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Yield Gap Analysis of Wheat (*Triticum aestivum*) Production in Morocco using a Light Use Efficiency Model (LINTUL) and Geostatistical Approaches

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IFDC FERARI Research Report No. 12

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Bouchra Darkaoui[1,2], Prem S. Bindraban[2], Isaac Newton Kissiedu[2], Martin Jemo[1],
Anselme K.K. Kouame[2], Williams K. Atakora[2], and William Adzawla[2]

[1]Mohammed VI Polytechnic University, School of Agriculture, Fertilization and Environmental Sciences (ESAFE), Morocco
[2]International Fertilizer Development Center, USA
[*]Correspondence: pbindraban@ifdc.org

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ABBREVIATIONS

DVS	development stage
LAI	leaf area index
LI	light intercepted
LINTUL	Light Interception and Utilization
LUE	light use efficiency
PAR	photosynthetically active radiation
RUE	radiation use efficiency
Tmax	maximum temperature
Tmin	minimum temperature
Tsum	temperature sum

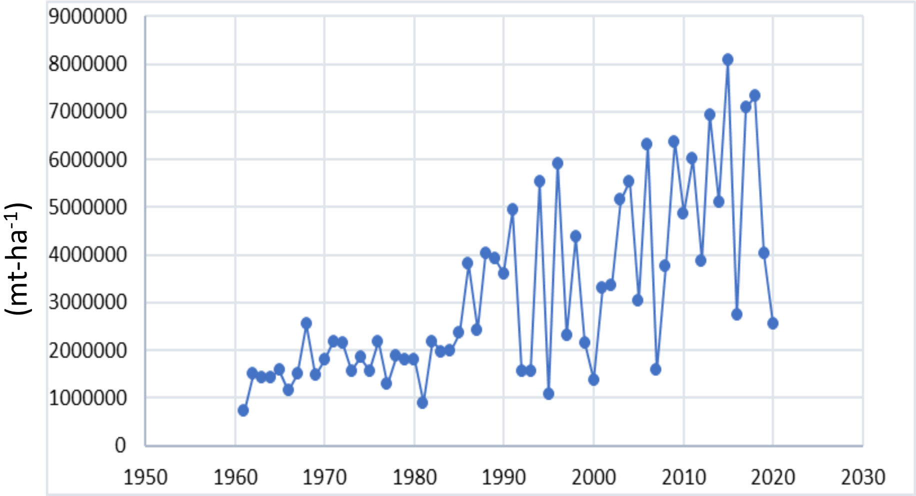
SUMMARY

Wheat (*Triticum aestivum*) is a staple food crop in Morocco that plays an important role in the food security of the country. However, the crop production capacity of wheat at the national level is among the lowest at only at 1.6 metric tons per hectare (mt ha^{-1}), compared to Egypt at 6.6 mt ha^{-1}. Several detrimental biotic and abiotic factors curtailing wheat yield include climatic limitations, insufficient soil fertility, and inadequate management interventions. To better understand these drivers, this work simulates yield using a modeling approach based on light interception and utilization (LINTUL-1). The potential and observed yield data cover the period from 2011 to 2019 in various provinces of Morocco. The LINTUL-1 model was calibrated using crop characteristics and preliminary data generated from wheat production in Morocco. Geostatic techniques were further employed to physically map the levels of current yield production. The results showed that at the national scale the average simulated potential yield reached 5.5 mt ha^{-1}, compared to an average observed yield of only 1.6 mt ha^{-1}. The resulting yield gap was calculated for several different regions at an average of 3.9 mt ha^{-1}. The yield gaps are controlled by many biotic and abiotic constraints, and the adoption of effective management techniques, such as fertilizer application, appropriate pest and disease management, and water management via irrigation, can reduce the gaps and contribute to food security in Morocco. Further studies to identify key factors that drive wheat yield variability at the regional yield level are envisaged to refine recommendations for farmers.

CHAPTER 1: INTRODUCTION

1.1 Background

Wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and maize (*Zea mays*) are the main cereal crops cultivated in Morocco on approximately 80% of the total agricultural land area. Wheat represents about 54% of total cereal production and is a main staple food in Morocco; it is indispensable in addressing the food and nutrition security and quality challenges in the country (Aït El Mekki, 2006; Jarlan et al., 2014). In Morocco, wheat is primarily consumed as bread and durum wheat flours at an average of about 172 kilograms (kg) per person per year, based on a population of 36.4 million inhabitants with an intake of about 0.472 kg per day. The country is among the top wheat-consumers in the world (Fardaoussi, 2016). Despite the importance of the crop, the total land area for wheat cultivation is around 4.3 million hectares (ha), with an annual production of about 4.3 million metric tons (mt) for common wheat and 2 million mt for durum wheat (FAO, 2022; Figure 1).



Source: FAOSTAT/FAO

Figure 1. Wheat Production in Morocco (mt)

The average wheat yield is only about 1.46 mt ha^{-1}; this is among the lowest in the world (Mrabet et al., 2012; Yigezu et al., 2021). Several abiotic drivers responsible for the low crop yield are climatic factors, such as inadequate water availability, soil nutrient availability to the crop, and farmer management practices (Khanfri et al., 2018). The biotic factors accounting for low yield are diseases and associated pests. At the country level, yield variabilities are largely explained by regional climatic differences. Loukos, Douyet, Marchouch, Settat, and Tessaout are the important wheat-growing regions of the country, where the observed grain yield at the farmer field level is around 4.7 mt ha^{-1}, 3.3 mt ha^{-1}, 3.1 mt ha^{-1}, 1.8 mt ha^{-1}, and 3.5 mt ha^{-1}, respectively (Pala et al., 2011). The observed yield falls far below the potential or simulated yield of about 8.5 mt ha^{-1}, 5.4 mt ha^{-1}, 5.2 mt ha^{-1}, 4.5 mt ha^{-1}, and 6.2 mt ha^{-1} for the respective regions of Morocco. The variation in yield gaps offers room for improvement in the current national yield production to reduce the country's dependency on international wheat imports (Pala et al., 2011). Regional and local factors for low wheat yield have received little research exploration in terms of observed and simulated yields from a modeling perspective (Epule et al., 2022a). Modeling can be a useful tool to attain a good understanding of the yield gaps that are relevant to the local environment through an estimation of the theoretical maximum yield (van Ittersum et al., 2013). The validity of a crop model relies on an accurate estimation of parameters that affect key crop growth processes. The amount of light intercepted (LI) by the crop and radiation use efficiency (RUE) are key parameters for estimating potential yield (het Lam, 2014). Therefore, the light intercepted by the crop and RUE have been used to investigate the interaction between crops and management practices and to explain yield differences in diverse production environments (Shah et al., 2004).

Light Interception and Utilization (LINTUL) is a relatively simple and robust modeling tool that can simulate biomass growth and yield of wheat for potential conditions (Wiertsema, 2015). LINTUL-Wheat uses tabulated values for dry matter partitioning and biomass growth rate, as a function of the amount of LI multiplied by the RUE parameter value, to simulate the growth process and predict the yield for the crops (Maas, 1993). However, this model has not been tested in Morocco, where wheat is cultivated across a range of environmental and climatic conditions (Epule et al., 2022a).

1.2 Problem Statement

Due to the importance of the cereal market to Morocco's economy, it is critical to obtain a better understanding of the factors governing the interannual variability in agricultural production, among which climate is by far the most influential (Jarlan et al., 2014). According to Pala (2011), the average wheat crop yield on farmers' croplands (0-5.5 mt ha^{-1}) was less than the average yield recorded at the research station and on-farm demonstration (0-7.3 mt ha^{-1}) and the simulated potential output (4.1-11.08 mt ha^{-1}). This gap between the observed and the simulated yield is driven by many biotic and abiotic constraints, such as water availability (Abderrazzak et al., 2011). Devkota and Yigezu (2020) assessed 2,296 fields cultivated by 1,230 households in 21 major wheat-growing provinces in the central parts of western Morocco, which account for 73% of the total national wheat production, and observed that the average yield under rainfed production conditions was 0.9 mt ha^{-1}. However, in irrigated areas, the average yield increased to 4.0 mt ha^{-1}. Thus, the sustainability of wheat production is at stake, as critical factors such as climate variables, specifically rainfall, evaporation, solar radiation, temperature, relative humidity, and wind speed, can negatively affect growth and yields (Epule et al., 2022b). The spatial and temporal nature of these factors requires both process modeling and geostatistical analysis to properly understand their individual effects on yield production.

Among the process-based models, LINTUL was chosen because it uses fewer parameters even though more complex models such as AquaCrop exist (Hsiao et al., 2009).

1.3 Activity Statement

This study of the interannual variability of wheat production across Moroccan provinces was conducted in three important steps. In the initial step, open source data for the daily minimum and maximum temperature, daily precipitation, solar radiation, wind speed, and physical and chemical soil characteristics were retrieved from various platforms. The daily temperature, daily precipitation, solar radiation, wind speed, and vapor pressure were further coded as explanatory/predictor variables of grain yield in the LINTUL-1 model to simulate crop growth and national wheat yield potential. In the second step, the national data were broken down into regional production for the observed and simulated yield and the yield gap was calculated. In the last step, the observed yield and simulated yield were used to build a digital map of observed and simulated yields and yield gaps of the national and regional yield production of wheat.

1.4 Justification Statement

Wheat is considered a staple food crop in Morocco. The growing population imposes a rising demand for wheat, and the country is highly dependent upon wheat imports. Moreover, there is high variability in the yield across provinces and a growing gap between the simulated potential yield and the actual yields attained by farmers. Therefore, crop modeling could be used to quantify this yield fluctuation, determine the yield gaps, and define appropriate context-specific interventions to address the low yields. The LINTUL-1 model can help us understand the factors that drive the yield gaps for each province under specific climate conditions and identify recommendations for the Moroccan farmers. This research will also serve as a baseline study for subsequent research in the domain of wheat production in Morocco.

1.5 Research Questions

- Can LINTUL-1 accurately estimate the national potential yield of wheat in the wheat cropping provinces of Morocco?
- Can the LINTUL-1 simulated potential yield explain the observed yield variability in the wheat cropping provinces of Morocco?

1.6 Research Objectives

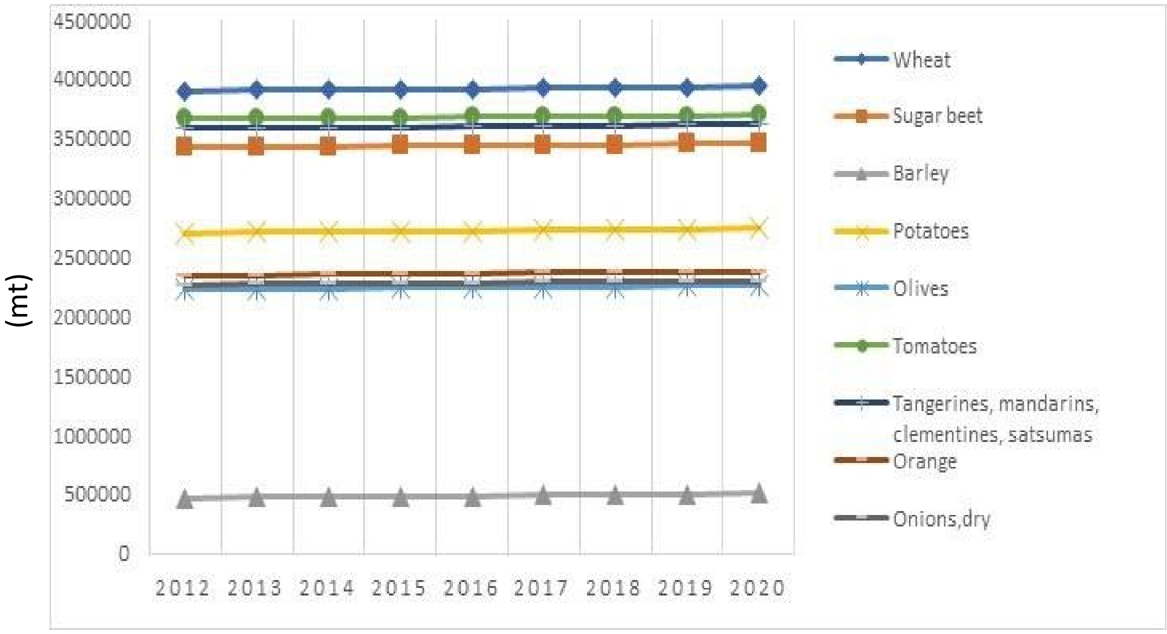
The general objective of this study is to assess the bread wheat yield gap variability from 2011 to 2019 in different provinces in Morocco using a crop model. Specifically, this study will:

- Estimate the national observed and simulated yield and yield gap to determine the potential yield of bread wheat in Morocco.
- Break down the national observed and simulated yield and yield gaps into regional production.
- Produce a map of the spatial provincial variability in the yield gaps using geostatistical techniques.

