Agroclimatic drought and vulnerability of rainfed cereal growing in the high plateaux of Sétif and Bordj Bou Arreridj

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Abstract: The regions of Sétif and Bordj Bou Arreridj are facing recurring episodes of drought, which are severely affecting cereal farming in rainfed areas, despite the efforts made in recent years. These droughts, mainly due to irregular and low rainfall, were analysed over an 80-year period (1940–2021) to assess their impact on cereal cultivation. The approach adopted is based on the Markov chain, incorporating criteria such as rainfall thresholds (above 0.1 mm and 5 mm), the number of rainy days, intensity, duration and monthly rainfall totals.The analysis identified three distinct periods (1940–1970, 1970-2000 and 2000-2021). An intensification of monthly droughts and their duration was observed between the first and second periods. The third period, although more recent, shows less severe droughts, thanks to relatively high rainfall between November and March, particularly in 2002/2003 and 2003/2004.Principal component analysis was used to generate monthly risk indices (r), ranging from -0.8 to +0.7, reflecting crop vulnerability levels from sowing to harvest. These results support strategic planning for cereal farming in semi-arid environments, while highlighting the need to take other environmental and technical factors into account.
Keywords: Water stress, frequency, intensity, vulnerability, cereal farming.

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1 Introduction

Agriculture remains the mainstay of the Algerian economy, accounting for 60% of jobs, particularly in rural regions (Bessaoud et al., 2019). These regions, which are mainly located in semi-arid areas, partly include the eastern plains, where extensive rainfed cereal growing predominates. This crop, which includes durum and common wheat, barley and oats, occupies 1.5 million hectares annually, alternating with an equivalent amount of fallow land. Despite public investment, average production of 13 million quintals has an average yield of 10.5 q ha^{-1}, higher than the national average (BSA, 1970-2021) but still four times lower than the world average (40.7 q ha^{-1}) (GBM, 2023).

Cereal growing in the eastern highlands takes place under average rainfall varying from 300 to 630 mm $year^{-1}$. Although these theoretical figures seem sufficient to meet cereal needs, the variability in annual production cannot be explained solely by average rainfall. Indeed, it is the intrinsic distribution of rainfall that leads to recurrent droughts in Algeria's agricultural regions.

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The WMO (2016) highlights drought as a natural phenomenon that is widespread throughout the world, and particularly damaging in vast semi-arid areas. This rainfall deficit, which can last for one or more seasons, causes a cascade of damage during agricultural seasons, such as crop and seed losses. These unfavourable situations have economic repercussions, resulting in limited investment and a reduction in the workforce, reaching 12% in 2018 (Bessaoud et al., 2019).

In Algeria, harvest losses represent between 30% and 35% of sown areas (Maghreb Émergent, 2016; Khris, 2021), generating costs estimated at 1 billion Algerian dinars (Zaid, 2016), or nearly 6,831,954 euros. In Tunisia, these losses vary between 6% and 10% (Presse Magazine, 2022), with costs approaching two billion Tunisian dinars (over €800 million) in 2016 (ENPARD, 2016). In France, a country more favourable to cereal growing, losses in 2021 reached 40% (Hugo, 2022), with costs amounting to around €69 billion between 1989 and 2019 (France Agricole, 2021).

According to the FAO (2018), agricultural losses due to droughts (2005-2015) in developing countries are estimated at 29 billion dollars. The OWM (2020) points out that drought, considered from a climatic, hydrological, agricultural and socio-economic point of view, is a medium- and long-term concern. Currently, drought, associated with climatic disturbances, is affecting not only the countries of North Africa, the African Sahel, Central America, the Indian subcontinent and China, but is also spreading to industrialised countries with temperate climates (Atlas Magazine, 2012). This situation generates risks for all countries, modifying the water cycle and contributing to the reduction of soils, i.e. 400,000 hectares per year in Algeria (Safar-Zitoun, 2019) and 10,000 to 30,000 hectares per year in Tunisia (Medeaterre, 2022), a neighbouring country. These ups and downs in agricultural production and yields indirectly lead to socio-economic drought, impacting on food security. Questions are being asked about the development of droughts in Algeria, particularly in the high plateaux of Sétif and Bordj Bou Arreridj, which are dominated by rain-fed cereal crops.

