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Impact of rainfall variability on cereal yield in the Fez-Meknes region (Morocco)

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ABSTRACT

The Fez-Meknes region is distinguished by its agricultural vocation and its emergence as a hub in the agro-food industry. This study aims to assess the main crop yield, production, and percentage of the agricultural area within each province of the Fez-Meknes region from 2000 to 2020, based on an analysis of descriptive statistics and cartography data. The objective is to determine the national ranking of autumn cereals within the region. Then, multiple linear regression between precipitation and cereal yield in the region's provinces was established, and the trend in sown areas and cereal yield was analysed using the Man Kendall test. The results revealed that the area sown to autumn cereals accounted for 15% of the national cereal area. Despite that, regional cereal production is ranked second nationally after the Casablanca-Settat region, with a small difference that does not exceed 1.5%. Regarding regional provinces, Taounate and Taza account for almost half of the region's cereal production. The correlation coefficient between monthly precipitation and cereal yield ranged from 0.51 in Boulmane province to 0.84 in Fez and Moulay Yaacoub province. The coefficient of determination ranged from 0.21 in Boulmane province to 0.70 in Fez province. On the other hand, precipitation in November, December, January, and March had the greatest impact on cereal yields. The differences between observed and estimated yields using multiple regression are acceptable in all region's provinces, especially when only one predictor was retained. Finally, the Man-Kendall test indicates that the area sown to autumn cereals has a slight downward trend of 4965 ha/year, with a significance of $\alpha = 0.07$. However, cereal yield also tends to increase by 0.34 q/year with a p- value $\alpha = 0.12$.

Keywords: grain yield; autumn cereals; trend analysis; linear regression, Fez-Meknes region.

INTRODUCTION

Wheat and barley are among the most widely cultivated cereals in the world after maize, with a total production of 929 million tons in 2022 (FAO, 2022). They are cultivated in the temperate zone between 30° and 60° north latitude, and between 25° and 40° south latitude (Lav Shallal Mare et Esho 2006). This production is essential for food security. These are grasses grown for their edible seeds (Stewart et Lal, 2018). Indeed, by 2050, a 70 to 100% increase in grain supplies is needed to feed the world's projected 9.8 billion people (Wang et al., 2018).

Unlike most developing countries, which have opted for industrialization as a key factor in their development, Morocco has integrated agriculture at the center of its development policy from the very first years of independence. For this reason, cereal farming plays a dominant role in the structure of the national agricultural system, covering 5.3 million ha (Belmahi et al., 2023) or 59% of the national Utilized Agricultural Area, which represents 8.8 million ha.

The average value of crop production accounts for 68% of the gross domestic product (GDP) (Belmahiet al., 2023; Harbouze et al., 2019) and constitutes the basis of human nutrition in Morocco, where wheat consumption is 255 kg/capita/year, four times higher than the world average. Almost all autumn cereal crops (wheat and barley) are sown in rainfed areas and represent for 93% of sown areas in arid and semi-arid regions of the country (Balaghi, 2006).

The distribution of sown areas of autumn cereals for the 2010–2021 period is as follows: 43.6% soft wheat, 36.6% barley, and 20.6% durum wheat (ONICL 2022). Morocco was a cereal exporter from the 19th century until 1960. But since 1960, the country has become an importer of cereals (Akesbi, 2006). The volume of cereal imports has increased sharply. It increased from 4859 thousand quintals (TQ) in 1972–1973 to 57.05 TQ in 2019–2020. In other words, the import rate has multiplied by 1041%. Thus, Moroccan cereal production will cover only 64% of the population's demand in 2021 (Belmahi et al., 2023). Moreover, cereals accounted for almost 11% of the total value of agricultural imports at the end of 2018. This deficit can be explained by the demographic factor, agricultural land urbanization, population's eating habits, agricultural policy orientation which reserve fertile land for high-added value agricultural products (Qarouach, 1987), and the impact of climatic drought.

On the other hand, the cereals' deficit prediction would enable Moroccan decision-makers to make advance arrangements and plan the quantity of cereal imports (Balaghi et al., 2008). In addition to managing the risk of agricultural drought, particularly in the Fez-Meknes region; this agro-ecological zone is known for its high cereal production nationwide. Based on the statistical and cartographic analyses of data collected during the 2000–2020 period, the present study aims to assess the yield, production, and agricultural area devoted to cereal farming in the Fez-Meknes region of Morocco. In addition, cereal yield prediction has been estimated using linear regression based on monthly rainfall.

STUDY AREA

The Fez-Meknes region is situated in the center-north of Morocco, between 34.9 and 32.58 N latitudes and -2.8 and -5.9 W longitudes (Figure 1). The Rifaine chain to the north and the Middle Atlas Mountains to the south define its boundaries. Its total surface area is 40 423 km^2. It covers 5.7% of the national territory and 4.46 million residents inhabit (12.1% of the national total) according to the 2024 General Population and Housing Census. It comprises 7 provinces and two prefectures, with 161 rural communes and 34 urban communes (Belmahi et al. 2023; Haut-Commissariat au Plan, 2020; Haut-Commissariat au Plan, 2024). The region is dominated by the mountainous relief, where altitudes range from 17 to 3298 meters (1590 m at Mount Outka, 1721 m at Mount Bou Messaoud, 1950 m at Mount Habri, 1965 m at Mount Tazekka, 3190 m at Mount Bouyablane, and 3298 m at Mount Bou Nasser).