CHAPTER 2: LITERATURE REVIEW

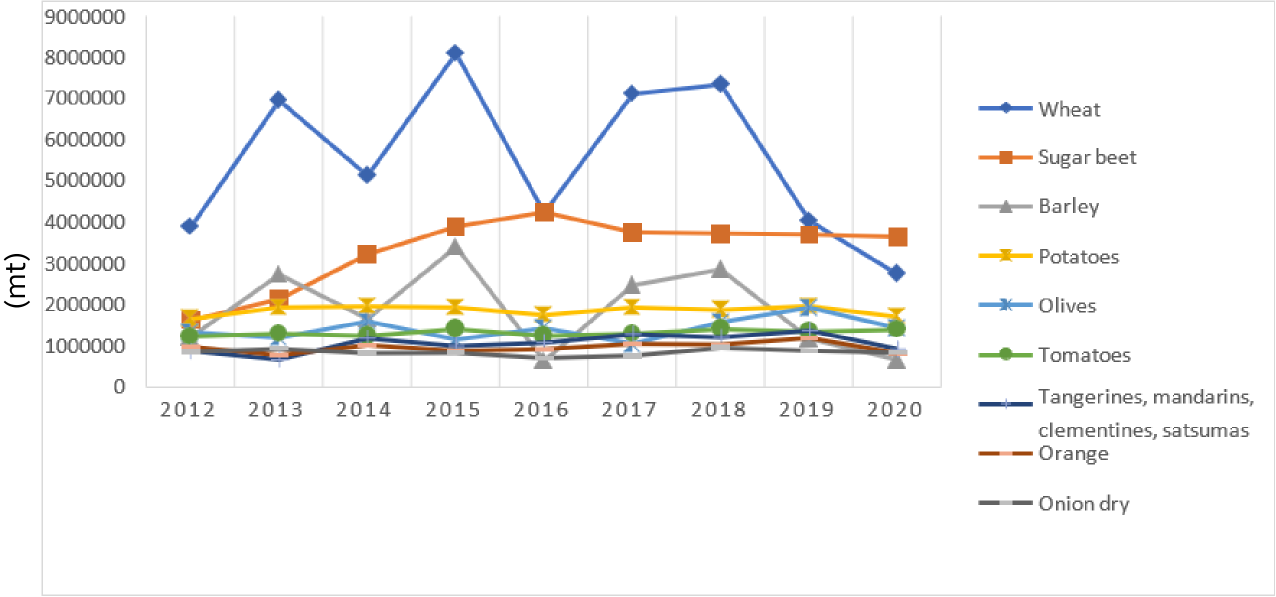
2.1 Agriculture in Morocco

Agriculture is the primary source of food, income, and employment for many rural populations and plays a crucial role in the economies in the Mediterranean area (Harmanny and Malek, 2019). In Morocco, the agriculture and food production sectors are key contributors to the national economy, accounting for 15-20% of the gross domestic product (GDP) of the country (Harbouze et al., 2019). The agriculture sector employs 44% of the country's workforce (Karim and Mansouri, 2015), 65% of whom reside in rural areas (Brouziyne, 2021). Morocco has the greatest agricultural employment rate in the Mediterranean region (33%), with just 1% of the 1.5 million farmers cultivating an area greater than 50 ha and 70% cultivating less than 5 ha (MADRPM, 2019). The major staple crops include wheat, sugar beet, barley, potato, olive, tomato, tangerine/mandarin, and orange (Figure 2). Agriculture occupies 9.2 million ha (13%) of the country's total land area of 71.08 million ha (Mrabet et al., 2012). The main crops in terms of devoted surface area are wheat at about 5 million ha (43%), barley (35%), and other tree crops such as citrus and olive, fodder crops, legumes, and vegetables at 1.6 million ha, 0.4 million ha, 0.3 million ha and 0.2 million ha, respectively (Figure 3; Brouziyne, 2021).



Source: FAOSTAT (FAO, 2022)

Figure 2. Annual Production of Major Food Crops (mt), 2012-2020



Source: FAOSTAT (FAO, 2022)

Figure 3. Annual Harvested Area of Major Food Crops (ha), 2012-2020

Wheat is a key food in Morocco, with a high consumption level (172 kg per capita), considered one of the largest in the world. However, this quantity is still not totally met by domestic production. Wheat is the most eaten cereal, accounting for 30% of all agricultural import expenditures (Balaghi, 2017). Wheat is used to make a variety of foods, including bread, cookies, couscous, and pasta. Due to the high demand for bread, bread wheat is the cereal that contributes the most to the country's food security, with two-thirds of its production destined for human consumption; durum wheat contributes one-fourth of the cereal ration (Balaghi et al., 2012).

2.2 Generalities of the Wheat Crop in Morocco

2.2.1 Ecology of Wheat

Wheat (*Triticum spp)* is considered one of the "big three" cereal crops in the world (Shewry, 2009). Wheat is a C3 plant that grows well in cool climates and is suited to a wide range of climates, from moist temperate to dry and heavy rainfall conditions and from warm-humid to dry-freezing conditions (Acevedo et al., 2002). The ideal growing temperature for wheat is between 18°C and 24°C, whereas the minimum and maximum growth temperatures range from 3°C to 4°C and from 30°C to 32°C, respectively, with a 120- to 180-day growing period; it requires 4-6 hours of sunshine per day (Getie, 2015). Wheat is classified into two categories based on the season of sowing: spring wheat and winter wheat. In contrast to spring wheat, which has a brief vernalization phase, winter wheat requires a long duration of cold temperatures for flowering. Spring wheat is typically sown between March and May and should be harvested between July and September; this crop has a four-month growth cycle, which is significantly shorter than that of winter wheat. Wheat crops can be cultivated on sandy loam soils with pH levels ranging from 5.5 to 6.5 (Wang et al., 2018).

Morocco presents suboptimal agrometeorological conditions for growing wheat. Wheat is grown in six major agroecological zones in the country, ranging from a typical Mediterranean climate on the northern coast to continental conditions in the central regions and mountainside areas in the West High Atlas and semi-arid environments in the southern part of the wheat-growing area north of the Sahara (Khanfari et al., 2018). Soft wheat production is concentrated in the Atlantic plains of Morocco, from semi-arid to sub-humid provinces, whereas durum wheat is mostly cultivated in the semi-arid southwestern plains (Bregaglio et al., 2015).

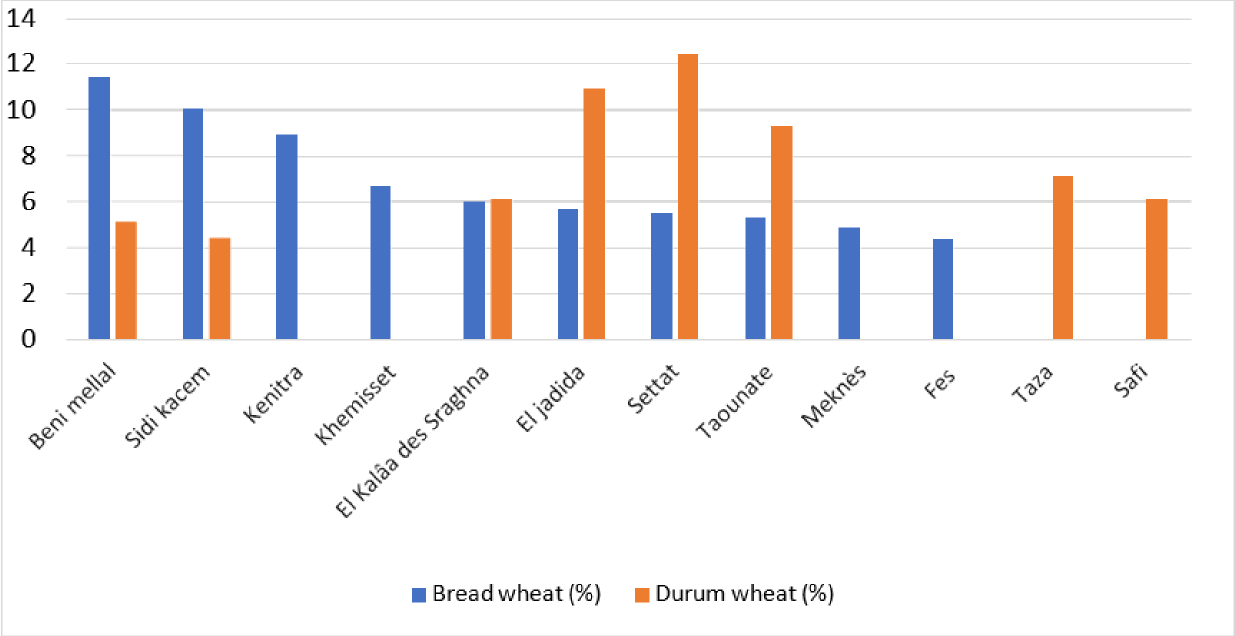
2.2.2 Cultivation Period of the Wheat Crop

Winter wheat grain is sown in autumn, around November, and finishes its vegetative growth cycle in the winter and its reproductive cycle in spring. Even though the rainy season begins in October, sowing can only take place in November for practical reasons, such as ease of tilling the soil and correct timing of the wheat cycle within the rainy season. Sowing grains too early in October, even under optimal moisture conditions, exposes the wheat to high temperatures, causing development to accelerate, resulting in a reduction in the number of tillers and a shorter cycle. These two factors contribute to low yields. In addition, early season rainfall in September and October supports the early development of weeds, which may later be eradicated by plowing before seeding in November. The physiological maturity of this crop is marked by the cessation of grain growth and the start of drying. The ultimate time of maturity for harvesting at 12% moisture content varies by area, ranging from May in the southern regions, such as Haouz, Rehamna, and Abda, to August in the mountainous regions. The various cropping periods have been defined by Food and Agriculture Organization of the United Nations (FAO; Balaghi et al., 2012).

- Tillage period: 25 days, between September 23 and October 18
- Sowing period: 18 days, between October 18 and November 5
- Wet period: 137 days, between November 5 and March 22
- Growing season: 183 days, between October 18 and April 19

2.2.3 Wheat Production

In urban regions, bread wheat accounts for approximately 70% of consumption, whereas in rural areas, it accounts for 66% (FAO, 2022; Juárez, 2021), with an average production of 5 million mt of bread wheat and 248,000 mt of durum wheat for 2021 (Fardaoussi, 2021). The production of bread wheat is mainly concentrated in the provinces of Beni Mellal, Sidi Kacem, Kenitra, Khemisset, Kalaat Sraghna, El Jadida, Settat, Taounate, Meknes, and Fes. These 10 provinces contribute more than two-thirds (69%) of the of the national bread wheat production, while the other provinces each contribute less than 4% of production. Durum wheat production is concentrated in the provinces of Settat, El Jadida, Taounate, Taza, Kalaat Sraghna, Safi, Beni Mellal, and Sidi Kacem These eight provinces provide 61% of the national production of durum wheat, while other provinces each contribute less than 4% of production (Figure 4; Balaghi et al., 2012). The country's cereal production is highly variable, with local dams providing irrigation.



Source: Balaghi et al. (2012)

Figure 4. Wheat Production by Province (%)

2.2.4 Constraints to Wheat Production

Wheat is the now most widely planted crop, representing about 27% of the total arable land growing area within the Mediterranean region. It provides humans with 18% of their daily intake of calories and 20% of their protein consumption (Royo et al., 2017). However, its production is limited by many factors that are subdivided into biotic and abiotic constraints. The biotic constraints include diseases such as stem rust caused by *Puccinia graminis f. sp. tritici*, leaf or brown rust caused by *P. triticina*, and stripe or yellow rust caused by *P. striiformis f. sp. tritici (Pst*); these are the most common wheat diseases that result in significant output losses (Khanfri et al., 2018).

The most significant abiotic constraint for wheat cropping in Morocco is drought (Bregaglio et al., 2015). A temperature increase of 2.3-4.3°C and a decrease of 41% in precipitation by the end of the current century are negatively affecting groundwater storage, the availability of soil moisture, agricultural and hydro-energy production, and environmental quality (Meliho et al., 2020). Droughts impact rainfed crops the hardest, with wheat being the most affected, and an increase of 1°C in temperature has been proven to result in a 6% decline in wheat production (Bouras et al., 2020).

The impact of climatic conditions and the limited water supply are major sensitivities putting the Moroccan agriculture sector at great danger, especially considering the continuously changing climate within the country. Other constraints include the high quantity of imports of this staple food crop, accounting for 5.5 million mt of wheat during 2020/21, in order to meet domestic demand (ONICL, 2021).

