conditions in real-time.

Each system has specific strengths. For example, the European MARS system stands out for the high accuracy of its forecasts at the national level. CropWatch ensures continuous monitoring and issues reference bulletins. The Canadian ICCYF tool provides real-time updates. As for CRAFT, it generates interactive scenarios at local scales.

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[24] https://agri4cast.jrc.ec.europa.eu/

[25] http://www.cropwatch.com.cn/

[26] https://www.fas.usda.gov/

[27] CGIAR is the world's largest global agricultural research network.

[28] https://www.statcan.gc.ca/en/statistical-programs/document/5225_D1_T9_V1

These successes are based on several pillars: the integration of multi-source data, the use of satellite remote sensing, the involvement of expert analysts, continuous performance evaluation, and regular public dissemination of results.

These best practices inspire avenues for improvement of CGMS-Maroc, both in terms of the data collected, the forecasting models, and the involvement of stakeholders. In the short term, the priority recommendations are optimizing yield statistics, merging meteorological data, developing a dynamic crop mask, transforming CGMS-Maroc into a collaborative system, strengthening peer evaluation, and improving public dissemination.

The implementation of this ambitious roadmap will position CGMS-Maroc as a leading system at the international level. It will become a reference in the service of sustainable agriculture in the face of the challenges posed by climate change.

Table 9 : Comparative analysis of leading global crop yield forecasting systems.

System	Organization	Data Used	Methodology	Coverage	Strengths
CGMS-Maroc	INRA, IAV Hassan II, GDM, DSS	Weather data, remote sensing, agricultural statistics	Similarity analysis, statistical models, machine learning	Morocco	Real-time monitoring, Unified platform, crop mask
MCYFS	JRC (European Commission)	Weather data, remote sensing, WOFOST model	Statistical and agrometeorological models	European Union	Accurate forecasts at the national level
CropWatch	Institute of Remote Sensing and Digital Earth (China)	Weather data, remote sensing	Statistical models and machine learning	International	Real-time monitoring, quarterly bulletins
USDA-FAS	United States Department of Agriculture	Weather data, remote sensing	Statistical models, analog years	International	Wide range of information products
CRAFT	CCAFS	Weather data, remote sensing, crop models	Crop model simulations	South Asia	Interactive scenarios, forecasts at the local level
ICCYF	Agriculture Canada	Weather data, remote sensing	Statistical and time series models	Canada	Real-time updates, early warning system

By providing accurate and timely information on crop conditions and yield forecasts, CGMS-Maroc will aid in developing targeted policies and interventions that enhance food security, support rural livelihoods, and promote efficient resource use. The roadmap also offers opportunities for international collaboration and knowledge sharing. Engaging with other leading yield forecasting systems will allow CGMS-Maroc to benefit from shared expertise and best practices while contributing its own insights and innovations to the global community.

Enhancing cereal yield statistics for precise forecasting

In CGMS-Maroc, yield forecasts are generated at the provincial level to align with the available spatial scale of statistics. Due to provinces containing diverse communes and some not represented in the DSS database, constructing precise statistical models for predicting yields at the commune level remains a challenge. The ACCAGRIMAG project aimed to spatialize yields across all communes, aspiring to enable yield predictions at the rural commune level within CGMS-Maroc (Figure 38). A geostatistical model was developed to delineate the spatial relationships between sampled units' yields. Although innovative, this model encountered relative errors above 10% in various agricultural zones due to insufficient sample size and missing data for several cropping seasons. To improve the accuracy of yield predictions at the communal (district) level, implementing refined sampling strategies is critical.

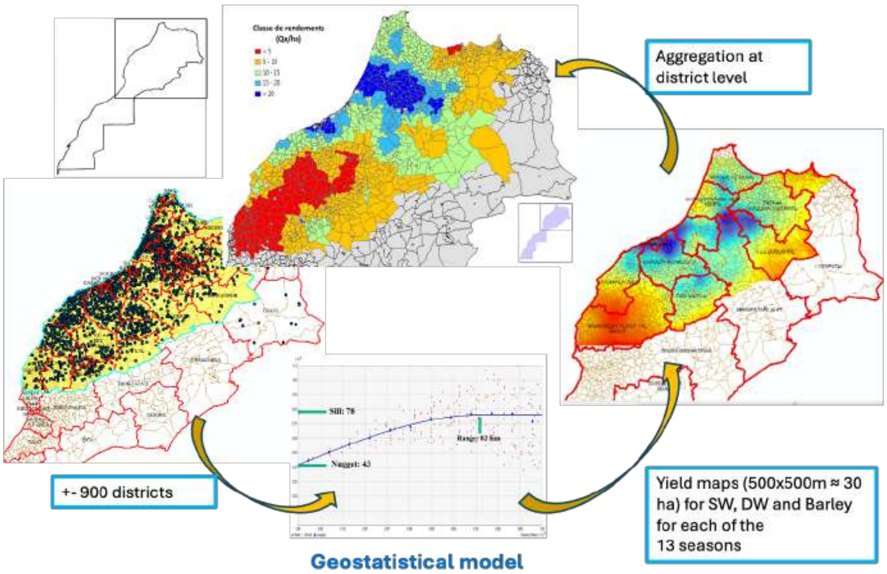

Figure 38 : Spatialization of observed yield data from sampling units (Balaghi et al., 2017).