The most important plateau is the Sais Plateau, whose soil is among the most fertile in the country and produces the highest yield of vegetables and grains. The hills are distributed primarily in the north and south, constituting an intermediate zone between the plains and the mountains. In terms of climate, the region is marked by a Mediterranean climate, with continental and orographic effects having an important role in establishing subtleties in the distribution of temperature and precipitation (Kessabi et al., 2024). The region's Mediterranean climate changes to an arid steppe climate towards the east and south-east of the region.

Dominated by its rural communes, the agricultural sector is an element of the region's economy. It contributes 22.1% of the wealth produced in the region and around 16% of the national agricultural Gross Domestic Product (Haut-Commissariat au Plan, 2022). Concerning the social impact, the agricultural sector is the region's leading job provider, accounting for 40% of jobs offered in 2019 (Haut-Commissariat au Plan, 2020). The regional utilized agricultural area represents 15% of the national agricultural area, of which 53% is reserved for cereals (Belmahi, 2024). Cereals are sown on an area of 802 × 10^3 ha/year from 2000

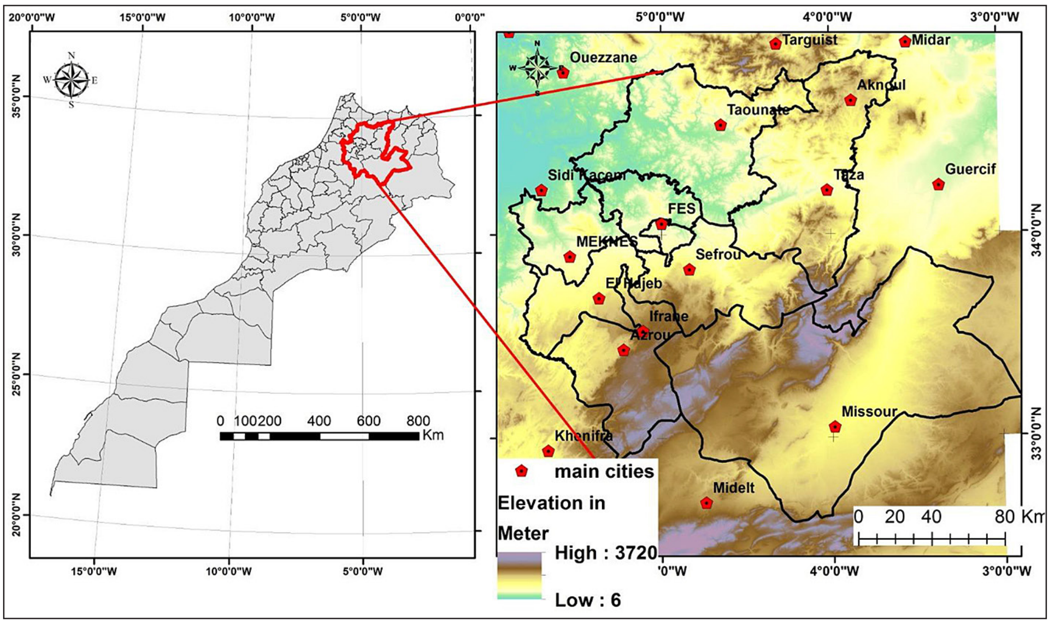

Figure 1. The study area's geographical location

to 2020. Regarding cereal production, the region is at the top of the national ranking contributing 20% (annual average reaching 13.6×10^3 quintals (q)). It ranks second after the Greater Casablanca-Settat region; the difference is only 1.43%. The region is dominated by soft wheat at 51%, then durum wheat at 28% and barley at 21%. The average grain yield for these three cereals is 17 q/ha, versus 12 q/ha at national level from 2000 to 2020 (Belmahi, 2024).

DATA

Data on autumn cereals were obtained from the Ministry of Agriculture, Sea Fisheries, Rural Development, and Water and Forests of Morocco. The database contains yield in quintals, production in tons, and area sown in hectares. Rainfall data are provided by the National Directorate of Meteorology and the Sebou Hydraulic Basin Agency; these data are based on monthly rainfall records. All these institutions are officially affiliated with the State. Table 1 shows the observation period and the geographical location of the various provinces in the Fez-Meknes region.

MATERIALS AND METHODS

Linear regression

To determine the relationship between cereal yield and monthly rainfall, we used multiple linear regression for each province in the Fez-Meknes region. In addition, this work is based on descriptive statistical analysis and cartographic work to show the potential of the Fez-Meknes region in terms of yield, production, and area sown over the period 2000–2020.

Table 1. Geographical location of the studied provinces and the corresponding observation period

Ordre number	Province	Latitude	Longitude	Altitude	Observation period
01	Taza	34.13	-4.01	522	1980–2019
02	Fez	34.03	-4.59	482	1980–2018
03	Taounate	34.32	-4.38	566	1980–2018
04	Meknes	33.54	-5.33	531	1980–2018
05	Sefrou	33.49	-4.50	823	1980–2018
06	El Hajeb	33.41	-5.22	1000	1995–2017
07	Ifrane	33.31	-5.06	1665	1982–2010
08	Boulmane	33.03	-3.59	2029	2000–2018

The multiple regression method we have chosen is called "stepwise" by SPSS (Statistical Package for the Social Sciences). With this method, the model adds the variable that contributes most significantly to model improvement, i.e., the variable with the highest correlation with the dependent variable. If this is not the case, the model removes it and determines a second predictor. When SPSS adds a variable to the model, it assesses if its contribution is significant. The contribution of the variable, having the lowest one, has also been evaluated to ensure that it remains significant. In this way, redundant variables can be eliminated. The multiple linear regression model is written as follows (Rakotomalala 2011):

$$Y = a_1X_1 + a_2X_2 + ... + a_nX_n + K \quad (1)$$

where: Y – yield estimated by the multiple regression model (q/ha); $a1$ – regression coefficients; K – constant of the multiple regression model; $x1$: rainfall (mm) of a given month 'i' explaining the yield.