2.3 LINTUL-1 Model Approach

LINTUL-1 is a dynamic and deterministic physiological model that calculates potential crop growth. This model simulates crop yield based on two main processes: crop development and radiation-driven growth. The wheat plants begin manufacturing assimilates on the day of emergence; the amount produced is influenced by the daily amount of photosynthetically active radiation (PAR), the leaf area index (LAI), and the light utilization efficiency (LUE). Since the daily temperature is the limiting factor in the early stages of development, this affects LAI growth the most. Later, the expansion of leaf biomass determines the increase in LAI. Leaves wilt throughout the growth season: first due to shade over a specific leaf area and then due to the leaves aging as the growing season comes to a close. The overall amount of assimilates generated and the portion of these assimilates that is assigned to the organ under discussion govern the growth of leaves and the other plant organs (stems, roots, and grains). Depending on the plant's stage of growth, a certain portion of the allocation goes to the organs. All assimilates are distributed to the grains after anthesis. Plant growth halts if development does as well (het Lam, 2014).

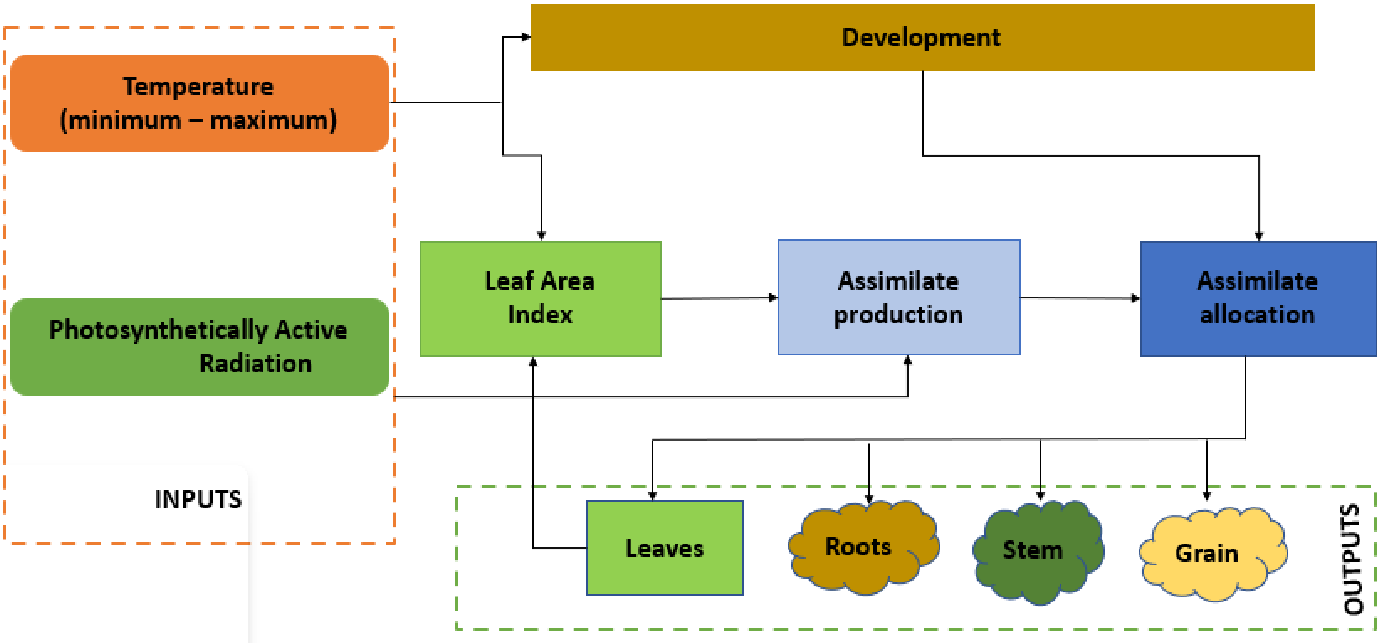


Figure 5. Overview of the Main Inputs, Processes, and Outputs of the Basic LINTUL-1 Program

CHAPTER 3: METHODOLOGY

The methodology of data extraction and exploitation is split into three sections: data collection, data treatment, and crop modeling. Figure 6 summarizes the entire process.

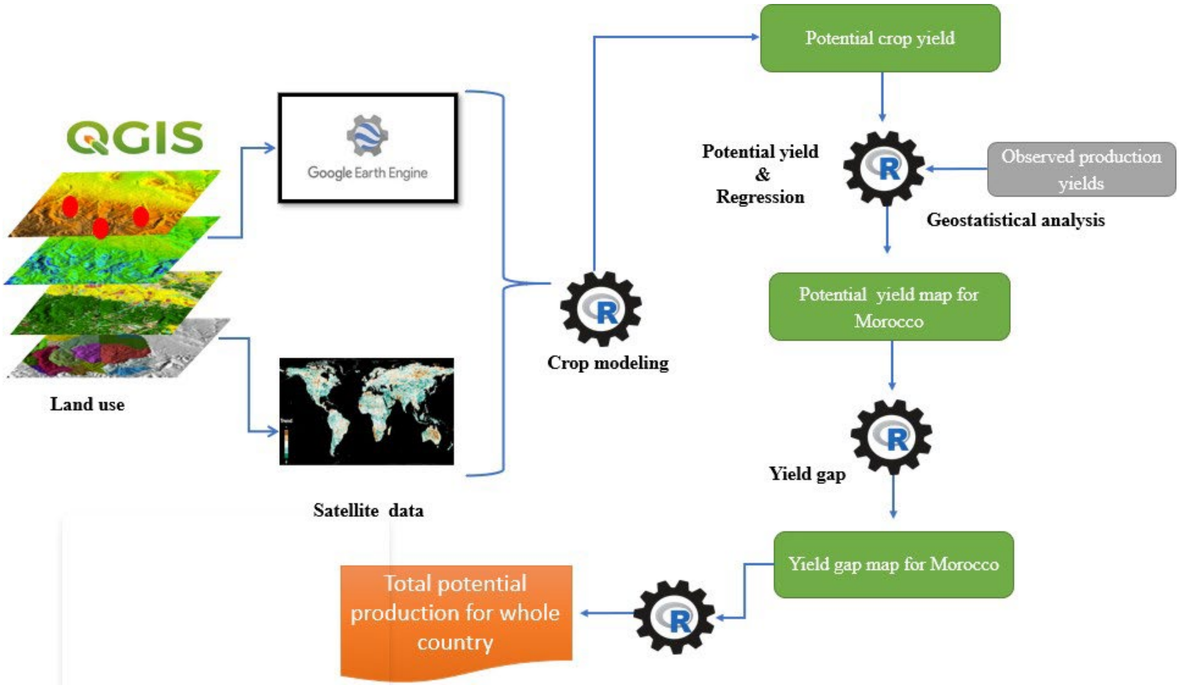


Figure 6. Conceptual Framework of the Methodology Used in This Study to Simulate Yield Potential and Gap of Wheat Yield in Morocco

3.1 Study Area

Morocco is a North African country with a semi-arid climate affected by the Atlantic Ocean, Mediterranean Sea, and Saharan Desert (Knippertz et al., 2003). Its rainy season runs from November to April, coinciding with the cereal growing season, and there is variability across space and time. Morocco's northern region receives larger levels of annual precipitation, which can reach 900 millimeters (mm), while the country's central region has a low level of precipitation of less than 350 mm. Similarly, the temperature also has a great geographical fluctuation. When compared to other parts of the nation, locations with high elevation, such as the Atlas Mountains, have cold weather (Bouras et al., 2020). Wheat is the main rainfed crop, occupying up to 83% of the rainfed agricultural area in Morocco (Devkota and Yigezu, 2020). Early sowing takes place in November if sufficient precipitation occurs at this time, while sowing can be extended to January in the case of delays in precipitation. Late sowing typically results in lower yields than early sowing due to both a reduction in cultivated area and the fact that the later part of the season coincides with times of high temperatures, which can reduce yields. Harvest usually takes place around the end of May.

3.2 Data Collection and Pre-Processing

Because of the absence of data on the geographic coordinates of the experiments, fertilizer input data from 2011 to 2019, and daily weather data from 2011 to 2019, some regional data were mixed with provincial data, soil property data on the in-situ station, and the coordinate system of the experiments from the OCP program Al Moutmir. A logical scientific process was used to extract the statistical data variables from various sources, including Google Earth Engine ERA5 at a resolution of 11,132 meters and SM2RAIN-ASCAT (2007-2021) global daily satellite data at a resolution of 10 kilometers (Brocca et al., 2019).

Geographic information system (GIS) techniques were used to extract the environmental data, including daily minimum and maximum temperatures (Tmin and Tmax), daily precipitation, daily vapor pressure, daily wind speed, and daily solar radiation, to use as inputs for crop modeling. Part of the workflow involved following a scientific approach to randomly sample agricultural locations based on land cover maps that define where bread wheat is grown in Morocco in order to get the best representation of aggregated bread wheat production yield. Figure 7 shows the study area, 10 randomly sampled points in each province represented by red dots, and agricultural land locations represented by green dots in Morocco.

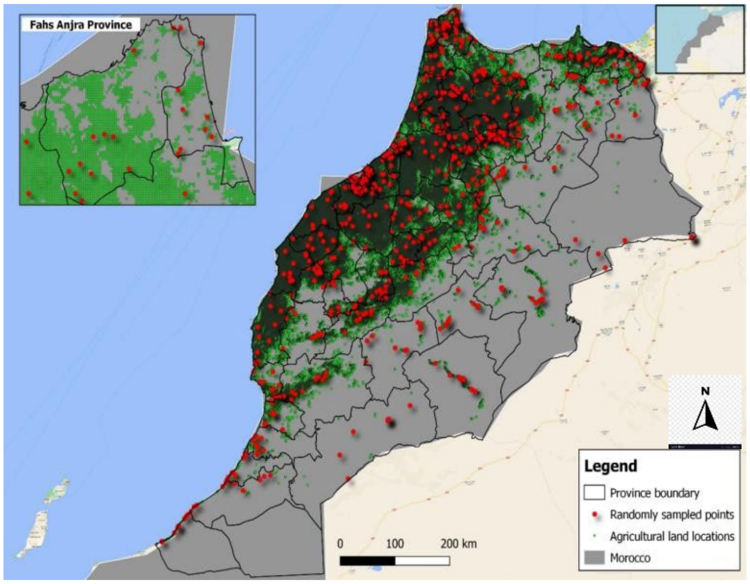


Figure 7. Wheat Production Areas in Morocco Used in This Study

3.2.1 Precipitation

Precipitation is of major importance in completing the soil moisture balance. Data on precipitation was mainly extracted from SM2RAIN-ASCAT (2007-2021) global daily satellite data, which has a resolution of 10 kilometers (Brocca et al., 2019). Figure 8 shows the distribution of rainfall over the growing season for 2011-2020.

3.2.2 Temperature

When it comes to simulating plant growth, air temperature is the primary variable. The crop model requires daily minimum and maximum air temperatures. Across Moroccan provinces, air temperature was extracted from Google Earth Engine ERA5 datasets, prepared by the European Centre for Medium-Range Weather Forecasts. Figure 8 shows the distribution of the temperature data recorded from 2011 to 2020.

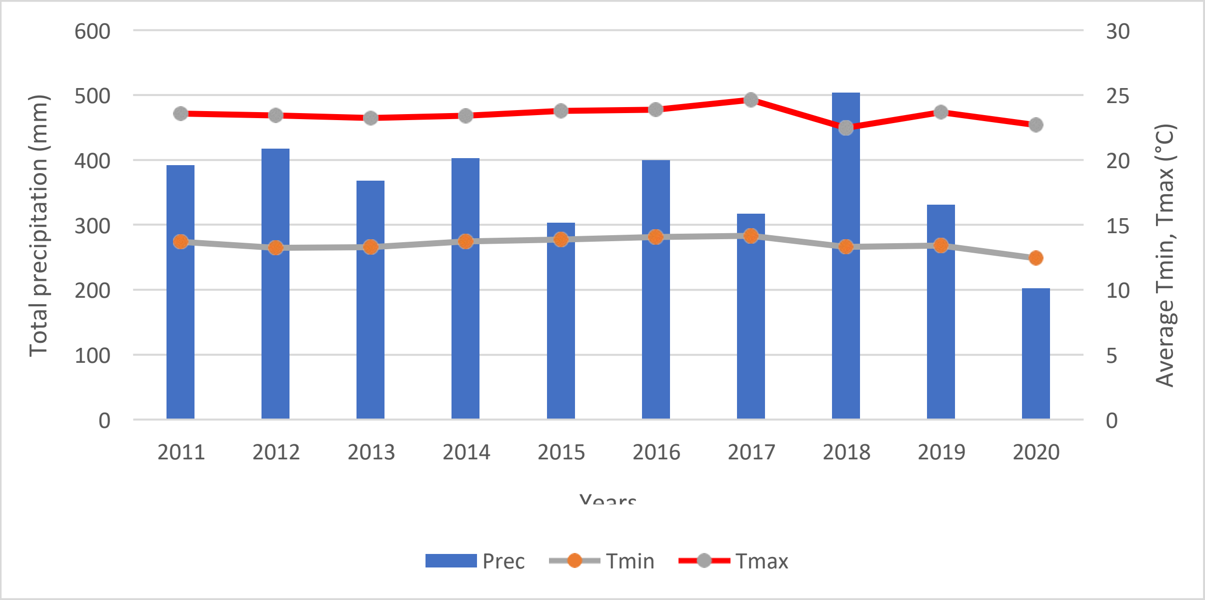


Figure 8. Distribution of Precipitation and Temperature (Tmin, Tmax) Recorded during the Growing Season for 2011-2020

3.2.3 Radiation Measurement

Radiation is the primary driver of plant development, since the plant uses the energy to promote the photosynthetic process. The plant may use a portion of the radiation that penetrates the atmosphere and reaches the surface, known as downwelling shortwave surface radiation. PAR is described as radiation with a wavelength range of 400-700 nanometers (Spitters and Schapendonk, 1990). This is where variable extraction from Google Earth Engine ERA5 datasets began.