In a context of increasing climate variability, the issue of drought trends in Algeria is attracting growing interest, particularly in the high plateaus of Sétif and Bordj Bou Arreridj. In these regions, rain-fed cereal farming, a strategic but highly vulnerable activity, is directly exposed to climate variations. This study aims to provide answers by analysing the duration, intensity and severity of drought episodes over the long term. Identifying the critical periods and phases of water stress that are most decisive for the cereal cycle will enable a better assessment of the agroclimatic risks specific to this area.

Beyond simple climate characterisation, this research adopts an integrated agronomic approach, which is essential for guiding strategies for adaptation, planning and sustainable crop management. It makes an important contribution to the scientific understanding of agricultural vulnerabilities in semi-arid environments, while providing relevant decision-making tools to address the challenges posed by current and future climate variability.

2 Materials and methods

2.1 Study area

The study area covers the high plateaux of Sétif and Bordj Bou Arreridj, located in the semi-arid eastern region of eastern Algeria, between 35°39' and 36°43' N latitude and between 4°20' and 6°26' E longitude (Figure 1). In this region, winter cereals such as durum and common wheat, barley and oats are rain-fed every year, covering an average area of 328,381 hectares, or 1/5 of the total area.

2.2 Rainfed cereal analysis data

Data on cultivated areas, production and yields are taken from the agricultural statistics bulletins (BSA, 1970-2021). This information is essential for assessing and simulating the vulnerability of cereal crops to the hazards of drought. The approach is established by quantifying the variation in yields generated by drought hazards.

2.3 Drought analysis data

Droughts in the highlands of Sétif and Bordj Bou

Arreridj are assessed by referring to data on rainfall amounts (Px mm) and the number of rainy days (rd), recorded at the synoptic stations of the National Meteorological Office (NMO). Spatio-temporal data series over 80 years, spread over three distinct periods (1940-1970), (1970-2000) and (2000-2020), with monthly time steps from September ('S') to August ('Ao'), have been developed in the laboratory (1940-2021) (Dalila et al., 2022). The time step chosen makes it possible to define the beginning and end of the climatic and agroclimatic drought seasons with reference to predefined Rainfall thresholds: '$R \geqslant 0.1$ mm, $R \geqslant$ 5mm, $R \geqslant 10$ mm, $R \geqslant 20$ mm and $R \geqslant 30$ mm.

The first threshold makes it possible to evaluate the evolution of climatic droughts, their intensities and frequencies, in space over 80 years. The second threshold is used to locate and define the agroclimatic droughts characterising the climate of rainfed cereal growing. The last three thresholds provide an idea of how well the water needs of cereals are being met.