To enhance the precision of yield forecasting at smaller administrative scales in Morocco, it is crucial to consider more comprehensive and systematic sampling strategies. Complementing existing data with alternative sources and methods, such as remote sensing data or machine learning techniques, can provide additional information and improve prediction accuracy at finer scales. These approaches can help capture small-scale variations in weather conditions, vegetation indices, and other factors influencing crop yields.

Adaptive crop masking: Capturing the dynamics of cereal cultivation

Crop masks play a pivotal role in the spatiotemporal filtering of satellite data for agricultural analysis. Global initiatives, such as GLC2000 (Mayaux et al., 2004) and GlobCover (Tchuente et al., 2011; Neumann et al., 2007), have generated land cover maps that serve as major references despite their limitations in accuracy and spatial resolution.

For instance, the European Space Agency's (ESA) GlobCover[29] initiative provides a map of land cover types in Morocco at a 300-meter spatial resolution. However, the reliability of these spatial databases is compromised by the scarcity of ground validation data. Moreover, these masks remain static, capturing a snapshot at a specific point in time, while crop rotations exhibit significant variability from one campaign to another, influenced by agro-climatic conditions.

A critical challenge, therefore, lies in the development of dynamic crop masks that are regularly updated through the automated processing of high temporal resolution satellite images. This seasonal adaptation is crucial for accurately reflecting the spatiotemporal evolution of agricultural areas. In Morocco, the evolution of cereal crop rotations, driven by the agricultural

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[29] http://due.esrin.esa.int/page_project68.php

strategies of the "Green Morocco Plan" and "Green Generation," renders the static mask of CGMS-Maroc obsolete.

The fluctuations in cereal areas due to interannual climate variations can only be accurately traced using an annual dynamic crop mask. Creating this mask, however, involves extensive methodological efforts, such as analyzing time series of satellite imagery and integrating field verification data. This dynamic mask represents a major methodological challenge for optimizing the performance of CGMS-Maroc.

Collaborative crop monitoring system: Harnessing the power of crowdsourcing

Meteorological data collected from ground stations and satellite indices like NDVI play critical roles in predicting rainfed crop yields in systems like CGMS-Maroc. While these data offer valuable macroscopic perspectives, they may overlook local details that significantly influence yields at the plot level. Crop yields are influenced by a multitude of local factors that are often difficult to capture through satellite remote sensing alone, such as local weather conditions, biotic and abiotic stresses, topography, soil characteristics, and agricultural practices.

To address this challenge, CGMS-Maroc must harmonize spatial data with more granular local information. Crowdsourcing emerges as a powerful tool to diversify data sources and engage stakeholders in the data collection process. By harnessing the collective knowledge and observations of farmers, agronomists, and local experts through mobile applications, CGMS-Maroc can tap into a vast pool of information that complements remote sensing data.

A user-friendly and intuitive mobile application is crucial for the success of crowdsourcing in CGMS-Maroc. The app should allow users to easily report observations, share insights, and provide feedback on a wide range of factors, including crop growth stages, pest and disease incidence, water stress, and overall crop health. Structured data input formats and incentives for participation, such as personalized recommendations and alerts, can encourage widespread adoption and sustained engagement from users.

Figure 39 illustrates the potential for bidirectional interaction between CGMS-Maroc and its users through a collaborative system. Farmers and advisors can contribute their observations and expertise, while receiving personalized recommendations and alerts based on the system's analysis of the collected data. This two-way communication fosters a sense of ownership and engagement among users, encouraging active participation in the monitoring process.

The integration of ground sensor data can further enhance the precision of CGMS-Maroc. By deploying a network of sensors in agricultural fields, the system can capture real-time measurements of key parameters such as soil moisture, temperature, and humidity. This sensor data complements human observations and remote sensing imagery, providing a more comprehensive understanding of the crop environment.

Crowdsourcing can also facilitate the dissemination of knowledge and best practices. As farmers and advisors contribute their experiences and observations, the system can identify successful strategies and share them with the broader community. This knowledge-sharing feature promotes the adoption of sustainable and efficient agricultural practices, ultimately leading to improved crop yields and resilience.

To maximize the benefits of crowdsourcing, CGMS-Maroc must develop robust data validation and quality control mechanisms. Automated algorithms can detect and filter out anomalous or inconsistent data points, while expert review and validation ensure the reliability of the crowdsourced information. Incentive structures and gamification techniques can further motivate users and maintain their long-term engagement.

In addition to enhancing data collection, crowdsourcing can also contribute to the refinement of CGMS-Maroc's predictive models. By integrating user-generated data with remote sensing data and ground sensor information, the system can create a rich and dynamic dataset that reflects the true state of crops at the field level. This data can be used to train and validate machine learning models, improving their accuracy and robustness.