3.2.4 Wind Speed

Wind speed is another important factor that affects plant development; a high or low wind speed can have a detrimental impact on the leaf area, which can harm the plant's photosynthesis. After extracting the starting variables for eastward and northward wind speed from Google Earth Engine ERA5 datasets, the average wind speed was calculated using the following formula:

$$Ws.avg = \sqrt{Wsu^2 + Wsv^2}$$

Where Ws.avg (m s^{-1}) is the average wind speed, Wsu is the west to east flow (eastward wind) rate (m s^{-1}), and Wsv is the south to north flow (northward wind) rate (m s^{-1}).

3.2.5 Vapor Pressure

Vapor pressure was calculated using the following formula, starting with the calculation of relative humidity and the saturated vapor pressure and then multiplying these to get the vapor pressure in kilopascals (kPa):

$$Relative\ humidity\ = 100\ \times \frac{\frac{17.625\ \times TD}{e243.04 + TD}}{\frac{17.625\ \times T}{e243.04 + T}}$$

$$Saturated\ vapor\ pressure\ = 6.11\ \times e \left(\frac{17.2\ \times\ T}{243.04 + T} \right)$$

Where TD is the dew temperature (°C), T is the daily temperature (°C), and the constants 17.625 and 243.04 are derived from the Magnus formula (Parish and Putnam, 1977).

$$Vapor\ pressure = Relative\ humidity * Saturated\ vapor\ pressure$$

3.3 Model Runs

3.3.1 LINTUL-1

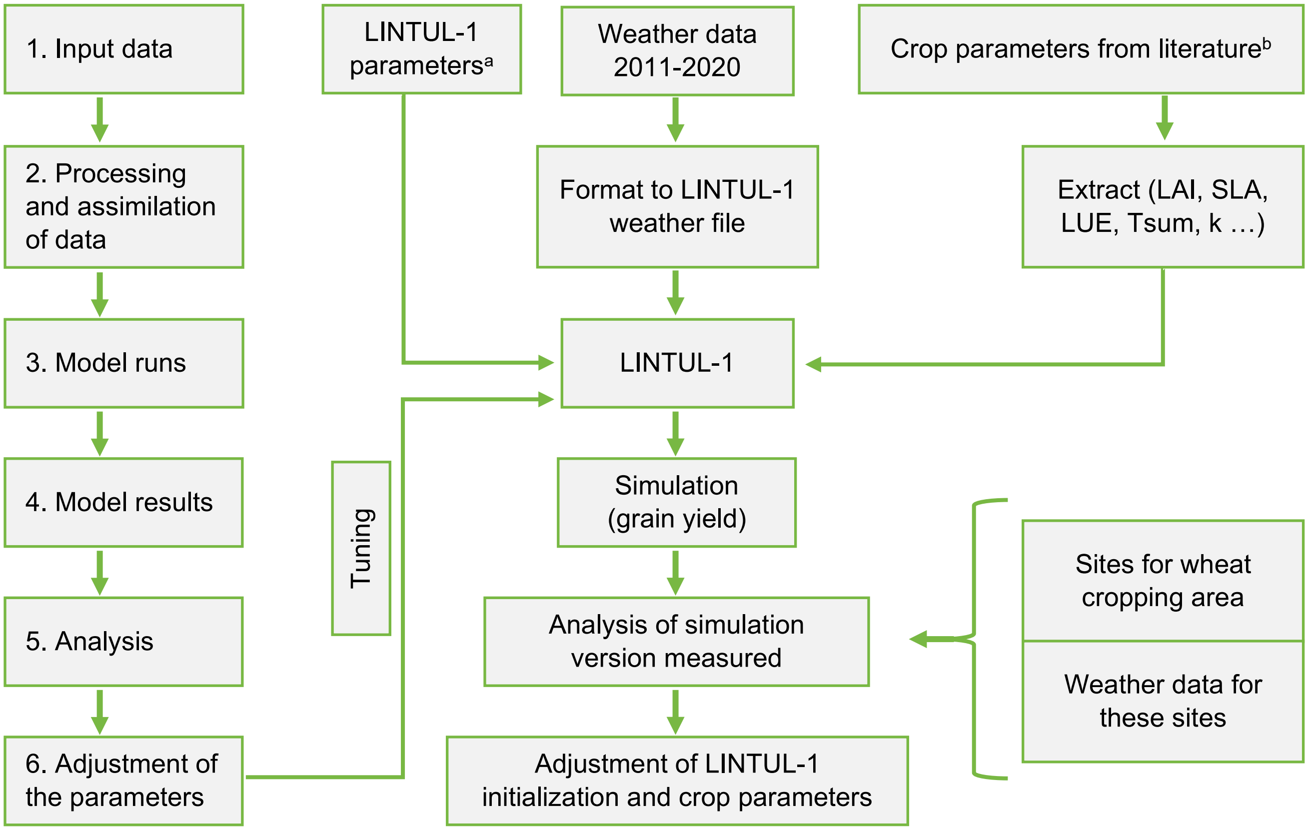
The LINTUL model was first developed by Spitters (1990) and Spitters and Schapendonk (1990) to simulate the dry matter accumulation based on RUE. This model uses the energy framework that links dry matter production to the quantity and efficiency of solar radiation received by the plant, suggesting that dry matter accumulation is proportional to the amount of PAR intercepted by the plant (Khabba et al., 2020).

3.3.2 Model Calibration

The LINTUL-1 model has been applied in a variety of conditions in different crops, including winter wheat (het Lam, 2014). Therefore, calibration was needed for several crop and weather parameters. Many of these parameters can be found in the literature, and some originate from LINTUL-1 for spring wheat from the Netherlands. Crop characteristics and starting parameters are the main components of this calibration. A complete list of all parameters, together with their calibrated values, can be found in Table 1. The results were examined using correlation analysis on the calibrated parameters, with measured values as a reference. A complete overview of the calibration and validation phases is shown in Figure 9.

Table 1. *Overview of Crop Parameters for Bread Wheat, including the Calibrated Value*

Variable	**Abbreviation**	**Value**	**Unit**	**Source**
Initial leaf area index	LAII	0.11	m^2 m^{-2}	
Maximum leaf area index	LAI max	7		Confalonieri et al. (2015)
Specific leaf area	SLA	0.026	$m^2.g^{-1}$	
Extinction coefficient for PAR	K	0.6	-	Toumi (2016)
Relative growth rate of LAI during exponential growth	RGRL	0.012	1/(°C d)	Richter et al. (2010)
Temperature sum threshold for leaf growth	TSUMJUV	620	°C	Toumi (2016)
Base temperature	Tb	5	°C	
Temperature sum at anthesis	TSUMAN	1,186	°C	
Day of crop emergence	DOYEM	310	-	Balaghi et al. (2012)



(a) Spitters, 1990; Spitters and Schapendonk, 1990; (b) Richter et al., 2010; Balaghi et al., 2012; Confalonieri et al., 2015; Toumi, 2016

Figure 9. *Overview of the Entire Process of Calibration, Validation, and Assimilation of LINTUL-1 for Morocco Parameters*

A. Starting Parameters

The crop model's initial settings are crucial. The day of emergence (DOYEM) is particularly important, since it dictates when the temperature sum (Tsum) and biomass accumulation begin. The day of emergence cited in the main articles was not accurate; therefore, it was set at 310 days, at which time the model gave us the potential yield (Balaghi et al., 2012).

B. Crop Parameters

A detailed summary of all crop parameters, their calibrated values, and the sources of this information is available in Table 1. The extinction coefficient for PAR (K) was set at 0.6 (Toumi, 2016) and the LUE was set at 3.3 g MJ^{-1} to account for the large amount of biomass generated. The number of days at an effective temperature after emergence is essential in LINTUL-1, since it is utilized as a development measure of the values of the Tsum for commencement, aging, and maturity, which were set at 620, 1,186, and 2,080, respectively.

3.3.3 Model Calibration, Validation, and Testing

After calibrating the LINTUL-1 model for 2011-2019 for wheat, its performance was evaluated based on field experiments from published articles from different sites in different growing seasons without modifying any of the calibrated parameters. Then, the performance was tested though correlation analysis of grain yields and dry matter produced.

CHAPTER 4: RESULTS

This section addresses the major research question of whether LINTUL-1 can simulate the potential bread wheat yield for the entire Moroccan wheat cropped area during 2011-2019 and presents the calculations of the yield gaps across Moroccan provinces.

4.1 LINTUL-1 Simulation Model on Experimental Stations

4.1.1 *Grain Yield Simulation*

Figure 10 represents the relationship between the yield gap-dependent variables with the observed grain yield independent variable from several sites of field experiments. There is a strong negative correlation between the yield gap and the observed yields. The correlation for control treatments (fertilizer application 0 kg ha^{-1}; R² = 92%) is in line with low rates (≤120 kg ha^{-1}; R² = 86%) and high rates (>120 kg ha^{-1}; R² = 87%) of fertilizer application. The yield gap is very high when the observed grain yield is low and decreases as the observed grain yield rises; this gap decreases with an increasing fertilizer application rate. As the fertilizer application rate increases, the observed grain yield increases as well and starts to approach the potential yields (Figure 11). When bread wheat is grown in the experimental trials under favorable conditions with fertilizer and irrigation, the production starts to reach the potential yield level (Appendix 1).

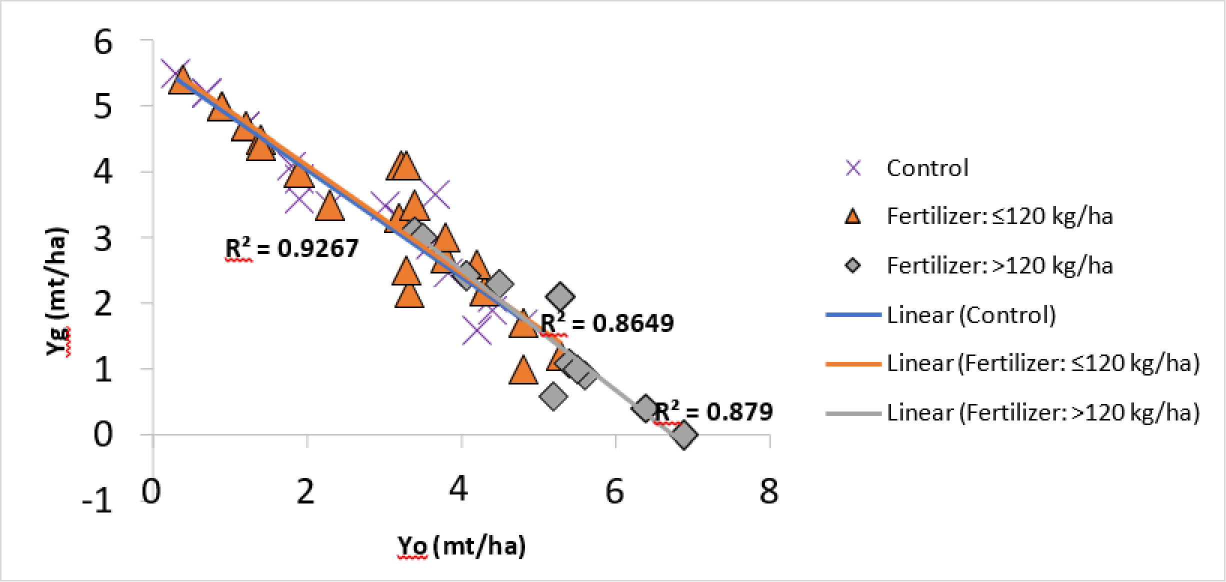


Figure 10. Yield Gap versus Observed Yield (mt ha^{-1})