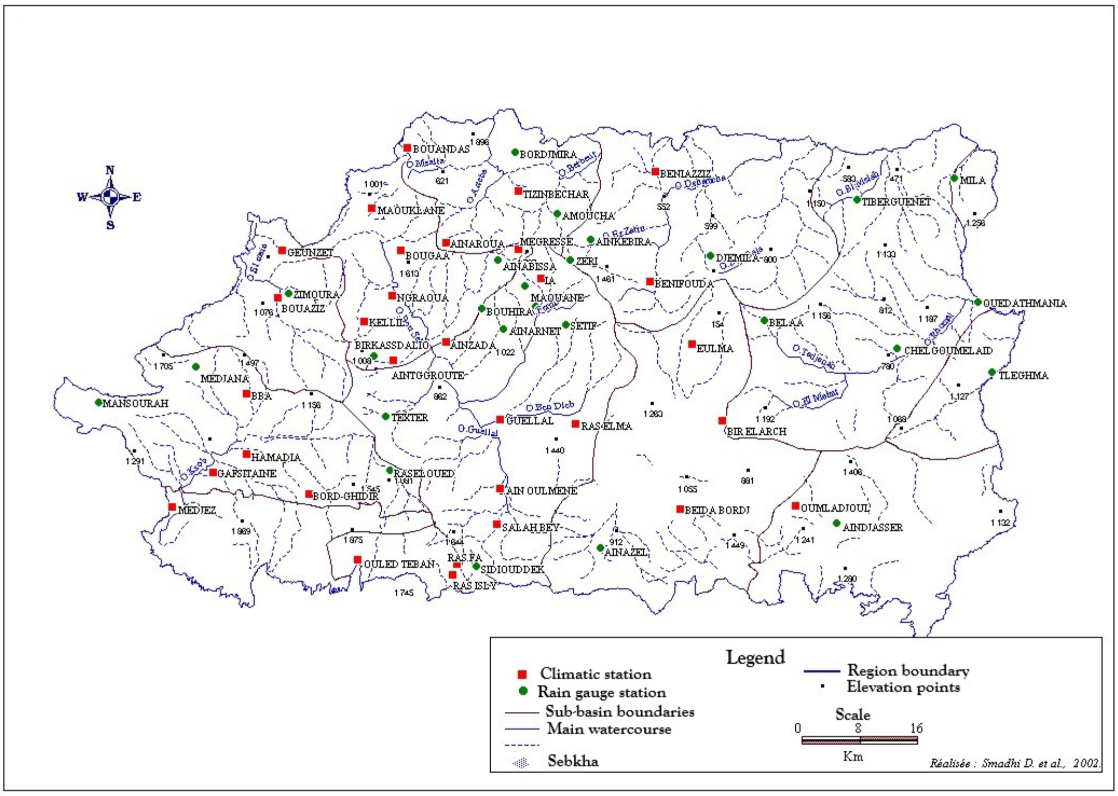

Figure 1 Geographical location of the study area

2.4 Development, intensity and frequency of climatic droughts at the 0.1 mm threshold

Climatic droughts with a threshold of 0.1 mm, considered as random events, on the scale of the high plains of Sétif and Bordj Bou Arreridj, are evaluated by the Standardised Rainfall Index (SRI) as proposed by Nicholson et al. (1988). The WMO (World Meteorological Organisation) recommends the use of the index, identified as $Ri = (Ri - Ra)/S$ with Ri: rainfall for year i (mm); Ra: average inter-monthly rainfall for each month over the study period (mm); S: standard deviation of inter-monthly rainfall over the same period. Applied to a number of variables equivalent to 960 (80 × 12), this index is used to define the duration and intensity of droughts. The results, expressed as probabilities, are quantified as follows: a figure equivalent to '0' indicates median rainfall amounts compared with the climatological series (reference averages; $1 \leqslant$ SRI $<$ -1). Negative figures reflect drought conditions (or deficits), while positive figures express wet conditions (or surpluses).

Series of figures (SRI) are obtained and synthesised using frequency analysis (F), an approach that Serra et al. (2016) argue is underdeveloped for Mediterranean droughts. The aim of this analysis is to assign to the series of SRI values a relative frequency and a cumulative frequency expressed in quantiles according to the normal distribution, introducing the notion of non-exceedance (Pn) assigned to each SRI value in the series, thus expressing the return time (*Tr*): Tr=1/(1-F) according to Rosbjerc et al. (1992) and Ancey et al. (1999).

The empirical probability formula (EPF) is based on sorting the series by increasing value, so that each value is assigned its rank *r*. This is followed by the second empirical probability formula (EPF), based on their distributions. This approach highlights the distribution function of the series *F(x)* and the probability density function (PDF) of the observed values. The aim is to produce a summary table of the probabilities of monthly drought risks, in relation to their frequency and intensity, which may be low, medium, moderate, severe or even very severe. The laborious calculations are carried out using 'Statistica version 5.1' software.

2.5 Trend in agroclimatic droughts with a threshold greater than 5 mm

The agroclimatic droughts that occur after the first climatic droughts are analysed with reference to the indices defined by Hills and Morgan (1981). These authors specify that a day is considered dry if the rainfall is less than 5 mm. According to Guerrero-Salazar and Yevjevich (1975), droughts or dry sequences represent sequences of events of the same type, preceded and followed by different events. Their duration and probability of occurrence are studied in order to estimate the risks. Sivakumar (1991) refers this definition to the rainfall duration, between the beginning and the end of the rains, but also to the calculation of their probabilities of occurrence on a monthly scale, in the absence of soil moisture data. The stochastic model, based on the Markov chain process, makes these laborious calculations possible. It is commonly used in modelling meteorological processes where the evolution of a system is influenced by random events, such as the simulation of dry sequences. According to Abi-Zeid (1997), the model can be applied to any alternating series of two states. The approach is described, highlighting the essential steps and the associated equations.