So, in this case, the yield has been chosen as the variable to be explained (dependent) and monthly precipitation as the explanatory variable (independent) that can affect cereal yield.

Trend analysis: Mann-Kendall test and Sen slope estimator

For trends in areas sown to autumn cereals and in cereal yields, we applied the non-parametric Mann-Kendall (MK) test and the Theil-Sen slope estimator. This test is considered as one of the most popular non-parametric tests employed by scientists worldwide to characterise trends and their significance in time series data. The positive Z value of MK test means an upward trend and conversely a downward trend (Chen et al., 2024; Kessabi et al., 2022). The MK test statistic S is calculated using the formula below (Achite et al., 2021):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \quad (2)$$

where: n is the data number. xi and xj represent the values of the data at times j and k ($j > k$) and the sign function is given as follows:

$$\text{sgn}(x_j - x_k) = \text{sgn}(R_j - R_i) = \begin{cases} +1, \text{if } (x_j - x_k) > 0 \\ 0, \text{if } (x_j - x_k) = 0 \\ -1, \text{if } (x_j - x_k) < 0 \end{cases} \quad (3)$$

The variance of S is given as,

$$Var(S) = \frac{[n(n-1)(2n+5)] - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18} \quad (4)$$

where: t_i is the number of ties of extent i and m is the number of tied rank groups. For n larger than 10, a Z test statistic is valid under the null hypothesis of no correlation. However, it approximates a standard normal distribution as the test statistic of MK as shown below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, \text{if } S > 0 \\ 0, \text{if } S = 0 \\ \frac{S-1}{\sqrt{Var(S)}}, \text{if } S < 0 \end{cases} \quad (5)$$

If a linear trend is present in a time series, then the true slope may be determined using a simple non-parametric method described by [20]. Estimates of the slope of n (n - 1)/2 unique pairs are first calculated by:

$$Q(i,j) = \frac{X_j - X_i}{j - i} \; for \; i,j = 1,2 \dots n \quad (6)$$

where: Xj and Xi represent the data values at times j and i ($j > i$) respectively. The median of these N values of Q is Sen's estimator of slope. After sorting the Q values, if N is even, Sen's estimator is obtained by:

$$Q_{med} = \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) \quad (7)$$

If N is odd, then Sen's estimator is calculated using the equation below:

$$Q_{med} = \left(Q_{\frac{N+1}{2}}\right) \quad (8)$$

Sen's estimator Qmed gives the rate of change and allows us to determine overall variation in all variables over the analysis period. In this case, Sen slopes are represented as the rate of change over 20 years (2000/2001–2019/20) expressed in hectare and yield/year.

RESULTS

Cereal crop distribution in the Fez-Meknes region

The area percentages devoted to autumn cereals are concentrated in the provinces of Taounate (37%) and Taza (19%). However, they remain low in the provinces of Moulay Yaacoub at 10.4%, Meknes at 8.5, El Hajeb at 8.03%, Sefrou at 6.7%, Boulmane at 5.3% and Ifrane at 4.5%. Almost half of the region's cereal production

(48%) was produced by the provinces of Taounate (30%) and Taza (18%).

Moreover, even though Meknes had a smaller cereal area, it still contributed 13.7% to regional cereal production. This can be explained by the soil conditions and farming practices more conducive to high productivity in this province (nitrogen fertilization, pesticides, weed control, tillage). It should be noted that the provinces of El Hajeb and Moulay Yaacoub, in which the agricultural area devoted to cereals is 8% and 10% respectively, contributed equally to the regional production of 12% (Figure 2).

On the other hand, the province of Taza contains 56% of the almond area, and almost half of the forage crops are found in the provinces of Ifrane and Meknes (49%). However, the province of Moulay Yaacoub is characterized by industrial crops, which account for 64% of the region's agricultural area. Areas under pulses are predominant in the province of Taounate, with a sown area of 38%. This province also has 41% of the region's olive area, 70% of its citrus area, 100% of its sugar crops, and 35% of its rosaceous fruit area. Poultry farming and market gardening are mainly found in El Hajeb province with 68% and 34% of the region's surface area, respectively (Table 2).

Spatial variability of autumn cereal yields in the study region

Analysis of cereal yields shows heterogeneity between the Fez-Meknes region provinces. For durum wheat, the Meknes province leads with an average yield of 24 q/ha followed by the El Hajeb province (21 q/ha). Next comes the province of Sefrou (20 q/ha), followed by the Fez province (19 q/ha). Yields in the other provinces ranged from 17 q/ha in Taounate to 13 q/ha in Boulmane. This region has an average yield of 18 q/ha, which is higher than the national average for durum wheat of 15.7 q/ha. Concerning soft wheat, the Meknes province is also in first place, with an average yield of 24 q/ha, followed by the El Hajeb province with 23 q/ha. Next comes the Sefrou province with a yield of 21 q/ha, followed by the provinces of Moulay Yaacoub and Fez with 20 q/ha, and the other regional provinces having yields ranging from 18 q/ha in Ifrane to 12 q/ha in Boulmane.