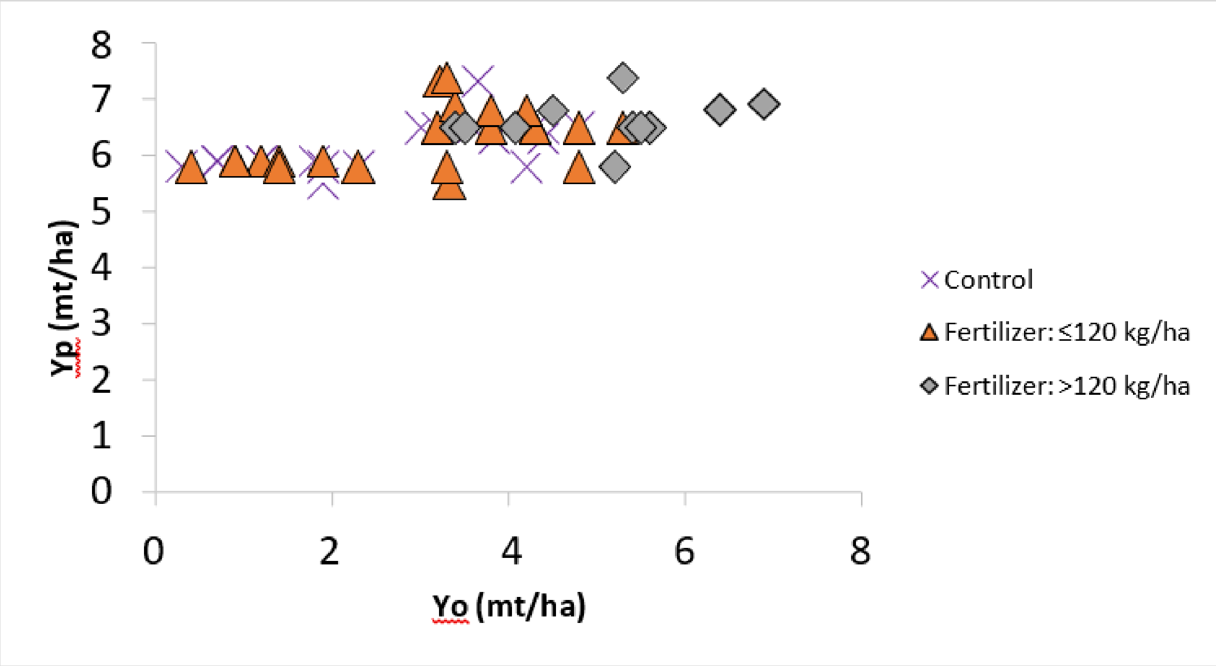


Figure 11. Simulated Grain Yield versus Observed Grain Yield (mt ha^{-1})

4.1.2 Dry Matter Simulation

Only three experiment sites had data available on biomass (Appendix 1). On site 1, the application of 250 kg ha^{-1} of fertilizer with irrigation appeared to increase dry matter up to the potential level; however, even at this high fertilizer application level, the potential was not reached without irrigation on site 2. The application rate was lower in site 3, but the biomass gap appeared modest (Figure 12).

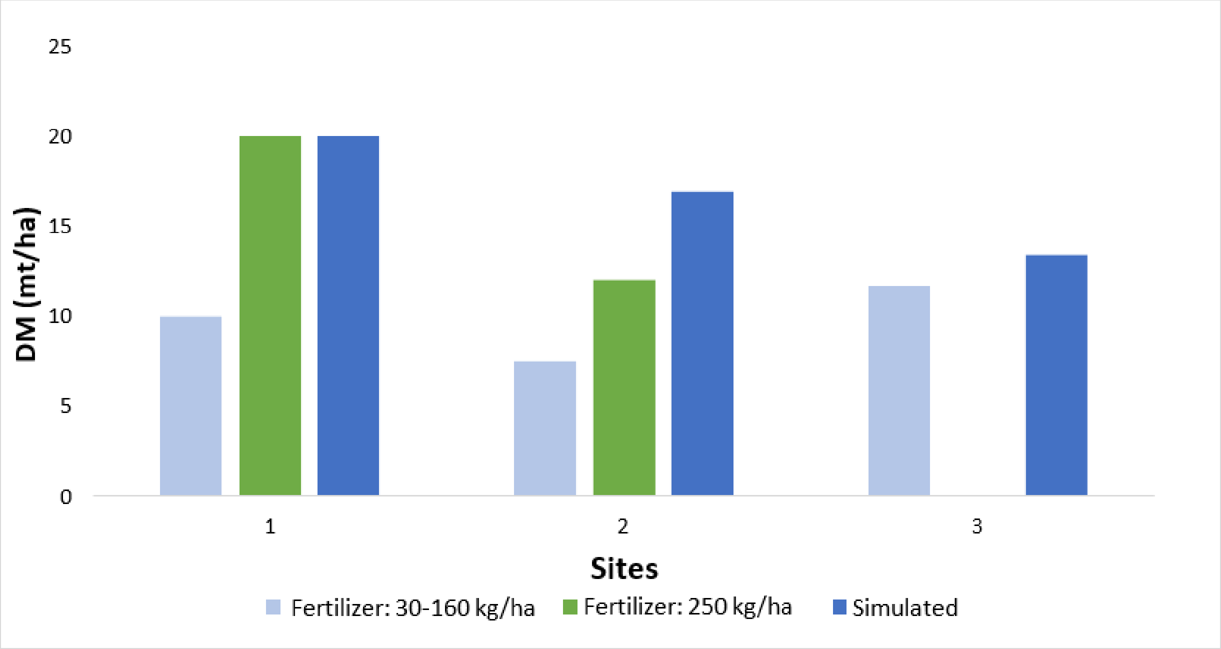


Figure 12. Simulated versus Observed Bread Wheat Biomass (mt ha^{-1})

4.2 National Simulation

The average grain yields predicted by LINTUL-1 for all the bread wheat cropped areas were higher than the average grain yields observed. There was no correlation between the observed wheat yield and the yields predicted by LINTUL-1 across the entire Moroccan cropped area from 2011 to 2019. In general, LINTUL-1 estimated significantly higher yields compared to the observed provincial yields. However, in the Atlas Mountains and the hot region of the country, the simulated yield was lower because of the temperature effect. The average provincial yield was an average of around 1.6 mt ha^{-1}, while the average simulated yield was 5.5 mt ha^{-1}, resulting in an average yield gap of about 3.9 mt ha^{-1} (Figure 14). The decline in the yield gap reveals that some provinces have very low yield and could potentially attain higher yields, while the production in some provinces is near the potential yield level (Figure 13). The differences between the observed and the predicted simulated grain yield can be attributed to various constraints (Appendix 2).

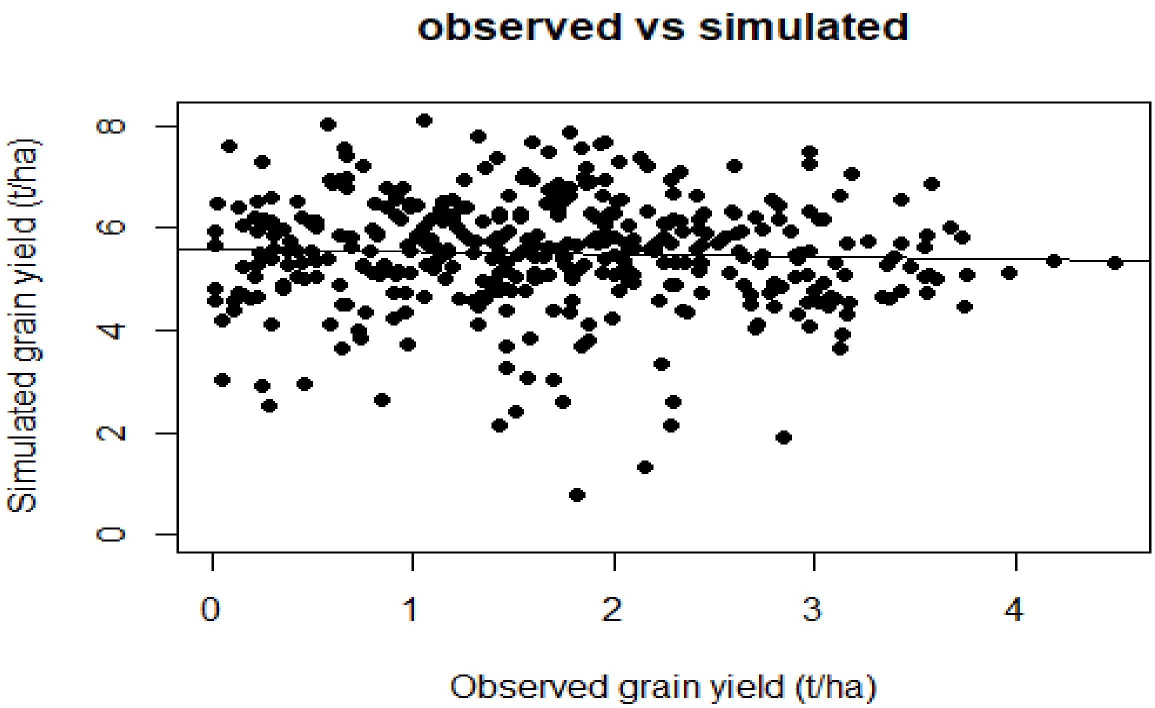


Figure 13. Comparison between the Simulated and Observed Grain Yield (mt ha^{-1}) in the Entire Moroccan Cropped Area during 2011-2019

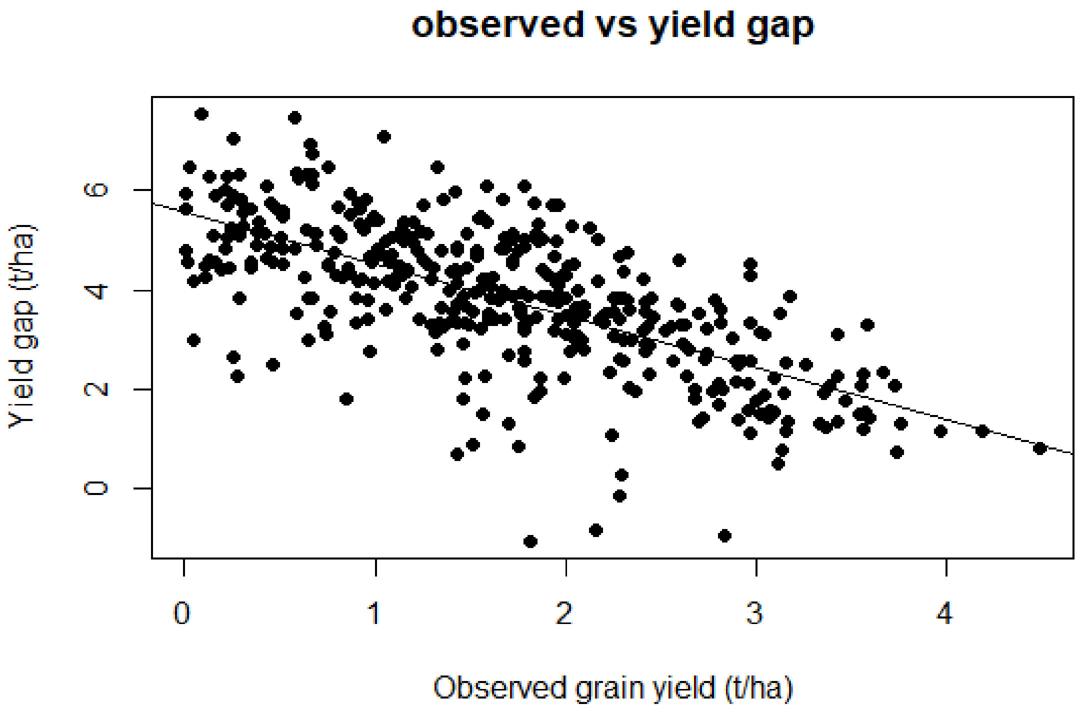


Figure 14. Yield Gap between LINTUL-1 Simulated Yield and Overall Observed Yield of Cultivated Areas in Morocco during 2011-2019