- The two states of the process, denoted *{Xt}*, are defined by a Bernoulli variable in which the:

- state 1 (*Xt* = 1): is a rainy (wet) state, representing all rainfall values above the threshold of 5 mm ;

- state 0 (*Xt* = 0): is a dry state (deficit), designating all values below this threshold;

- Two-state Markov chain modelling of order 1 implies that the state of the variable (rainfall) at time (*t*) depends solely on its state at time (*t-1*) (Parent and Bernier, 2007);

- The methodology consists of simulating matrices of new series, where each element can take the value 1 (rainy state) or 0 (dry state);

- The probability of transition between states can be defined by a transition matrix, denoted *P*, where *P(i, j)* represents the probability of moving from state *i* to state *j*. The transition process equations are represented by :

$P(Xt = 1 \mid Xt - 1 = 1) = p11$: Probability of remaining in state 1.

$P(Xt = 0 \mid Xt - 1 = 1) = p10$: Probability of going from state 1 to state 0.

$P(Xt = 1 \mid Xt - 1 = 0) = p01$: Probability of going from state 0 to state 1.

$P(Xt = 0 \mid Xt - 1 = 0) = p00$: Probability of remaining in state 0.

- Series matrices are generated, dry sequences are then simulated and identified by looking for occurrences of the dry state (0) on the basis of defined rainfall thresholds.

Four (4) assumptions are made, successively representing the best occurrences of receiving from September to May, the first R⩾5 mm, R⩾10 mm, R ⩾20 mm and R⩾30 mm over the average year. These rains, calculated at probabilities of 20%, 30%, 50% and 80%, estimate the tenacity of the cereal crop at dry sequence durations equivalent to 10, 15 and 20 days, during each month. The criteria established determine the vulnerability of the cereal crop to production, from germination to grain ripening under rainfed conditions, in the study regions. Iterative calculations, ranging from simple averages to the resolution of complex systems of equations, are facilitated by the use of Instat version 3.7 software, well adapted according to Sivakumar et al. (1993) to the calculation of climatic events, and by Excel.

2.6 Drought and vulnerability assessment for cereal crops

The vulnerability of cereal crops to drought in the high plateau regions of Sétif and Bordj Bou Arreridj is part of an in-depth analysis aimed at assessing agroclimatic risk. This assessment takes into account various aspects of risk effects, such as the duration, probability, intensity and frequency of risks related to water availability during the rainy cycle (S-Ma). The series of factors characterising the months from September to May are carefully ordered in descending order, with reference to climatically dry years (1970-2000) and less dry years (2000-2021). These factors are then correlated with agricultural production and yields, thus presenting an economic dimension.

A set of successive monthly data was used to develop spatio-temporal correlation matrices. These matrices were analysed using the statistical method of Principal Component Analysis (PCA), an approach referenced by several authors, including Merabti (2018) and Ogouwale (2020). The correlation coefficients resulting from these analyses were used to measure, identify and summarise the monthly risks of crop vulnerability to the challenges posed by drought.

The values obtained (expressed as *r*) represent risk indices, providing an overview of the sensitivity of crops to production under difficult climatic conditions. These indices could eventually play a key role in guiding water resource management plans. The practical application of these results would be to guide the sustainable socio-economic development of cereal growing. It is important to stress that the iterative calculations required for these analyses were facilitated by the use of Statistica version 3.7 software.

3 Results and interpretations

3.1 Climatic drought, intensity and frequency

Moderate climatic droughts, which characterise the rainy season (September to May) according to the 0.1 mm threshold, are clearly illustrated by the histograms shown in Figure 2. These graphs highlight the monthly distribution of water conditions using Standardised Precipitation Index (SPI) values. Wet months are represented by positive SPI deviations of up to +10%, while months close to the average show SPIs close to 0%. In contrast, dry months are marked by negative deviations of up to -10%.

The evolution of monthly drought reveals particularly dry conditions between 1940 and 1970, followed by worsening aridity during the period 1970-2000. On the other hand, the period 2000-2021 seems to show a slight improvement in water conditions, with signs of rehumidification observed in November, December, January, April and May, particularly in the wilaya of Bordj Bou Arreridj.

However, the representation of average droughts, which is used to define the different rainfall periods, partly masks the months when droughts are extremely severe (Figure 3). These intense episodes result in very negative SPI values, reaching -1.5 in November, -1.8 in February, and -1.5 in March and April. Similarly, these aggregated representations can obscure exceptionally wet months, when the SPI reaches +3 to +4, indicating a temporary easing of the drought. The irregularity of these extreme episodes, both dry and wet, reflects high interannual variability, with intensities varying according to the year and location.