The difference between durum and soft wheat yields, by provinces, is smaller; but, generally, in favor of soft wheat, except in two regions namely Taza and Boulmane. However, yields for both crops are the same in Meknes province. Barley yield reached a maximum of 19 q/ha in the province of Meknes, followed by El Hajeb (18 q/ha), Sefrou (16 q/ha), Taza, and Taounate (13 q/ha); while the lowest yield was recorded in

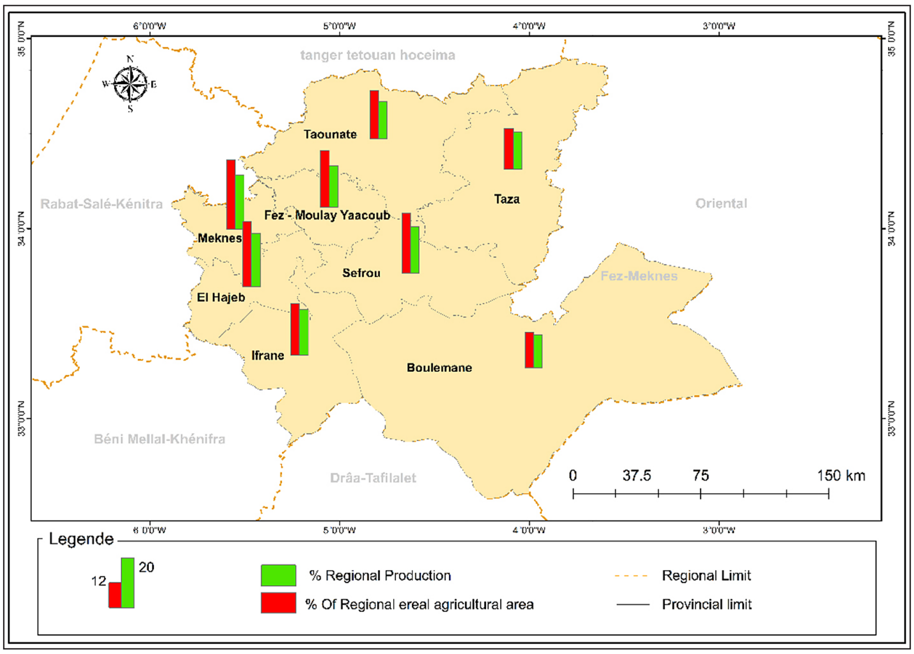

Figure 2. Percentage of agricultural area under cereals and their production according to province in the Fez-Meknes region

Table 2. Relative share of main crop area by province in the Fez-Meknes region (2019–2020)

Province	Citrus	Almond trees	Cereals	Fodder crops	Industri-al crops	Legu-mes	Market garden-ing	Olive trees	Oils-eeds	Rosace-ous crops	Sugar crops
Taounate	70.29	10.49	37.26	5.67	27.07	38.04	9.49	41.13	4.55	34.96	100.00
Taza	0.30	56.55	19.12	1.19	0.00	10.72	1.96	21.97	2.09	5.61	0.00
El Hajeb	0.17	11.87	8.03	12.55	3.09	5.61	34.17	5.37	6.55	16.73	0.00
Fez	0.00	1.25	0.00	8.86	0.00	1.44	1.30	0.86	14.11	0.93	0.00
Ifrane	0.00	0.20	4.51	26.43	0.00	1.09	9.72	0.18	0.00	14.89	0.00
Meknes	11.80	5.91	8.59	22.22	5.80	15.58	18.02	9.22	60.22	5.82	0.00
Moulay Yaacoub	16.54	1.17	10.46	11.93	63.92	18.04	12.17	8.97	4.08	1.26	0.00
Sefrou	0.90	7.56	6.68	1.60	0.06	9.22	5.68	8.58	8.38	14.75	0.00
Boulemane	0.00	5.00	5.35	9.55	0.06	0.25	7.49	3.72	0.00	5.04	0.00