Moreover, the detailed documentation of biotic and abiotic risks, as well as best agricultural practices, collected through crowdsourcing can be integrated into the models to improve local crop monitoring and yield forecasting. This knowledge can be disseminated to farmers and advisors in the form of guides and recommendations, promoting good agricultural practices at the national level.

Crowdsourcing has the potential to revolutionize crop monitoring in CGMS-Maroc by leveraging the power of collective intelligence. By engaging a wide range of stakeholders and providing them with user-friendly tools to contribute their observations and insights, the system can access a wealth of local knowledge that would otherwise be difficult to capture. This collaborative approach not only enhances the accuracy and granularity of the data but also fosters a sense of ownership and empowerment among users.

As CGMS-Maroc continues to evolve, the integration of crowdsourcing will play an increasingly important role in improving the accuracy, timeliness, and local relevance of yield predictions. By harnessing the collective knowledge and observations of farmers, agronomists, and local experts, the system can provide more targeted and actionable insights to support sustainable agricultural development in Morocco.

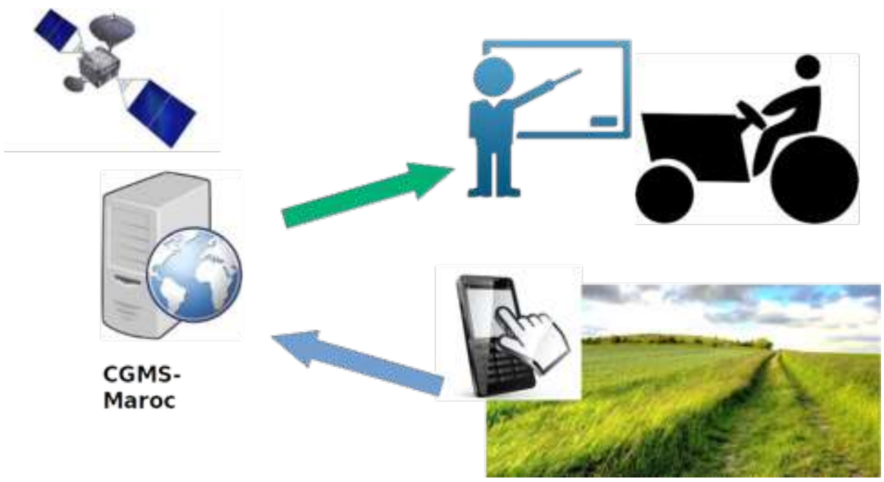

Figure 39 : CGMS-Maroc's potential for a crowdsourced monitoring system.

Seasonal yield forecasting: Leveraging seasonal weather forecasts

Seasonal weather forecasts have empowered agricultural decision-making, particularly in the context of cereal yield forecasting. By providing valuable insights into the expected meteorological conditions, such as average temperatures and total precipitation, for the upcoming month, these forecasts empower farmers, agricultural advisors, and policymakers to make informed decisions and develop proactive strategies to optimize cereal production in Morocco.

The integration of seasonal weather forecasts into crop monitoring and forecasting systems, like CGMS-Maroc, holds immense potential for enhancing the accuracy and timeliness of cereal yield predictions. By leveraging the power of these forecasts, stakeholders can gain a clearer understanding of the agro-climatic conditions that will likely prevail during the critical growth stages of cereal crops, enabling them to take appropriate measures to maximize yields and minimize climate risks.

Seasonal weather forecasts provide a probabilistic assessment of the anticipated weather patterns, typically expressed in terms of three scenarios: above, below, or near average. These scenarios are translated into user-friendly terms such as "warm," "normal," or "cold" for temperature, and "wet," "normal," or "dry" for precipitation (Figure 40 and Figure 41). By offering a range of possible outcomes, these forecasts allow decision-makers to consider different scenarios and develop contingency plans accordingly.

The GDM has been at the forefront of generating and disseminating seasonal weather forecasts since 1996. Through continuous advancements in modeling techniques and collaborations with international partners, GDM has significantly enhanced the skill and resolution of its forecasts over the years. The introduction of the ARPEGE-Climat V5.2 ocean-atmosphere climate model in 2012, operating at a spatial scale of approximately 55 km, marked a significant milestone in GDM's forecasting capabilities.

The integration of seasonal weather forecasts into CGMS-Maroc provides new opportunities for predicting cereal yields at the seasonal scale. By adding these forecasts into crop models, along with other relevant data, such as soil moisture and vegetation indices, the system can generate probabilistic yield forecasts that consider the anticipated weather conditions.

One of the key advantages of seasonal yield forecasting is the extended lead time it provides. By issuing yield predictions one to two months in advance, stakeholders gain valuable time to make informed decisions and implement appropriate strategies. For instance, farmers can adjust their sowing dates, select suitable crop varieties, optimize irrigation schedules, and plan for potential pest and disease outbreaks based on the expected weather patterns. Agricultural advisors can provide tailored recommendations to farmers, considering the specific agro-climatic conditions of each region. Policymakers can use the yield forecasts to develop proactive strategies for ensuring food security, managing grain reserves, and planning for potential market fluctuations.