This climatic instability, marked by alternating extreme conditions within the same month over the years, strongly affects the high plateaus of Sétif and Bordj Bou Arreridj. This finding is consistent with the IPCC's (2014) observations on the increase in the frequency and intensity of extreme events in semi-arid areas.

Furthermore, these results can be compared with similar studies conducted in other countries in the Maghreb and the Mediterranean basin. For example, research in Tunisia (Amri et al., 2011) and Morocco (Schilling et al., 2012; Hadria et al., 2020) show a comparable pattern of severe, irregular and increasingly frequent droughts, directly affecting agricultural systems. These comparisons confirm that droughts in the semi-arid Mediterranean region follow similar trends, although their impacts are modulated by local soil conditions, water management and agrarian structure.

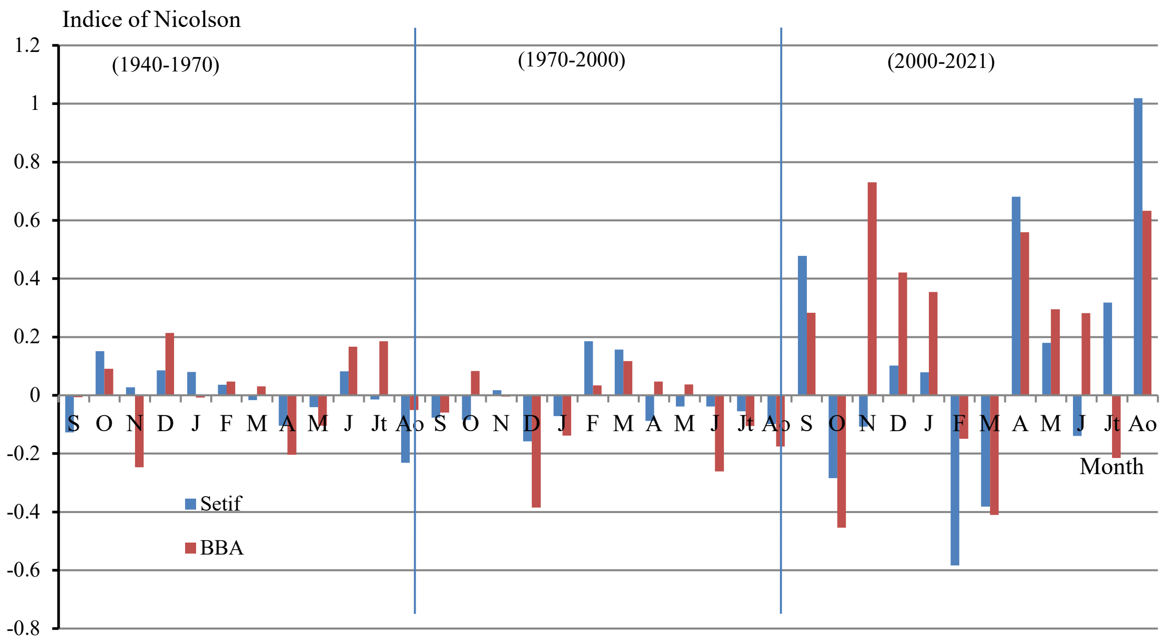

Figure 2 Distribution of rainfall droughts with a threshold ⩾ 0.1 mm, over 80 years (1940 to 2021)