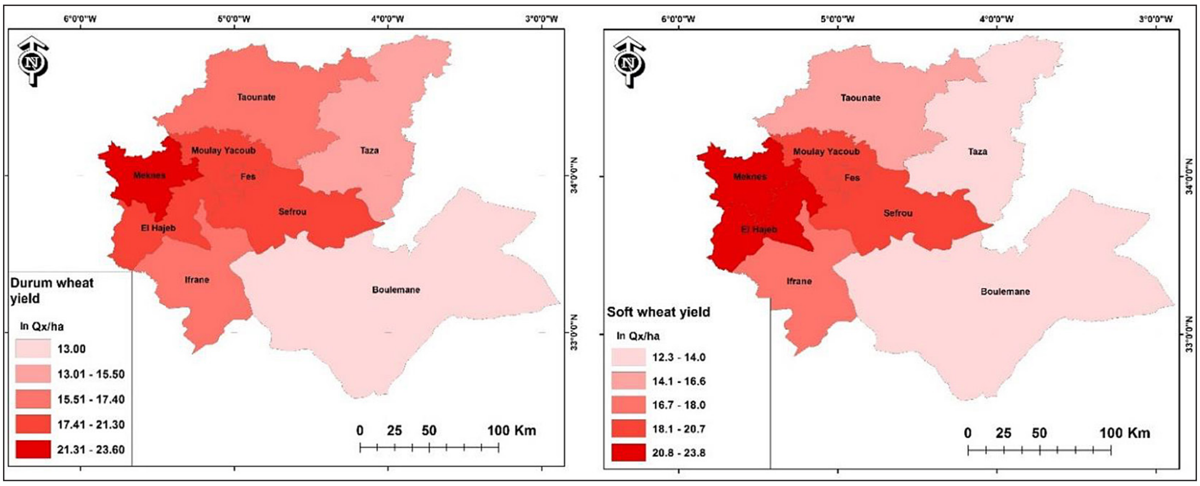

Figure 3. Soft wheat yield and Durum wheat in the Fez-Meknes region

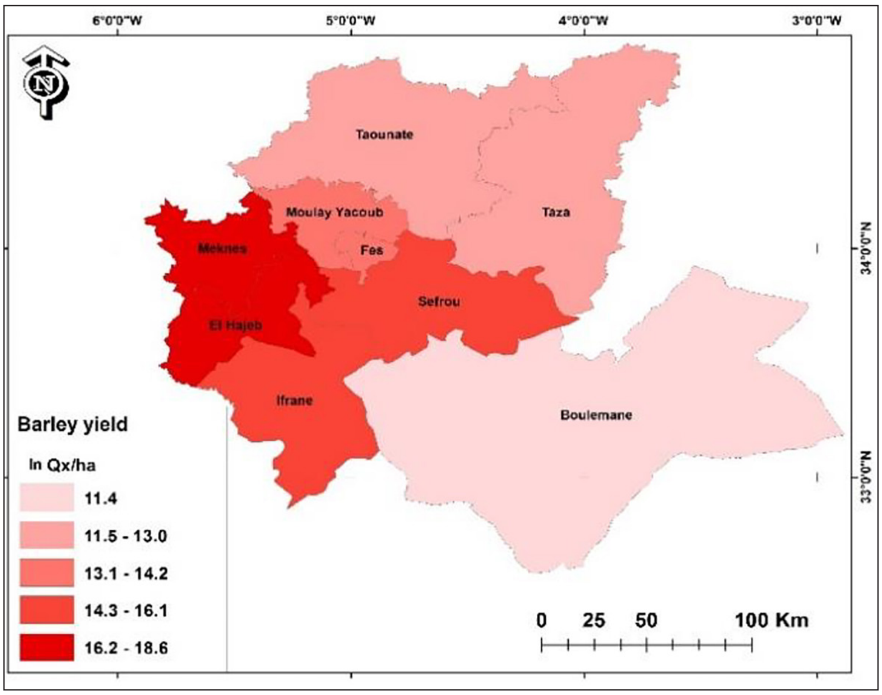

Figure 4. Barely yield in the Fez-Meknes region between 2010–2020

the province of Boulmane (11.5 q/ha). Over the 2000–2020 period, the average regional yield (15 q/ha) is higher than the national average (10 q/ha) due to the agricultural vocation of the Fez-Meknes region (Figures 3 and 4).

The highest grain yield of the three autumn cereals, over the study period (2000-2020), was recorded in the Meknes province (22 q/ha). Grain yields were very high for wheat reaching 23.7 q/ha compared with 18.6 q/ha for barley. Average yields in the provinces of El Hajeb, Taza, Moulay Yaacoub, Ifrane, and Sefrou are 18.5, 17.4, 17.3, 17.09, and 17.07 q/ha, respectively. Low yields were observed in Taounate (15.5 q/ha) and Boulmane (12.2 q/ha) provinces. Nevertheless, the regional yields are greater than the national for the main cereals. Interannual variability in autumn cereal yields (coefficient of variation) was highest in the province of Taza (50%) and the provinces of Moulay Yaacoub and Fez (43%). On the other hand, it varied between 37 and 41% in the provinces of Meknes, Sefrou, Taounate and El Hajeb. The relatively lowest temporal variability was recorded in the mountainous region, where it reached 29 and 31% in Boulmane and Ifrane, respectively. This is due to the effect of relative humidity (which increases with altitude) and temperature (which decreases with altitude).

Furthermore, an analysis of cereal production by province revealed that the provinces of Taounate and Taza produce almost half of the region's cereal production. These provinces respectively account for 30 and 18.5% of total regional cereal production during the 2000–2020 period, despite having almost equal agricultural land designed for cereals (53% versus 52%). The contribution of the provinces of Moulay Yaacoub-Fez, Meknes and El Hajeb varies from 14% to 11%, while the provinces of Boulmane, Sefrou and Ifrane recorded a low percentage of cereal production, although the area sown to cereals increased. This is generally explained by soil poverty, family-type micro-farms, and low use of agricultural inputs. The results also showed that the provinces of Taounate and Taza rank second to last in terms of cereal yield. This can be explained by the fragility of their environments, due to the presence of regosols or poorly developed soils of erosion , especially as most of these two provinces belong to the Pre-Rif hills. Additionally, cereal farming in these two provinces is essentially traditional, of the substance type, so yields are low.

Temporal variability in area sown, yield and cereal production

The Man-Kendall test indicated that the area sown to autumn cereals has a slight decreasing trend of 4965 ha/year, with a significance of $\alpha = 0.07$. This trend can be explained by the orientation of farmers towards more cost-effective crops that are adaptable to climate change, notably with government subsidies after the implementation of the Green Morocco Plan in 2008 and the Generation Green Strategy in 2020. The average area sown reached 802 thousand ha/year over the 20 years from 2000 to 2020, with a coefficient of variation of 8%. Moreover, cereal production increased by 25.05×10^3 q/year, with a P-value of