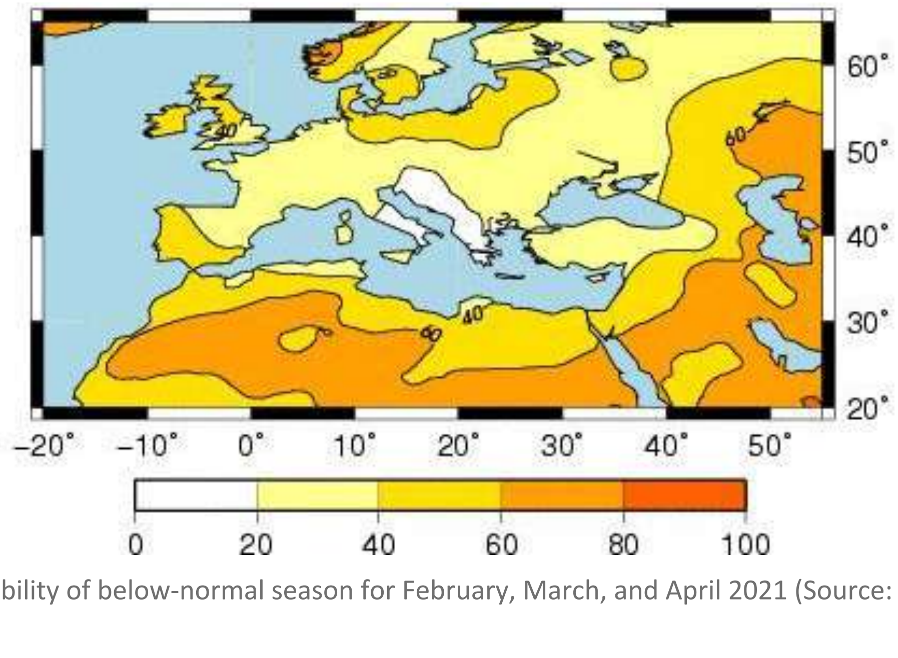

Figure 40 : Probability of below-normal season for February, March, and April 2021 (Source: GDM).

To further enhance the accuracy and resolution of seasonal yield forecasts, CGMS-Maroc aims to leverage the state-of-the-art Weather Research and Forecasting (WRF) model. WRF ingests data from the "Extended-Range ER-M-climate" model developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and applies dynamic downscaling techniques to refine the spatial resolution to 12 km, specifically tailored to the Moroccan context (Figure 42). This high-resolution approach enables the system to capture local variations in weather patterns, which can have significant impacts on cereal yields.

Moreover, the WRF model's ability to provide forecasts up to four weeks in advance, with results structured by week, allows for a more granular and dynamic assessment of the evolving weather conditions. This level of detail is particularly valuable for cereal yield forecasting, as it enables the system to capture the critical growth stages of the crops and assess the potential impacts of weather variability on yield formation.

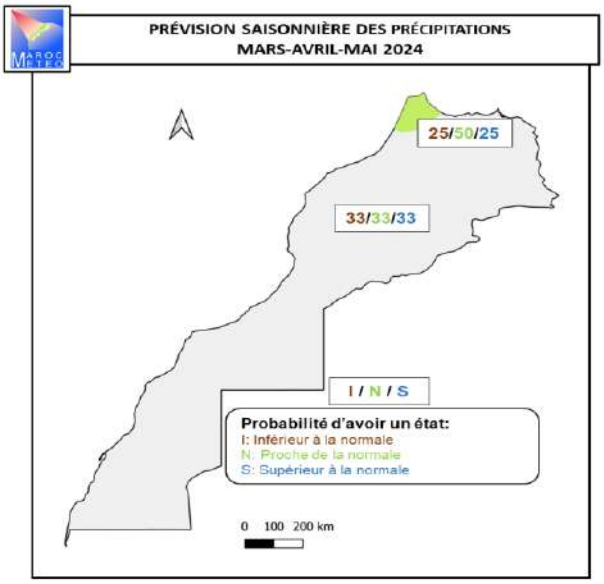

Figure 41 : Probability of near-normal season for the extreme north of Morocco in March, April, May 2024 (Source: GDM).

The integration of seasonal weather forecasts and high-resolution modeling techniques into CGMS-Maroc will represent a significant step forward in cereal yield prediction. By providing timely, accurate, and actionable information, the system will empower stakeholders to make informed decisions and implement proactive strategies to optimize cereal production. This not only contributes to improving food security and economic stability but also promotes sustainable agricultural practices by enabling farmers to adapt to the anticipated weather conditions.

However, it is important to acknowledge that seasonal yield forecasting is not without challenges. The inherent uncertainties associated with weather forecasts, particularly at longer lead times, can propagate into the yield predictions. The complex interactions between weather, soil, and crop management practices may not be fully captured by the models, leading to potential discrepancies between forecasted and actual yields. Moreover, the skill and reliability of seasonal weather forecasts can vary depending on the region, season, and specific meteorological variables being predicted.