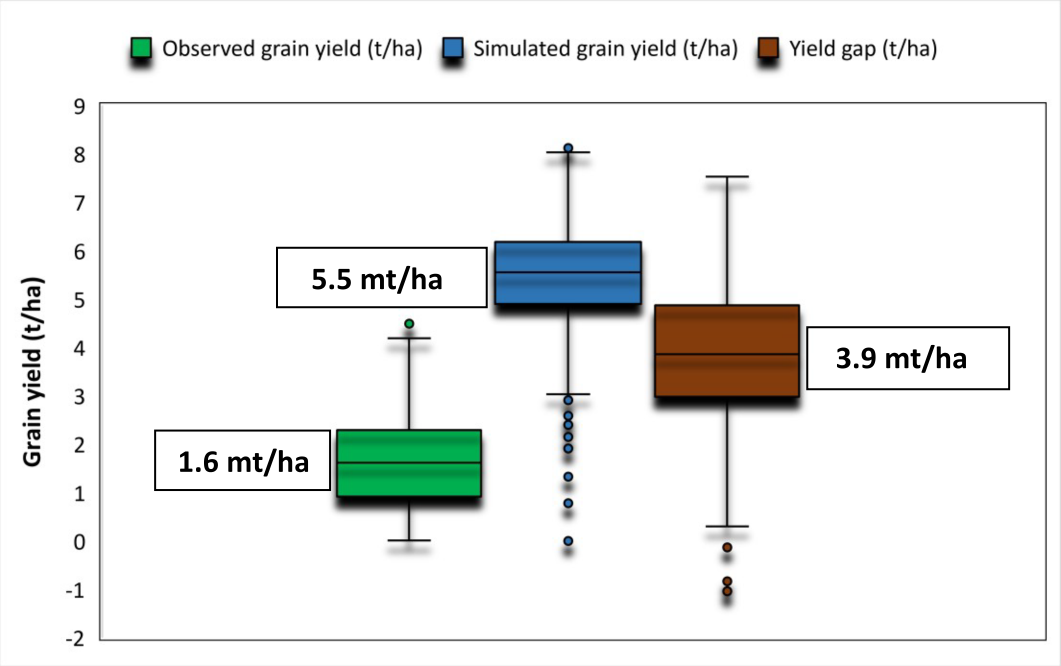


Figure 15. Average Simulated and Observed Grain Yield (mt ha^{-1}) and the Yield Gap in the Entire Moroccan Wheat Cropped Areas during 2011-2019

4.3 Regional Simulation

Figure 16 reveals the importance of the developmental stage (DVS) in the partitioning of assimilates or dry matter in Chichaoua Province toward the leaves. This started at emergence (Julian day 310) and resulted in a rapid increase in the LAI until the maximum level of 7 m^2 m^{-2} was reached around day 75 of the next year, which allowed the interception of more light and deeper penetration needed for optimum growth and development. The LAI maintained this maximum value until day 95, when the growth of the leaves stopped, the allocation of assimilates declined, and leaf death started, resulting in a decrease of the LAI to 0.2 m^2 m^{-2} at harvest. The allocation of assimilates partitioned toward the storage organs began at day 95 of the following year, quickly reaching a maximum of 7.5 mt ha^{-1} at maturity on day 160. A low LAI value and yield level were attained in Kalaat Sraghna. The allocation of assimilates toward the leaves started at emergence, day 310 (DVS=0), increasing quickly from 0 m^2 m^{-2} until the maximum of 4 m^2 m^{-2} was reached around day 35 of the next year. This was stable until day 425, when the growth of the leaves completely stopped, the assimilates to the leaves decreased, and leaf death caused a rapid decline to 0.2 m^2 m^{-2} at maturity. Allocation of assimilate partitioned toward the storage organs began at day 35 of the next year and increased quickly, reaching the maximum of 4.8 mt ha^{-1} on day 115. This gap between the two provinces was due to the difference in growing temperature, as shown in Appendix 4.

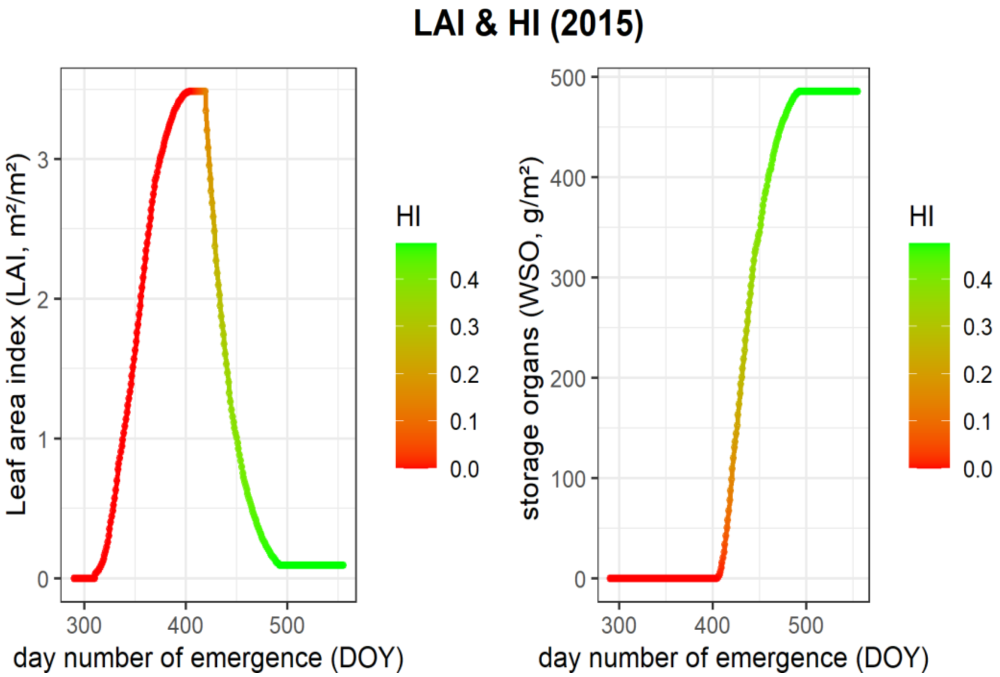


Figure 16. Simulated Leaf Area Index (LAI) and Storage Organs for Kalaat Sraghna, 2015

4.4 National and Provincial Bread Wheat Yield Prediction Maps

4.4.1 Timeseries Potential Yield Map during 2011-2019

Based on the 10 points randomly selected by province, a simulation of the potential yield was done based the aggregation of 2, 3, 4, and the maximum number points from each province by year from 2011 to 2019. Then, a timeseries potential yield map was done based on the maximum aggregated points that would be more representative of the province. The highest potential yield simulated was in the northern part of the country and surrounding Atlas Mountain, reaching up to 8 mt ha^{-1}. However, the lowest potential yield simulated appeared in Atlas Mountain (blue), where it ranged from 0 to 2 mt ha^{-1} (Figure 17).

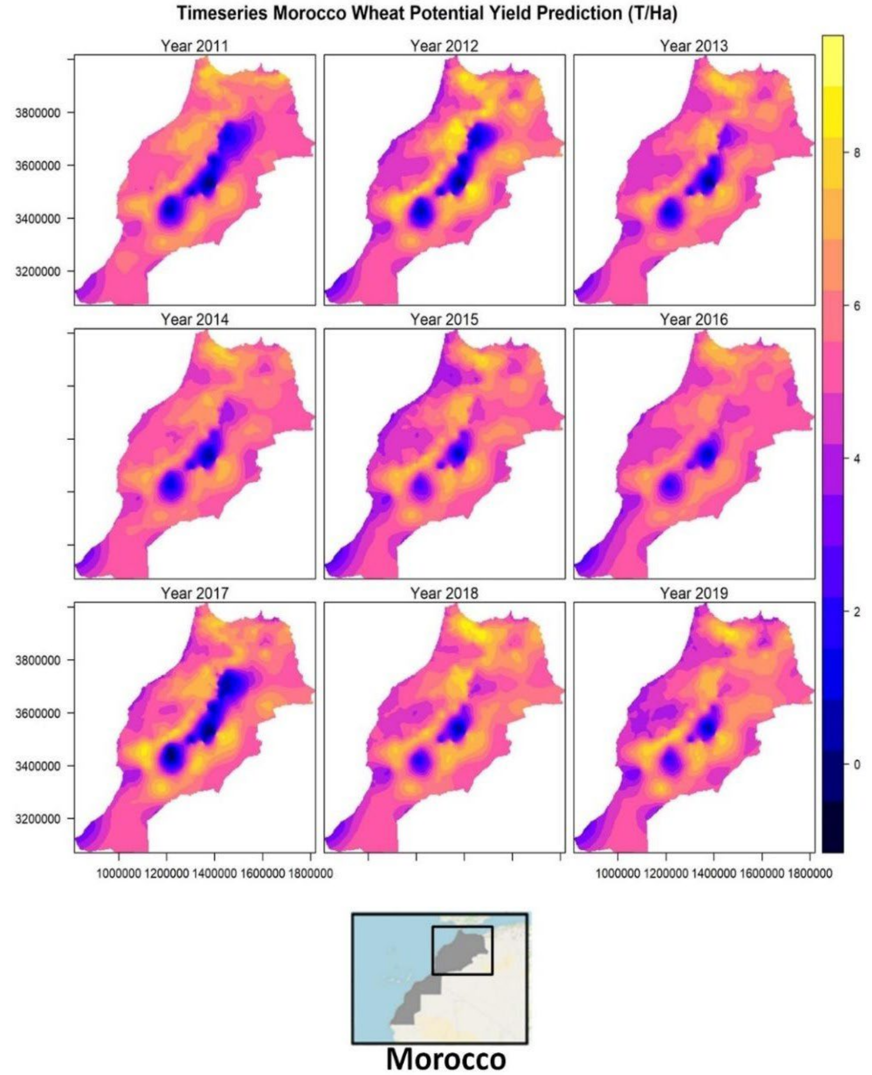


Figure 17. LINTUL-Predicted Wheat Potential (mt ha^{-1}) by Year for the Entire Cropped Area of Morocco

4.4.2 Standard Deviation of Morocco Bread Wheat Cropped Area during 2011-2019

Figure 18 shows the standard deviation of the simulated potential yield in Morocco from 2011 to 2019. The difference in the simulated potential yield was small from year to year and not significant, at up to 0.5 mt ha^{-1}, represented by blue in the map. However, in the mountain area, the simulated potential yield was unstable from 2011 to 2019 at a value of 1.5 mt ha^{-1}, represented by yellow in the map.

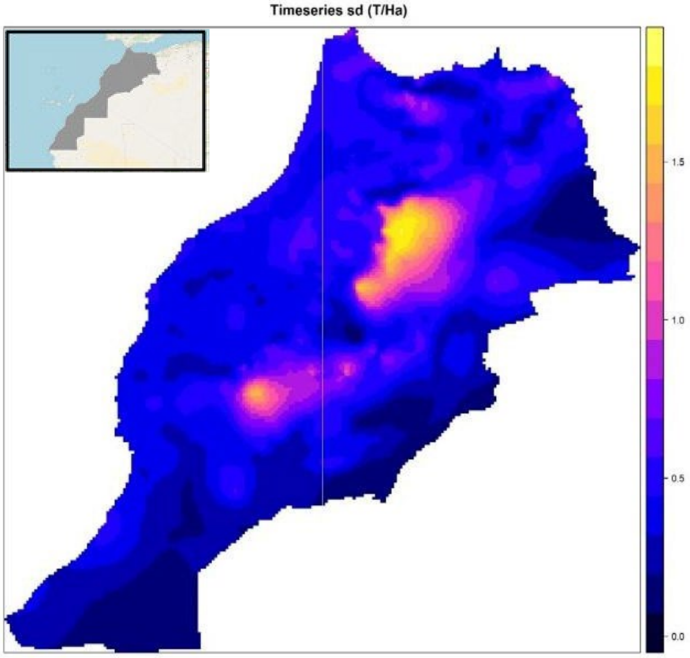


Figure 18. Standard Deviation of Morocco Wheat Cropped Area from 2011 to 2019

4.4.3 Yield Gap Map

The yield gap was calculated based on the aggregated 2, 3, 4, and maximum randomly selected points by each province (Figure 19). Since the difference was not large, the maximum was chosen to produce the yield gap map. With this reference to the small variations shown in the timeseries standard deviation map, a yield gap map was produced with the assumption that the variations over the years (2011-2019) was minimal (sd $\leq$ 0.5). Therefore, the yield gap map shown in Figure 20 could represent the reality for any of the individual years considered. In the northern part of the country, the gap was more significant, reaching up to 6 mt ha^{-1}, represented by Chefchaouen and Al Hoceima, the northeast by Oujda and Figuig, and the central and west by M'rirt. The yield gap differed from one place to the other in the remaining areas. In addition, the uncolored areas in the map on the right either did not have any information about wheat production or the model could not simulate the potential yield because of the inability of the Google Earth Engine to provide the weather data for these locations.