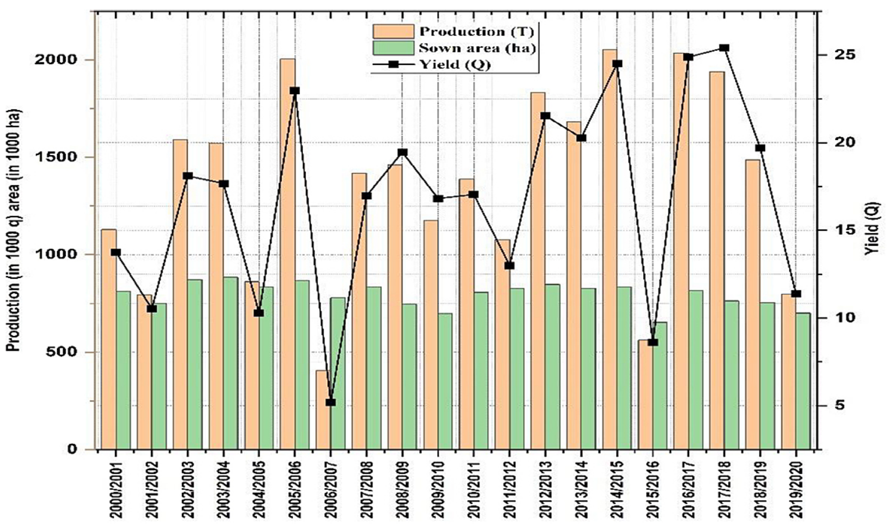

Figure 5. Evolution of area, yield, and production of autumn cereals in the study region

0.3. Cereal yield also tends to increase by 0.34 q/year, with a p-value α = 0.12.

Annual production and yields of the main cereals in the Fez-Meknes region are marked by pronounced inter-annual fluctuations (Figure 5), depending on climatic conditions. During the 2000-2010 period, cereal production averaged 12.4 million quintals; this production increased to 14.8 million quintals in the second decade (2010–2020). It should be noted that rainy years saw high levels of production (20 million quintals in 2005–2006), while dry years saw very low levels (4 million quintals in 2006–2007). where the coefficient of variation of cereal production is 37% over the period studied.

The regional cereal production importance at the national level

From Figure 6, we can deduce the following results:

- The Fez-Meknes and Casablanca-Settat regions are characterized by soft wheat production followed by durum wheat. The Rabat-Sale-Kenitra region specializes in soft wheat production; in the 2000–2020 period, the annual percentage of soft wheat was 76% (8.4 million q/year), compared with durum wheat and barley productions of 10% and 13%, respectively.
- Regions with an arid to semi-arid climate are marked by the relative importance of barley cultivation, as is the case of the Oriental, Marrakech-Safi, and the Souss-Massa regions, although their production is low, except for the Marrakech-Safi region which produced 22% of annual national barley production during the 2000–2020 period.
- The South-East and Guelmim-Oued Noun regions are characterized by low cereal production (4%). Soft wheat accounts for almost half of regional cereal production (49%) over the 2000–2020 period.
- The Fez-Meknes region is distinguished by its superiority in soft wheat production at 51%, then durum wheat at 28% and barley at 21%. It plays a leading role in national cereal production, with a contribution of 20%, representing an annual average of 13.6 million q/year over the 2000–2020 period. It comes second after the Casablanca-Settat region, with a gap of just 1.43%. Indeed, cereal farming is one of the region's most important crops, due to favorable climatic conditions and fertile soils, particularly in the Saïss basin and in the provinces of Taounate, Moulay Yaacoub, Sefrou, and Taza. In addition, farmers prefer to grow soft wheat because of its high production, especially following the introduction of new genetically modified cultivars, and its good price on the market.

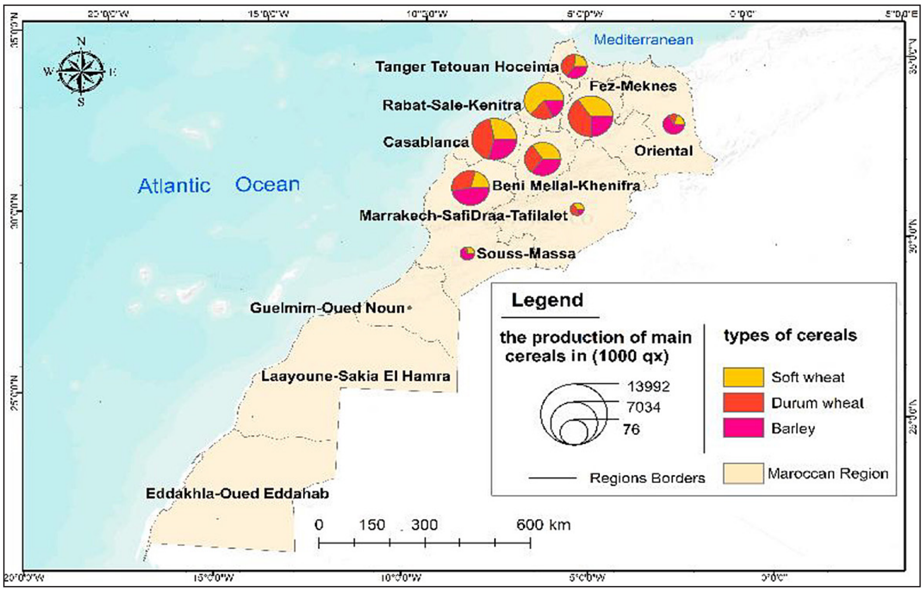

Figure 6. Production of the main cereals by region in Morocco during the 2000–2020 period

Table 3. Multiple linear regression between yield and precipitation in the different provinces of the study region

Province	R	R^2	P-value	Regression model
Taza	0,69	0,48	0.001	Yield = 3.101+0.050* november +0.022* December
Fez	0.84	0.70	0.000	Yield = 0.530+0.101*november+0.102*f+0.043*d
Taounate	0.60	0.36	0.001	Yield = 9,6+0.036* november +0.022*January
Meknes	0.72	0.53	0.004	Yield = 14.449+0.076*november-0.065*March
Sefrou	0.78	0.61	0.023	Yield = 3.833+0.08*november +0.066* February +0.039*j
El Hajeb	0.74	0.56	0.036	Yield = 16.361+0.70*november-0.089*March
Boulmane	0.51	0.26	0.030	Yield = 8.143+0.090*April
Ifrane	-	-	-	No variable has been entered in the equation