To address these challenges, CGMS-Maroc will need to continuously refine its modeling approaches, incorporate new data sources, and validate its forecasts against observed yields. Collaborations with agricultural experts, researchers, and end-users will be crucial to improve the system's performance and ensure its outputs are relevant and actionable for decision-makers.

Furthermore, effective communication and dissemination of the seasonal yield forecasts will be key to maximizing their impact. The forecasts should be presented in a clear, user-friendly format, accompanied by appropriate guidance and uncertainty estimates. Engaging with stakeholders through workshops, training programs, and outreach activities will help build trust and promote the uptake of the forecasts in agricultural decision-making.

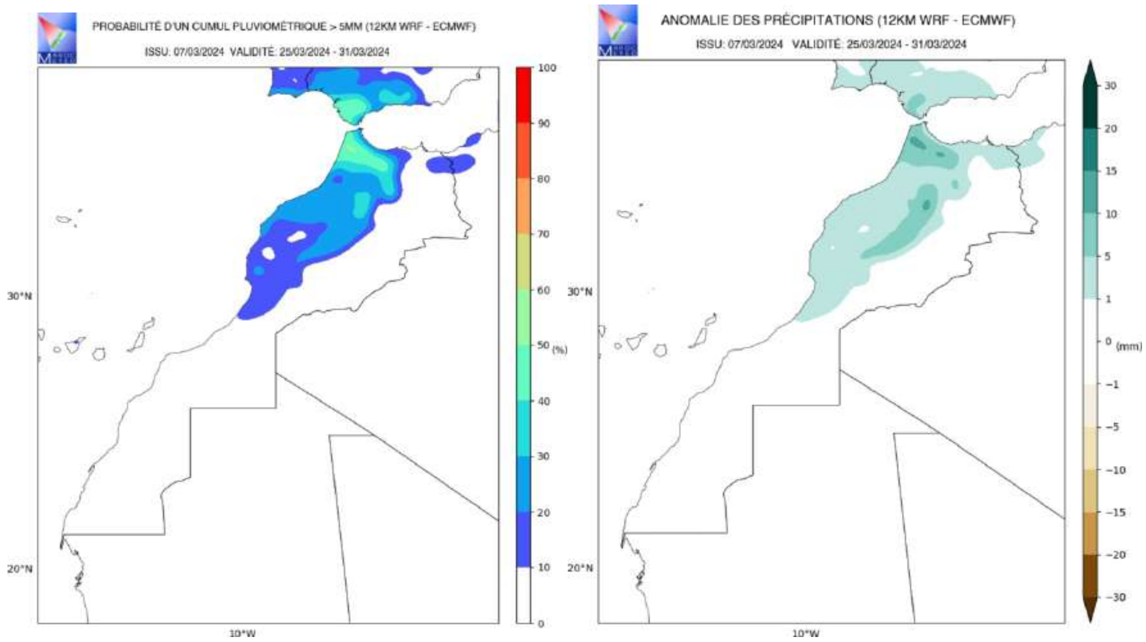

Figure 42 : Probability of cumulative rainfall > 5mm and precipitation anomaly from March 25 to 31, 2024, intra-seasonal forecast established on March 7, 2024 (Source: GDM).

Empowering stakeholders through effective dissemination

Currently, CGMS-Maroc provides crucial information for monitoring the cropping season and forecasting cereal yields, aiding the Ministry of Agriculture's services. Users can easily access key seasonal indicators like precipitation, temperature, and vegetation indices, tailored for specific administrative regions, with just a click.

However, to extend the usage of CGMS-Maroc beyond the Ministry of Agriculture, a comprehensive strategy is required. This strategy should not only enhance awareness of the platform's capabilities but also provide essential training for its effective utilization. With a well-structured dissemination plan, CGMS-Maroc could become an invaluable resource for all stakeholders in the agricultural sector. It has the potential to lead in managing climate risks, boosting crop yields, promoting sustainable farming practices, and driving overall economic growth in the nation's agriculture sector. By equipping stakeholders with necessary data and tools for informed decision-making, CGMS-Maroc could significantly bolster the resilience and prosperity of Morocco's agricultural landscape.

In the realms of research and education, CGMS-Maroc stands as rich source of data and capabilities. It offers a robust platform for predictive analysis of crop yields, facilitating in-depth studies into the impacts of various factors such as climate change, soil health, and plant diseases. The system's comprehensive data on weather and crop conditions lays the groundwork for interdisciplinary research, effectively bridging the gap between agriculture and climatology. Moreover, the platform serves as a valuable educational resource, enabling students and researchers to delve into advanced agrometeorology, fostering a profound understanding of the field and nurturing the development of essential skills.

Ensuring excellence through external peer review

CGMS-Maroc should establish a comprehensive external peer review mechanism to complement internal quality assurance and provide an independent evaluation of the system's data, models, forecasts, and processes.

A panel of experts from relevant fields such as agronomy, climate science, remote sensing, statistics, and computer science should be assembled. Panel members would be recognized experts in their fields, selected in consultation with leading agricultural universities and research institutions in Morocco. Furthermore, academic partnerships would enhance capacity building and enable CGMS-Maroc to stay at the forefront of scientific advancements relevant to its domain.