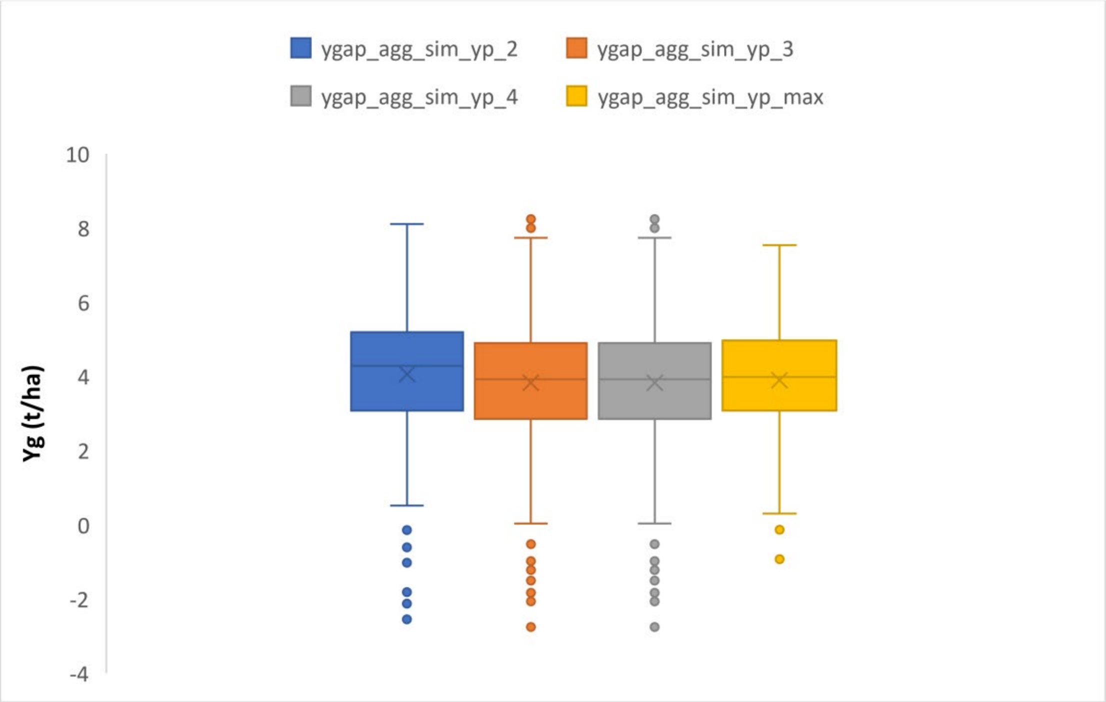


Figure 19. Comparison of the Yield Gap Based on the Randomly Aggregated Points from 2011 to 2019

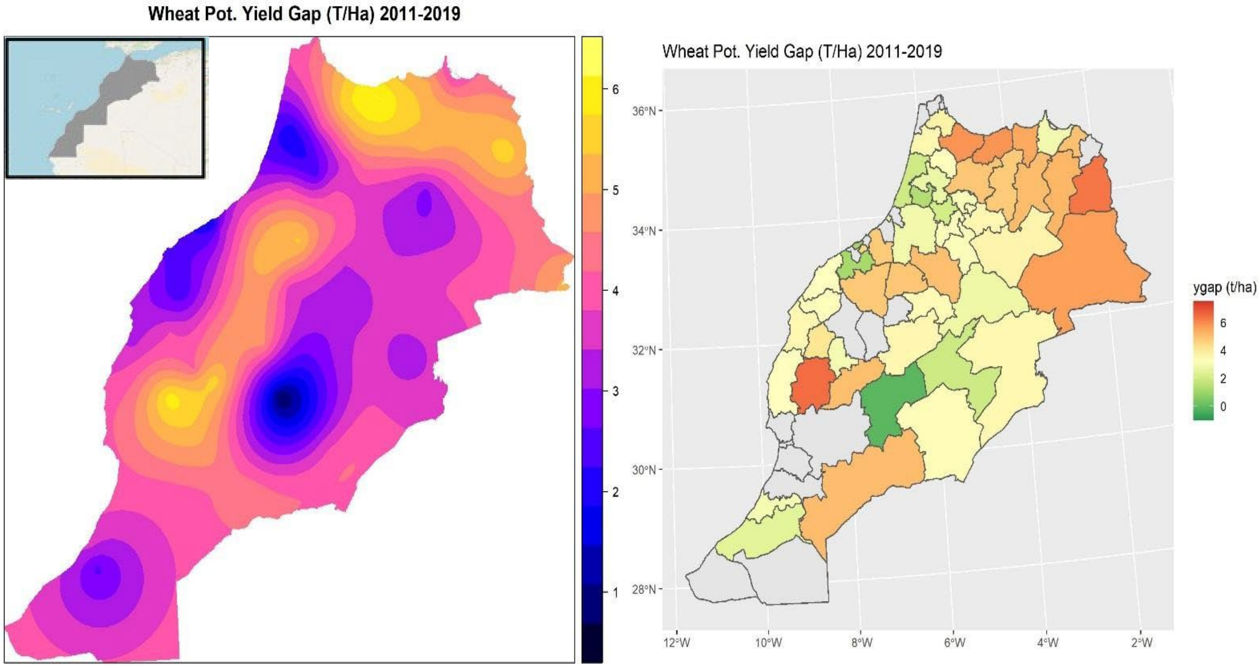


Figure 20. Potential Wheat Yield Gap (mt ha^{-1}) of (a) the Entire Cropped Area and (b) by Province during 2011-2019

4.4.4 Provincial Production Map

Figure 21 shows the observed and simulated spatial provincial distribution of bread wheat production by environmental conditions: the greener the map, the higher the production. However, the darker the red, the lower the production. In the provinces of Taounate, Khemisset, Settat, and Beni Mellal, bread wheat production from 2011 to 2019 was more significant at around 380,000 mt. However, these provinces have the capacity to produce up to 880,000 mt, 43% more than the reality. On the other hand, most of the provinces had low observed or simulated production due to the unfavorable bread wheat growing conditions. The country produced 39 million mt of bread wheat during 2011-2019 in the cropped areas. However, the simulated yield was 123 million mt, a gap of 84 million mt, as shown in Figure 22.

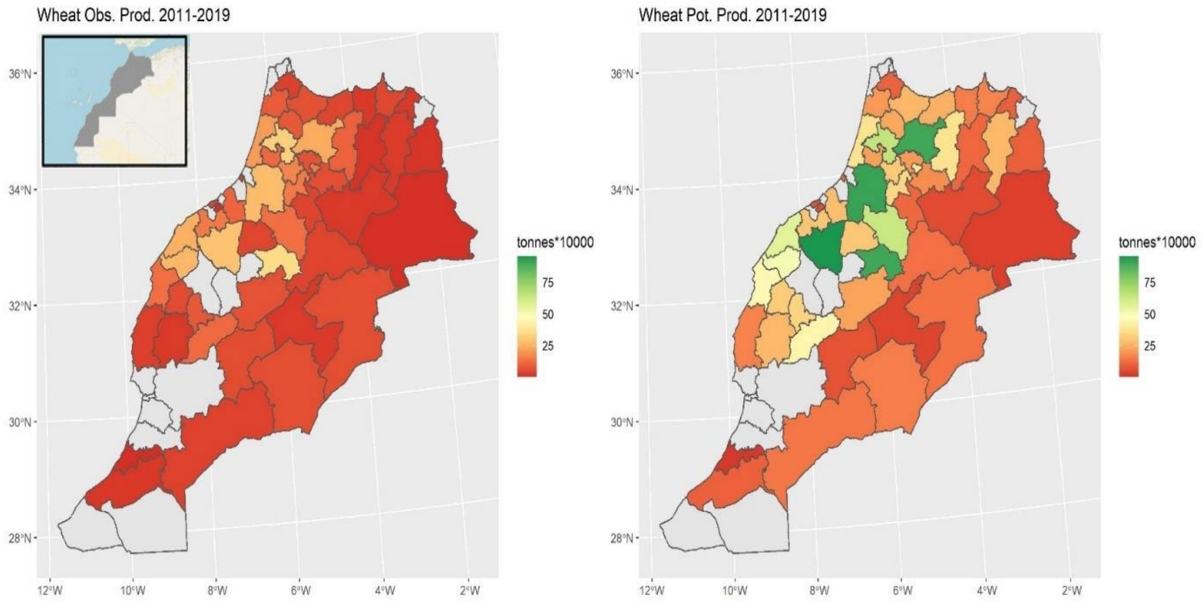


Figure 21. Observed and Simulated Wheat Production (mt) of the Entire Cropped Area by Province during 2011-2019

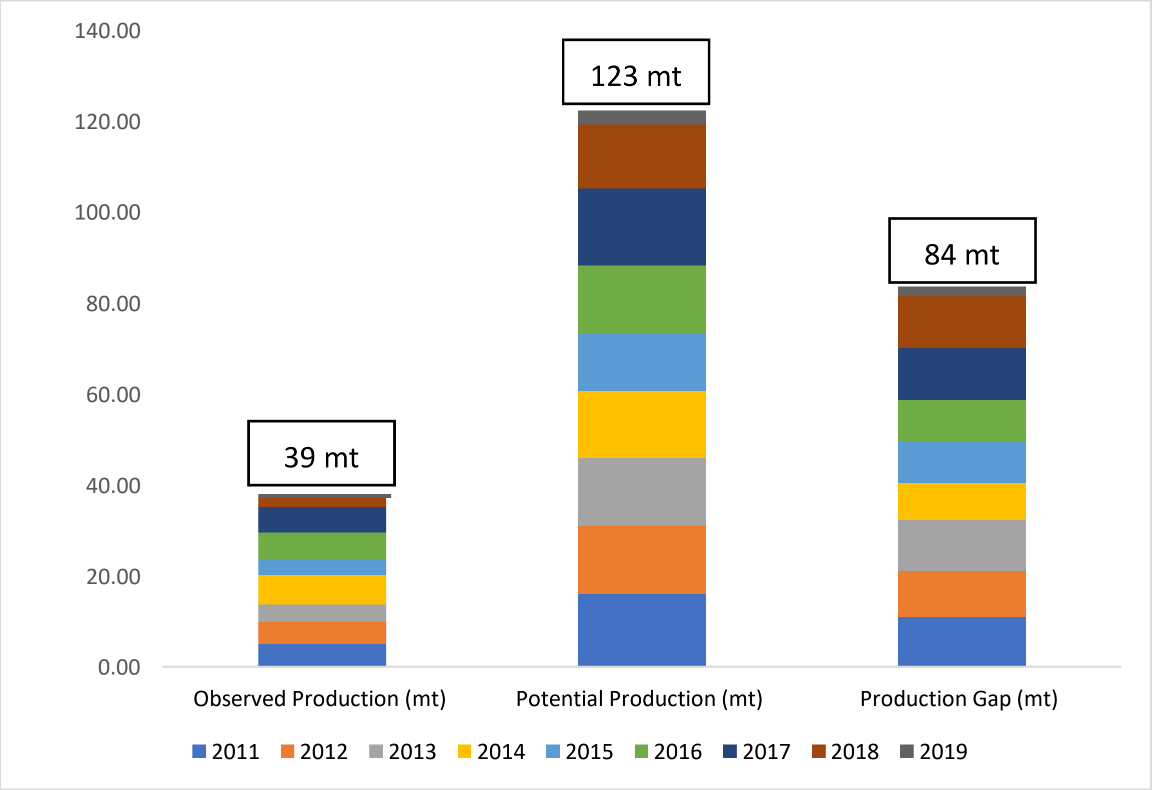


Figure 22. Observed and Simulated Wheat Production and the Production Gap (mt) for the Entire Country from 2011 to 2019

CHAPTER 5: DISCUSSION

To study the performance of the LINTUL-1 model, several field experiments were used to validate the model. With optimum growing conditions for wheat with the application of fertilizer and irrigation, production increased to the potential level simulated using LINTUL-1. Along the same lines and according to the findings from previous studies in Morocco, a significant loss of production can occur with an inadequate supply of water and fertilizer (Khan, 2000) and any water shortage during the growing period of wheat leads to a reduced yield potential (Kostić et al., 2021).