Multiple linear regression between cereal yield and monthly precipitation in the Fez-Meknes region

The predictors are monthly precipitation in the 7 provinces correlated with cereal yield in each province. The results obtained showed that the multivariate correlation coefficient is significant with a 5% error margin; it ranges from 0.5 L in Boulmane province to 0.84 in Fez province, according to the multiple regression model. The coefficient of determination (R^2) varies between 0.21 in Boulmane province and 0.70 in Fez province, confirming the precipitation influence on cereal yield variability in all cereal-producing provinces in the region (Table 3). Other factors can mitigate the impact of precipitation on yield, including the nature of the soil on crop production, maximum temperature during the reproductive phase, and the role of inputs and production technologies. Precipitation in November, December, January, and March is most correlated with cereal yield. These results confirm those obtained by (Bouras et al. 2020) in Morocco, which highlight the importance of November precipitation, followed by January, February, and March. The p-value is significant ($p < 0.05$) in all provinces at a 5% probability except Ifrane province. Thus, the independent variable contributed significantly to explaining the variability of the model.

The differences between estimated and observed yield using multiple regression is acceptable in the region's provinces, especially when only one predictor (precipitation) was retained; this means that the model better estimates cereal yield. Globally, rainfall had an impact on main grain yields in all Moroccan provinces. For example, a 50 mm drop in rainfall in Fez province reduced yields by 2.6 q/ha and 2 q/ha respectively, while a 100 mm drop reduced yields by 5.2 q/ha and 4 q/ha respectively.

DISCUSSION

Cereal production plays a strategic role in the Fez-Meknes region. It constitutes the main source of income for a large part of the population. Indeed, the region is dominated by the rural character of its communes, with 161 rural communes populated by approximately 1.7 million inhabitants in 2014, and livestock of 5.4 million heads. As a result, the cereal sector is an essential component of the regional economy and contributes to combating rural exodus, especially since a significant part of cereal production is intended for the livestock sector as food. However, a comparison between the production and consumption of cereals, particularly for wheat, which is consumed by the majority of the population at 255 kg/capita/year, reveals that the deficit is growing in favor of imports, which increased by 911% over the period 1971–2021. Consequently, Morocco's dependence on the international market is increasing, with an import dependency rate of 39.8%, while food self-sufficiency represents 60.2% for the decade between 2012 and 2021 (Belmahi et al., 2023). So, the role of yield forecasting is of crucial importance for the national economy and local population, since it guarantees the country's food security and ensures sufficient supply of the main cereals on the national market, given the region's weight in national production (20%).

An analysis of the area sown to autumn cereals at provincial level in the Fez-Meknes region shows that the provinces of Taounate and Taza account for more than half of this area, with 37% and 19% respectively. These two provinces also account for almost half of cereal production, with respective contributions of 31% and 19% for the 2000–2020 period. This is due to the extent of the rural environment, which is characterized by a vast expanse of plains and plateaus used for rain-fed cultivation of autumn cereals, in the absence of the material conditions needed to switch to intensive, high-productivity agriculture. However, cereal yields per hectare remain moderate in these two provinces due to the fragility of their environment, caused by the presence of poorly developed regosols or erosion soils (Tribak et El Garouani, 2009), and the limited use of inputs. However, cereal yields are increasing in the provinces of El Hajeb and Meknes due to favorable soil conditions and agricultural practices that promote higher productivity (nitrogen fertilization, pesticides, weed control, soil tillage). The non-parametric Mann-Kendall trend test for cultivated area in the Fès-Meknès region indicates a slight decrease, with a non-significant p-value ($\alpha = 0.07$). This can be explained by farmers' orientation towards more profitable tree crops, as part of public policies to adapt to climate change, particularly after recurrent agricultural droughts, as well as the impact of low sales prices during good yield years. On the other hand, cereal production and yield in the Fez-Meknes region showed an upward trend, with increases of 25.05×10^3 q/year and 0.34 q/year respectively. These positive trends in cereal wheat yields around the world have been widely documented (Ahmad et al., 2015; Gizaw and Assegid, 2021; Jarlan et al., 2014; Peltonen-Sainio et al., 2009), and have been associated with the selection of improved genotypes, better crop management and higher input levels.

The equations of the multiple linear regression have very strong correlation coefficients in most of the provinces of the region: r = 0.72 in Meknes, r = 0.74 in El Hajeb, r = 0.78 in Sefrou and r = 0.84 in Fez, indicating that positive changes in rainfall translate into changes in grain yield. The determination coefficient varying between 0.26 in the province of Boulmane and 0.70 in the province of Fez. Nevertheless, this result is lower than those obtained (Feki et Douguedroit, 2003) in Tunisia, where the authors found correlation coefficients in excess of 0.90, with R^2 varying between 0.88 and 0.91, and by (Sellam and Poovammal, 2016) en India ($R^2 = 0.72$). However, it is better than those reported by (Jarlan et al., 2014), where the authors observed a correlation coefficient of 0.55 between rainfall and wheat yield in Morocco. Furthermore, it is close to those obtained by (Ed-Daoudi et al., 2023), ($R^2 = 0.76$), given that these authors chose three explanatory variables for the variability of wheat yield in the southeast of Morocco, namely precipitation, temperature, and soil moisture. It is also noted that the low impact of precipitation on mountainous provinces such as Boulemane and Ifrane is due to the orographic effect (altitude factor), which provides significant moisture for agricultural production, as well as the effect of surface slope, where overland water flow is a common phenomenon in these provinces, thus reducing the effect of precipitation on agricultural yields. This result is in agreement with that obtained by (Feki and Douguedroit, 2003) at Silliana in Tunisia.