The main responsibilities of this panel would include:

- Thoroughly reviewing the data sources used by CGMS-Maroc for robustness, representativeness, and potential biases.
- Assessing the strength of the methodologies and underlying assumptions of the predictive models: choice of variables, modeling techniques, validation.
- Verifying the rigor of validation processes for model assessment: statistical metrics, benchmark standards.
- Monitoring the interpretation and communication of results and forecasts for clarity, transparency, and actionability for users.
- Making recommendations to improve processes, workflows, and documentation.

The expert panel could meet regularly, at least twice a year, to review progress and provide timely recommendations. Special reviews might be undertaken following major system updates or before significant operational milestones. Input from the expert panel would be sought through virtual meetings, on-site reviews, collaborations on research projects, student projects, and classroom discussions.

All panel members would be required to sign non-disclosure agreements to protect proprietary data or methods used in CGMS-Maroc. Feedback from the panel would be fully documented and integrated into future development cycles for continuous improvement of the system.

In addition to the expert panel, CGMS-Maroc would seek peer review by participating in academic conferences, publishing in peer-reviewed journals, and engaging with the broader scientific community. Rigorous external evaluations across the entire crop monitoring and forecasting workflow would enhance the credibility and transparency of the system.

Capacity building: Empowering CGMS-Maroc with cutting-edge expertise

For CGMS-Maroc to reach its potential as a leading agronomic platform, substantial effort in human capacity development is critical. The implementation of anticipated technological advancements (like sensor webs, mobile apps, and deep learning models) and methodological innovations (such as participatory methods and big data analytics) demands a workforce with specialized skills, which are presently uncommon within the existing team.

To this end, a robust program of continuous education and strategic recruitment is crucial to provide CGMS-Maroc with the expertise necessary to fulfill its strategic ambitions. This initiative should encompass two key areas:

- **Technical training:** This involves equipping engineers and analysts with the latest in data science (data exploration, visualization, machine learning), geomatics (GIS, remote sensing), and software engineering (web and mobile development, interoperability). The goal is to empower them to update and refine the system's architecture, integrate cutting-edge predictive algorithms, enhance user interface usability, and optimize data management.
- **Thematic knowledge enhancement:** This focuses on bolstering the agronomic, ecophysiological, climatological, and socio-economic understanding of project managers and analysts. It aims to prepare them to innovate with new modeling

techniques for agro-systems, develop more effective indicators, conduct in-depth analyses of system outputs, and assist users in leveraging the platform’s data services.

The capacity strengthening program will operate through three strategic channels:

- **Tailored educational tracks:** Developing continuous, adaptable training programs, offered both in-person and online, to meet the specific requirements of roles such as data scientists, geomatic experts, modelers, agronomists, and agricultural advisors. Core courses will be shared to promote a cohesive understanding and appreciation of CGMS-Maroc’s mission and approaches.
- **Expert recruitment:** Proactively hiring individuals with expertise in the platform’s newly adopted technologies and focus areas to immediately contribute operational skills. Establishing a skill mapping process will help pinpoint critical recruitment needs promptly.
- **University collaborations:** Partnering with academic institutions to attract talent through internships or doctoral research on strategic R&D projects that align with CGMS-Maroc’s roadmap. These partnerships will also serve to familiarize future graduates with the system’s capabilities and streamline the recruitment of exceptional candidates.

This strategy to enhance technical and thematic skills will benefit from planned efforts to forge stronger national and international scientific partnerships. Joining networks of excellence will encourage the sharing of experiences and best practices and foster the professional growth of CGMS-Maroc’s staff. Engaging CGMS-Maroc personnel and external researchers in collaborative projects and workshops will be instrumental in spreading and embedding new knowledge and skills.

By investing heavily and consistently in its human resources through training and recruitment of new talent, CGMS-Maroc is setting the stage for its evolution into an integrated, top-performing agronomic platform, deeply embedded within its ecosystem. Developing a multidisciplinary team that stays current with the latest technological and scientific breakthroughs will help broaden the reach and impact of its offerings across a diverse and expanding user base. This proactive approach to skill development is fundamental to transforming CGMS-Maroc into a catalyst for a digital innovation ecosystem, promoting sustainable and resilient agriculture in Morocco and across Africa.

Roadmap's impact on CGMS-Maroc's future development

The comprehensive roadmap outlined above, encompassing advancements in cereal yield statistics, dynamic crop masking, collaborative monitoring, seasonal yield forecasting, dissemination, external peer review, and capacity building, sets the stage for CGMS-Maroc's evolution into a cutting-edge agronomic platform. By implementing these strategic initiatives, CGMS-Maroc will not only solidify its position as a national leader in agricultural decision support but also emerge as a model for integrated crop monitoring systems on the international stage. The system's enhanced capabilities, coupled with its commitment to collaborative innovation and knowledge sharing, will undoubtedly contribute to the development of resilient and sustainable agricultural practices in the face of climate change.