LINTUL-1 is designed to provide an estimation of potential yield. This potential yield is the level that the weather conditions allow, assuming that bread wheat growth and development are not compromised by factors other than climatic conditions, such as drought, fertilizer application, pest and disease management, crop management, or any other yield-limiting factors. This means that bread wheat should be grown under an ample supply of water and nutrients in a pest-, disease-, and weed-free environment under the prevailing weather conditions (Wiertsema, 2015). From the results of the LINTUL-1 simulation, the difference in the levels of the simulated potential of bread wheat across the Moroccan cropped areas is due to the difference in the climate conditions from one region to another. In the Atlas Mountain area, the simulated potential yield was very low (2 mt ha^{-1}) due to a highly elevated location, accompanied by cold weather (-15°C) during winter, which is the wheat growing season in the country. This is consistent with the previous study that revealed a negative effect of the freezing temperature and its duration on winter wheat plants and tillers and on grain yield, with mortality increasing greatly with decreasing temperature (Zheng et al., 2018). In addition, winter wheat survival is mainly influenced by minimum soil temperature during the overwintering period (Eckersten, 2016). On the other hand, in the hot regions the simulated potential yield was very low; due to the high temperature, the thermal sum is reached earlier, resulting in faster development of the crop. When a crop changes quickly from one developmental stage to the other, there is less time to intercept radiation and to produce dry matter. In general, the crop growth cycle will be shorter. According to Asseng (2011), increased temperature (>34°C) can have a drastic effect on grain yield, which is incorporated in LINTUL for winter wheat as a linear decrease in the RUE from 1 to 0 at temperatures between 30°C and 35°C (het Lam, 2014). In addition, the relative death rate of the leaves increases from 0.070 to 0.126 at temperatures between 30°C and 50°C. According to Getie (2015), the ideal growing temperature for wheat is between 18°C and 24°C, whereas the minimum and maximum growth temperatures range from 3°C to 4°C and from 30°C to 32°C, respectively, with a 120- to 180-day growing period, and it requires 4-6 hours of sunshine per day. Furthermore, a high or low temperature during the growing session could affect the LAI, since LAI is responsible for the grain yield accumulation and differs only with time and location. In the province of Chichaoua, LAI reached 7 m^2 m^{-2}. However, in Kalaat Sraghna, LAI was lower at 4 m^2 m^{-2}. This can be explained by a slight bias in the estimation of the degree days or by the wide range in the specific leaf area according to the development stage. However, these results are in accordance with other studies that used the LINTUL-1 model for LAI simulation for different crops, such as wheat (Maas, 1993) and cassava (Adiele et al., 2021). In addition, the LAI could be lower in the dry season and increase when rains returned (Maas, 1993).

LINTUL-1 revealed an average potential yield in our study of 5.5 mt ha^{-1} while the observed yield was 1.6 mt ha^{-1}, resulting in a gap of 3.9 mt ha^{-1}. We can say that the management practices in the

Moroccan fields were not great, leading to the huge gap between the observed and the simulated yields. These farm management practices should be managed according to the climatic conditions (precipitation, temperature). In order to further analyze the gap between the observed and the simulated potential yields calculated by LINTUL-1, previous studies were conducted in controlled conditions. According to Alaoui (2005), the choice of the variety of bread wheat is critical. Some varieties are adapted to only some climates and are only resistant to some major diseases. For example, the Achtar variety has good vigor, good grain quality, and acceptable resistance to major diseases, but it is not adapted to mountain areas, as are the Amal and Tigre varieties. In addition, pre-tillage operations could also affect the yield. A large gap between the potential and actual yields were found by the WOFOST model with tillage practices (Silva et al., 2019). Also, the sowing date in Morocco is not fixed. Early sowing takes place in November, but it can be extended to January in case of a delay in precipitation. However, late sowing typically results in lower yields than early sowing due to both a reduction in cultivated area and the fact that the later part of the season coincides with times of high temperatures, which can reduce yields. Other studies have confirmed the impact of sowing date on wheat yield potential. A work in China found that the yield gap of wheat decreased from 1200 to 400 kg ha^{-1} with adjustment in the sowing date (Yao et al., 2021). A study on the characteristics of small wheat farms in the North China Plain noted that sowing date was the most limiting factor for spikes per hectare, which was the most indicative factor of potential yield (Cao et al., 2019). Similarly, sowing date has clearly been found to significantly influence wheat yield potential in Pakistan (Khaliq et al., 2019).

Fertilizer inputs in Morocco are considerably limited at a rate of 66 kg ha^{-1} (Al Moutmir, 2021), while the recommendations according to the respective agroecological zone are 84 kg of N, 31 kg of P_2O_5, and 53 kg of K_2O for a grain yield of 2.4 mt ha^{-1} in the semi-arid zone; 140 kg of N, 68 kg of P_2O_5, and 88 kg of K_2O for a grain yield of 4 mt ha^{-1} in the more favorable area, 210 kg of N, 102 kg of P_2O_5, and 132 kg of K_2O for a grain yield of 6 mt ha^{-1} in the supplemental irrigation area, and 280 kg of N, 136 kg of P_2O_5, and 176 kg of K_2O for a grain yield of 8 mt ha^{-1} in the irrigated area (Alaoui, 2005). On the other hand, water is considered the most limiting factor for cereal production in Morocco, as only 20% of the total agricultural area is irrigated (Brouziyne, 2021) and wheat is considered a rainfed crop that is highly impacted by drought (Bouras et al., 2020). Along the same line, some studies have confirmed that in the region of Tensift Al Haouz, Marrakech, Morocco, optimum water and fertilization at 140 kg of N, 80 kg of P, and 102 kg of K, are needed to achieve the potential yield (Emmanuel et al., 2021). In addition, in the Mediterranean Ebro Valley, Spain, a study noted that, in high-potential years, the main constraint to growth was a lack of water (Abeledo et al., 2008). Another study highlighted the importance of supplemental irrigation and efficient use of rainfall and irrigation water in reducing wheat yield gaps in the Middle East and North Africa region (Pala et al., 2011). Finally, the large differences between observed and simulated yield levels can also be explained by less optimal plot management during growth (inadequate weed, insect, and disease control) as well as the weather conditions.

Our findings show that the studied Moroccan provinces are facing low and unstable bread wheat production. In fact, farmers do not use sufficient inputs (irrigation water, fertilizers, and pesticides) at the right time or they have adopted bad management practices, so their yields remain relatively low. Thus, they have attained very low productivity, sometimes even total crop failure. This situation has led to a sharp fall in the national wheat grain yield across the entire bread wheat cropping area. A system to analyze the trends and temporal variation in wheat grain yield at the national scale in terms of productivity potential and income is clearly needed. Such a framework should allow the integration of widely available phenological parameters. This will allow gains to be quantified to encourage managers, stakeholders, and farmers to adopt new technologies to minimize production risks.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

A total of 680 data points were extracted based on the land use map for the entire Morocco cropped area, and 10 representative points per province were used to run the spatial analysis of the variability of wheat production in Morocco in various regions.

The evaluation of the variability in the potential yield production of bread wheat was carried out using the LINTUL-1 model using the daily weather conditions, including temperature (min, max), precipitation, solar radiation, vapor pressure, and wind speed. Calibration of the model parameters for the crop and weather was done based on the literature, and some of these originated from LINTUL-1 for spring wheat from Netherlands. The simulated potential grain yield of bread wheat was dissimilar throughout the entire cropped area. The average simulated potential yield reached 5.5 mt ha^{-1} and the average observed yield was 1.6 mt ha^{-1}, resulting in an average yield gap of 3.9 mt ha^{-1}. The year-to-year variation in the spatiotemporal potential yield trend in Morocco was not significant in the major growing areas. There was a large gap (6 mt ha^{-1}) in the northern and middle west regions of Morocco; however, in the Atlas Mountain area, there was a considerably lower gap (2 mt ha^{-1}), which could be due to the low temperature at the high altitude.

The spatial analysis of the observed and simulated yields shows that there is high production potential along the belt from the southwest to northwest Morocco, compared to that of the southeast to northeast. Therefore, the areas with higher potential production, represented by Taounate, Khemisset, Settat, and Beni Mellal, should be prioritized for sustainable intensification, since they have the capacity to produce 43% more than what was produced in 2011-2019. Many factors can influence yields, including inputs (fertilizers, irrigation, pesticides), weather conditions, and crop management practices, which demonstrates that there is plenty of room for managers, farmers, and stakeholders to make an effort to increase the grain yield and the total production of bread wheat in developing regions. In this context, there is a particular urgency to narrow the prevailing large yield gaps and mitigate challenges resulting from the growing population, soil degradation, climate change, and seasonal variability of rainfall. Thus, further research on yield monitoring is required to deliver a greater contribution to food security.

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APPENDICES

Appendix 1. Effect of fertilizer on potential wheat yield on field experiments from literature

- https://docs.google.com/spreadsheets/d/1JTNqgdtlYz262x0iIGTz-VtMZ3gwCOImt/edit#gid=831350924

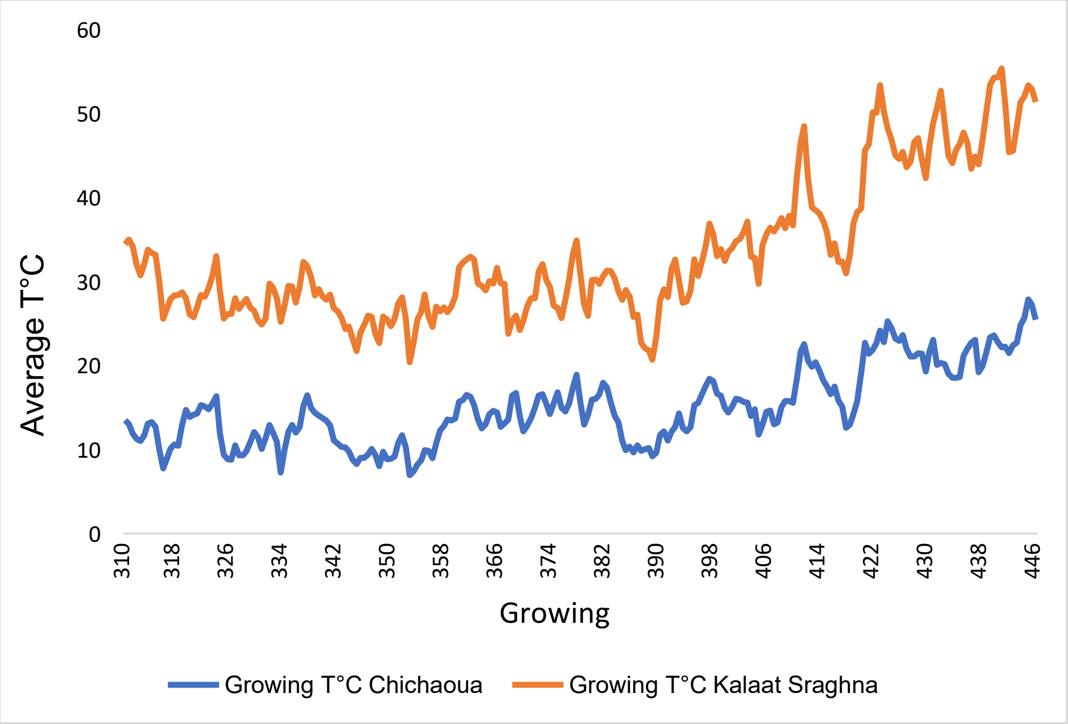
Appendix 2. Simulations: 60 simulations for model validation and 5562 simulations for whole wheat cropped area in Morocco from 2011-2019

- 60 validation locations - 5562 simulation locations

Appendix 3. Observed and simulated yield and yield gap/ of bread wheat grain yield by province over 2011-2019

- https://docs.google.com/spreadsheets/d/11ZL-zDV7HBeeoZFJ1Rk76sWe-vPI3JWPm/edit#gid=1768325851

Appendix 4. Growing temperature in Chichaoua in 2019 and Kalaat Sraghna in 2015



FERARI

FERTILIZER RESEARCH & RESPONSIBLE IMPLEMENTATION

FERARI is an international public-private partnership that builds science-based approaches to site-specific fertilization for widespread adoption by farmers in Ghana for improved food and nutrition security. This calls for a transformation of the fertilizer and food systems that must be driven by evidence-based agro-technical perspectives embedded in multi-stakeholder processes.

To support this transformation, the following institutions have partnered to implement the Fertilizer Research and Responsible Implementation (FERARI) program:

- International Fertilizer Development Centre (IFDC)
- Mohammed VI Polytechnic University (UM6P)
- OCP Group
- Wageningen University and Research (WUR)
- University of Liège (ULiège)
- University of Ghana (UG)
- University for Development Studies (UDS)
- Kwame Nkrumah University of Science and Technology in Kumasi (KNUST)
- University of Cape Coast (UCC)
- University of Energy and Natural Resources (UENR)
- Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED) College of Agriculture Education
- Council for Scientific and Industrial Research in Kumasi (CSIR-SRI) and in Tamale (CSIR-SARI) and its subsidiary (CSIR-SARI-Wa)

FERARI operates in conjunction with the Planting for Food and Jobs program of the Government of Ghana (GoG) to embed development efforts into national policy priorities to reach impact at scale. It trains five Ph.D. and two post-doctoral candidates and dozens of master's-level students in building the evidence base for its interventions.

FERARI conducts hundreds of fertilizer response trials on maize, rice, and soybean, on-station and also with farmers, and demonstrates them to farmer groups in the northern and middle belt of Ghana. It conducts surveys among farmers and actors in the value chain to understand the drivers for use of fertilizers and other inputs and the marketing of the produce to enhance farm productivity and income. It helps the GoG to establish a Ghana National Fertilizer Platform, developing its soil mapping expertise toward an information platform.

The content of this report is the sole responsibility of the authors of the involved institutions portrayed on the front page.

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Developing Agriculture from the Ground Up