Many studies, both global and national, have focused on the impact of climate change on the agricultural sector and how to adapt to it (Ahmed et al., 2022; Belmahi et al., 2023; Belmahi and Hanchane, 2021; Fatima and Et-Touile, 2021; Guiné, 2024; Mengistu et al., 2024; Pickson and Boateng, 2022; Taniushkina et al., 2024). In the Fez-Meknes region to reduce the impact of climate change on cereal farming, the Moroccan government has introduced several innovative techniques, including direct seeding, which was first applied in Morocco in 2012. This technological solution makes Moroccan agriculture more resilient in the face of climatic hazards. It protects the soil from erosion and maintains its biological and chemical structure, while increasing crop yields and quality by reducing the quantity of seeds needed for sowing.

Direct seeding also helps to reduce costs and labor compared with traditional tillage systems. It limits water losses due to evapotranspiration, optimizes use of the soil's useful reserve and improves crop tolerance to water stress during critical stages, particularly in semi-arid zones (Agri-Maroc.ma, 2020; Belmahi, 2024). This technique has proved its effectiveness, particularly during the 2019–2020 agricultural season, which has been marked by a scarcity of rainfall. For example, in a soft wheat field in the Oued Amlil commune (Taza province), yields reached 28 q/ha compared with 19 q/ha for a control field. These results confirm that direct seeding is a key lever in the agro-ecological transition, enabling cereal crops in rain-fed areas to adapt better to climate change while increasing yields under limiting climatic conditions.

At the same time, crop rotation also plays a crucial role in mitigating the effects of climate change. From an agronomic point of view, it helps to increase and stabilize yields, improve the seedbed and increase the soil's water retention capacity. Bioecologically, it stimulates microbial life, improves soil structure by promoting aeration and infiltration, preserves biodiversity and limits weeds. Finally, in environmental terms, it reduces water and wind erosion, limits losses of nutrients and pesticides, and reduces greenhouse gas emissions.

Other initiatives, such as the use of selected seeds, rational fertilization, and the establishment of agrometeorological monitoring systems, complement these efforts. Morocco developed the first integrated agrometeorological prediction system for cereal crops, called CGMS-MAROC (Crop Growth Monitoring System – Morocco), in 2012. This system, piloted by the National Institute for Agronomic Research in Rabat, is managed in collaboration with the National Meteorology Directorate and the Strategy and Statistics Directorate (Balaghi, 2014). It also benefits from the technological support of international institutions such as the Flemish Institute for Research and Technology, the Joint Research Centre of the European Union, the Research Institute of Wageningen University and the University of Milan.

CONCLUSIONS

As a result of the present work, the Fez-Meknes region has a high potential for autumn cereal production, occupying 53% of its utilized agricultural area. Its contribution to national cereal production is predominant, reaching approximately 20% with an annual production of 13.6 million q/year. Despite being only 15% of the total area sown to autumn cereals at the national level, the region ranks second after the Casablanca-Settat region with a small difference of 1.43% during the 2000–2020 period. Cereal production in the Fez-Meknes region is marked by the supremacy of soft wheat with a production percentage of 51%, followed by durum wheat with 28% and barley with 21%. Cereal crops in the region are mainly rainfed since irrigated land is reserved for high-value-added crops. However, the region also contains fertile plains and plateaus, such as the Saïss Plateau, the Tissa Plateau, and the Inaouene Valley. This improves autumn cereal production, particularly in humid and/or climatically dry years, provided that the duration of the growth cycle of the cereals (which is a biological factor) is suitable to the duration of water availability (which is a climatic factor) to obtain a quality product. Cereal yields reached 17 q/ha at the regional level, compared with 12 q/ha at the national level between 2000 and 2020. Cereal yields remain limited compared with the region's natural potential. Moreover, it has suffered from strong inter-annual fluctuation due to dryness, with a strong decrease in yield during dry years, such as the 2015–2016 agricultural year (5 q/ha). The analysis of regional cereal yield evolution reveals quite significant differences between provinces. Indeed, cereal yields are in descending order as follows: the provinces of Meknes, El Hajeb, Sefrou Taza, Fez, Ifrane, Taounate, Taza, and Boulmane. The obtained results also show the dependence between yield and precipitation in the different provinces of the region. Furthermore, the correlation coefficients in the provinces of Fez and Sefrou reach 0.84 and 0.78, respectively. There is a relationship with the precipitation during November, December, and February in Fez and with November, January, and February in Sefrou. The difference between estimated and observed yields using multiple linear regression is comprised between 23 and 29% in all provinces of the region, which means that the model provides a better estimate of cereal yield. The Man-Kendall test indicates that the area sown to autumn cereals has a slight downward trend of 4965 ha/year, with a significance of $\alpha = 0.07$. However, cereal yields also tend to increase by 0.34 q/year, with a p- value of $\alpha = 0.12$.

Finally, to optimize yields, guarantee food security for farmers, and avoid environmental migrants, management aspects and human determinants play a crucial role. In this context, several measures need to be applied throughout the region, including seed variety selection, agroforestry, crop rotation, appropriate use of fertilizers, and direct seeding to maximize yields. Farmers' access to agricultural insurance, training programs, extension services, and price support can help them invest in agricultural technologies in the context of Morocco's "Green Generation" strategy between 2020 and 2030. Finally, the accuracy of crop yield forecasts is crucial for farmers, policy makers and other stakeholders to make informed decisions about resource allocation and food security.

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