V. Conclusion: Driving sustainable agriculture through CGMS-Maroc

CGMS-Maroc has emerged as a transformative tool for monitoring cereal campaigns and forecasting yields across Morocco, revolutionizing agricultural risk management in the face of climate change. Born from a collaborative effort between national and international institutions, the system exemplifies the power of integrating agronomic research, digital technology, and decision support mechanisms to create a comprehensive and effective platform for agricultural decision-making.

The system's unique contributions lie in its ability to provide accurate, timely, and actionable yield forecasts by leveraging advanced data processing techniques, machine learning algorithms, and remote sensing technology. CGMS-Maroc's functional architecture, which seamlessly integrates diverse data sources and employs sophisticated modeling approaches, enables it to capture the complex interactions between climate, soil, and crop growth, resulting in robust and reliable yield predictions.

Moreover, CGMS-Maroc's impact extends beyond its technical capabilities, serving as a vital tool for driving sustainable agriculture in Morocco. By providing decision-makers with critical information on expected yields, the system supports proactive measures to optimize resource allocation, promote sustainable land management practices, and mitigate the impacts of adverse climatic events. This underscores CGMS-Maroc's role as a catalyst for the adoption of climate-smart agriculture and the development of resilient farming systems.

As CGMS-Maroc continues to evolve, its potential for future development is vast. The system's modular and extensible architecture allows for the seamless integration of new data sources, methodologies, and functionalities, ensuring its adaptability to the ever-changing landscape of agricultural challenges. The strategic roadmap outlined in this document, which encompasses advancements in cereal yield statistics, dynamic crop masking, collaborative monitoring, seasonal yield forecasting, dissemination, external peer review, and capacity building, sets the stage for CGMS-Maroc to become a cutting-edge agronomic platform, solidifying its position as a leader in agricultural decision support both nationally and internationally.

Furthermore, CGMS-Maroc's success serves as a model for integrated crop monitoring systems worldwide, demonstrating the transformative potential of harnessing digital innovation to support sustainable agriculture. By sharing its expertise and lessons learned, CGMS-Maroc can foster international collaboration, knowledge exchange, and capacity building, contributing to global efforts to enhance agricultural sustainability, resilience, and food security in the face of climate change.

In conclusion, CGMS-Maroc represents a groundbreaking tool that is driving sustainable agriculture in Morocco, empowering decision-makers with accurate, timely, and actionable information to optimize crop management, promote sustainable practices, and ensure food security. As the system continues to evolve and expand its capabilities, it holds immense potential to support the transition towards climate-resilient agriculture, inform evidence-based policy-making, and contribute to the long-term sustainability of farming communities in Morocco and beyond. By embracing the power of digital innovation and collaborative research, CGMS-Maroc is poised to play a pivotal role in addressing the complex challenges posed by climate change and paving the way for a sustainable future for agriculture.

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Supplementary materials and detailed appendices

Appendix 1 : List of GDM synoptic stations used in CGMS-Maroc.

WMO station number	Location	Date of commissioning
60155001	CASABLANCA-ANFA	01/03/1911
60127001	TAZA	01/01/1918
60250001	AGADIR INEZGANNE	01/03/1921
60150001	MEKNES	01/01/1924
60230001	MARRAKECH	01/01/1930
60195001	MIDELT	01/01/1931
60100001	TANGER-PORT	01/01/1931
60265001	OUARZAZATE	01/02/1931
60318001	TETOUAN	01/01/1935
60115001	OUJDA	01/01/1941
60220001	ESSAOUIRA	01/01/1941
60165001	EL JADIDA	01/11/1944
60135001	RABAT-SALE	01/05/1947
60190001	KASBA-TADLA	01/03/1949
60101001	TANGER-AERO	01/01/1950
60120001	KENITRA	01/01/1951
60185001	SAFI	01/07/1954
60160001	IFRANE	01/06/1956
60107001	AL-HOUCEIMA	01/01/1960
60191001	BENI MELLAL	01/01/1960
60200001	BOUARFA	01/01/1960
60141001	FES-SAIS	01/01/1961
60105001	LARACHE	01/02/1962
60096001	DAKHLA	01/07/1963
60060001	SIDI IFNI	01/01/1969
60156001	NOUASSEUR	01/01/1970
60210001	ERRACHIDIA	01/01/1973
60285001	TAN-TAN	01/11/1974
60033001	LAAYOUNE	01/01/1976
60340001	NADOR	01/01/1976
60252001	AGADIR AL MASSIRA	01/01/1978
60136001	SIDI SLIMANE	01/07/1979
60270001	TIZNIT	01/11/1982
60178001	KHOURIBGA	01/02/1984
60335001	SMARA	01/01/1987
60146001	MOHAMMEDIA	01/10/1989
60280001	GUELMIM	01/05/1990
60253001	TAROUDANT	01/01/1992
60106001	CHEFCHAOUEN	01/08/1994
60237001	OUKAIMDEN	01/08/1996

60177001	SETTAT	01/10/1999
60125001	COL DE TOUAHER	01/01/2002
60101002	TANGER-VILLE	01/01/2002
60340002	NADOR-AROUI	01/02/2002

Appendix 2 : Angstrom and Hargreaves coefficients of GDM stations used to calculate global radiation in CGMS-Maroc.

WMO_NO	ANGSTROM_A	ANGSTROM_B	HARGREAVES_A	HARGREAVES_B
60033001	0.412	0.356	0.035	8.384
60060001	0.358	0.441	0.021	13.131
60096001	0.412	0.356	0.035	8.384
60100001	0.317	0.467	0.053	3.429
60101001	0.317	0.467	0.053	3.429
60101002	0.317	0.467	0.053	3.429
60105001	0.287	0.509	0.045	5.056
60106001	0.174	0.639	0.047	2.096
60107001	0.289	0.533	0.05	4.284
60115001	0.336	0.45	0.048	2.573
60120001	0.285	0.504	0.045	4.604
60125001	0.65	0.098	0.038	6.681
60127001	0.288	0.599	0.046	4.53
60135001	0.289	0.499	0.044	5.238
60136001	0.081	0.68	0.032	4.571
60141001	0.274	0.513	0.046	2.91
60146001	0.305	0.485	0.035	9.282
60150001	0.286	0.506	0.047	3.288
60155001	0.305	0.485	0.036	8.14
60156001	0.355	0.453	0.044	4.162
60160001	0.209	0.586	0.049	2.785
60165001	0.305	0.485	0.036	8.14
60177001	0.264	0.525	0.045	3.795
60178001	0.287	0.494	0.047	4.061
60185001	0.351	0.43	0.047	5.08
60190001	0.304	0.483	0.046	3.089
60191001	0.285	0.508	0.043	3.89
60195001	0.334	0.455	0.038	6.642
60200001	0.403	0.413	0.046	4.835
60210001	0.355	0.43	0.042	5.767
60220001	0.351	0.43	0.047	5.08
60230001	0.291	0.508	0.042	5.113
60237001	0.288	0.599	0.046	4.53
60250001	0.345	0.445	0.032	9.689
60252001	0.384	0.403	0.051	2.84
60253001	0.369	0.43	0.036	7.236
60265001	0.355	0.43	0.042	5.767
60270001	0.374	0.41	0.037	8.237
60280001	0.412	0.356	0.035	8.384
60285001	0.412	0.356	0.035	8.384
60318001	0.242	0.552	0.039	5.599
60335001	0.412	0.356	0.035	8.384
60340001	0.123	0.649	0.041	1.059
60340002	0.123	0.649	0.041	1.059

Appendix 3: AURELHY methodology

The AURELHY methodology (Analyse Utilisant le Relief pour l'Hydrométéorologie, in English: Analysis Using Terrain for Hydrometeorology) is a spatial interpolation technique developed by Météo-France. It is specifically designed to account for the influence of terrain on meteorological variables such as precipitation and temperature. This method is particularly useful in mountainous regions where terrain can have a significant impact on local climate.

The AURELHY methodology utilizes digital terrain models to represent the topography and applies interpolation algorithms to estimate the values of meteorological variables between observation stations. It produces high-resolution meteorological maps, providing a more precise representation of weather conditions over complex terrain.

The AURELHY methodology is often used for mapping climatological normals, predicting precipitation and temperatures, and analyzing extreme weather events in mountainous regions.

The AURELHY methodology provides grid-point information based on observed data from a network of meteorological stations. This method involves three steps:

1. The first step involves finding the 15 eigenvectors through principal component analysis, explaining about 90% of the variance in terrain. For each grid point, a "landscape" is calculated as the set of altitudes of the 121 points within a square domain of 50 km grid spacing, centered on the point. The altitude of the central point is then subtracted. Principal component analysis is performed on all the resulting relative landscapes at each point of the territory to determine the first 15 eigenvectors. The 15 principal components and the smoothed altitude of the point compose the 16 predictors of the meteorological field at the measurement points. They are ranked by forward stepwise selection, and a stopping criterion obtained from the Fisher test is used to retain relevant predictors.
2. The second step involves developing the regression equation. The regression equation established on the sample of measurement points is then applied to every grid point.
3. The third method is used to correct the regression values calculated by kriging the residuals. At each measurement point, the difference (called the residual) between the measured value and the value calculated by regression is calculated. The residual is then interpolated by kriging.

Finally, the reconstructed climatological field is calculated at each grid point as the sum of the two terms obtained by regression and kriging of the residuals.

Annexe 1 : De Martonne index

The De Martonne index is a climatic index used to characterize the aridity or humidity of a climate. It was introduced by the French geographer Emmanuel de Martonne in 1926. This index is useful for assessing the dryness of a region and is calculated based on precipitation and average temperatures over a given period (usually monthly or annually).

The formula to calculate the Martonne index is as follows:

$$I = \frac{P}{T+10}$$

Where:

- *P* is the total precipitation amount (in millimeters) over the specified period, and
- *T* is the average temperature (in degrees Celsius) over the same period.

The index increases with the amount of precipitation and decreases with the average temperature, meaning that a high index indicates a more humid climate, while a low index indicates a drier climate. The De Martonne index thus allows climates to be classified into different categories of aridity and humidity, which is particularly useful in geographical and environmental studies.

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