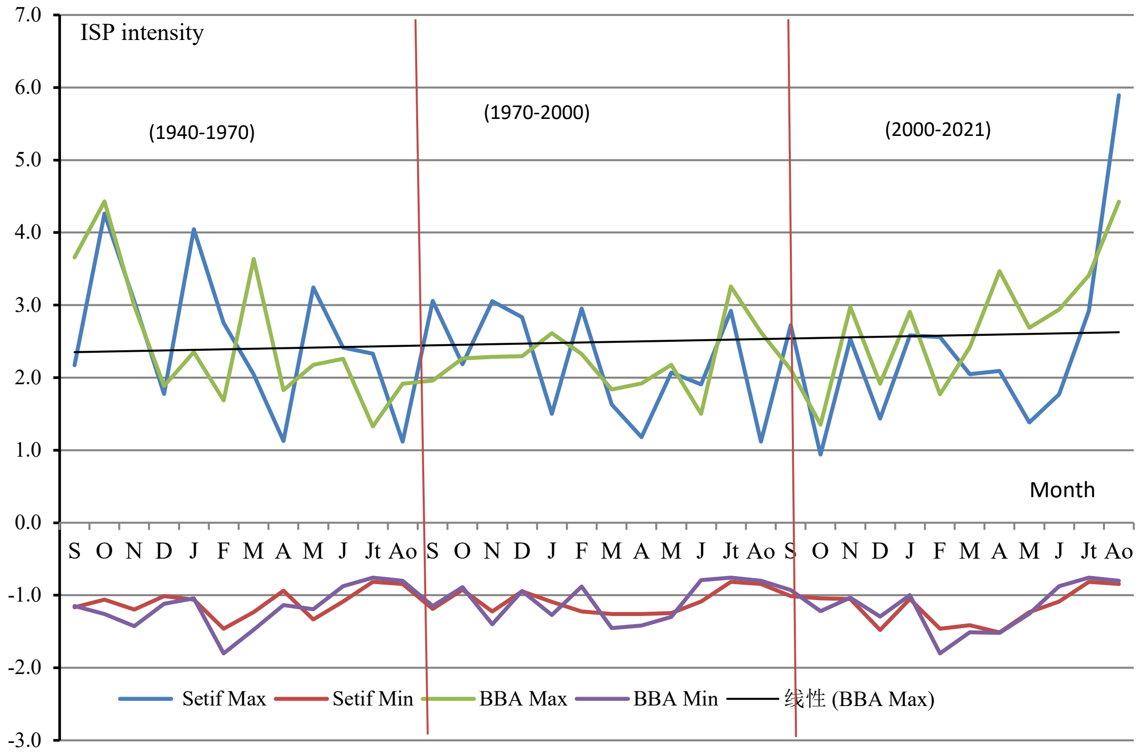

Figure 3 Distribution of maximum and minimum intensities over the 80-year period at Sétif and Bordj Bou Arreridj

The results presented above are reinforced by the analysis of cumulative frequencies of monthly droughts, which show a notable increase between the periods 1940–1970 and 1970–2000, followed by a relative decrease in recent years (2000–2021). In general, the characteristics of these droughts evolve in line with trends in precipitation and the number of rainy days per month observed in the highlands, as confirmed by the work of Dalila et al. (2022).

Table 1 Cumulative drought frequency by rainfall period

Années	1940/1970				1970/2000				2000/2021			
Rg Ms	Setif Eff	Setif % Cu	BBA Eff	BBA % Cu	Setif Eff	Setif % Cu	BBA Eff	BBA % Cu	Setif Eff	Setif % Cu	BBA Eff	BBA % Cu
S	19	63	18	60	18	60	23	77	12	63	10	50
O	17	57	16	53	18	60	20	67	12	63	13	65
N	20	67	20	67	16	53	21	70	11	58	8	40
D	11	37	10	33	18	60	23	77	13	68	14	70
J	18	60	10	57	20	67	17	57	10	53	13	65
F	17	57	15	50	17	57	14	47	10	53	15	75
M	16	53	15	50	15	50	15	50	12	63	10	50
Av	16	53	17	57	18	60	18	60	7	37	9	45
Ma	16	53	17	57	18	60	18	60	8	42	14	70

Note: Region: Rg; Dry months: Ms; Number of employees: Eff; Cumulative : % Cu; Bordj Bou Arreridj: BBA

3.2 Agroclimatic droughts

Climatic droughts, followed more markedly by agroclimatic droughts (Figure 4), reveal the frequent occurrence of dry spells during which the duration of droughts exceeds 10 to 15 days over 30-day periods, with probabilities greater than 60%. From the 20th day onwards, these probabilities decrease slightly, fluctuating between 40% and 55%. These results reflect high variability and a certain irregularity in precipitation, characterised by alternating rainy and dry days, without sufficient continuity to meet the water needs of crops.

This climatic behaviour confirms the prevalence of severe droughts that shape the agricultural climate of the Hauts Plateaux, particularly in the regions of Sétif and Bordj Bou Arreridj. This variability, which directly impacts the planning and yields of rain-fed cereal farming, is part of a dynamic observed in other Maghreb countries. Studies conducted in Tunisia (Amri et al., 2011) and Morocco (Hadria et al., 2020; Schilling et al., 2012) show similar phenomena of prolonged and fragmented droughts, affecting the regularity of effective rainfall and compromising crop cycles. These findings highlight the urgent need to develop regional adaptation approaches based on relevant agroclimatic indicators.

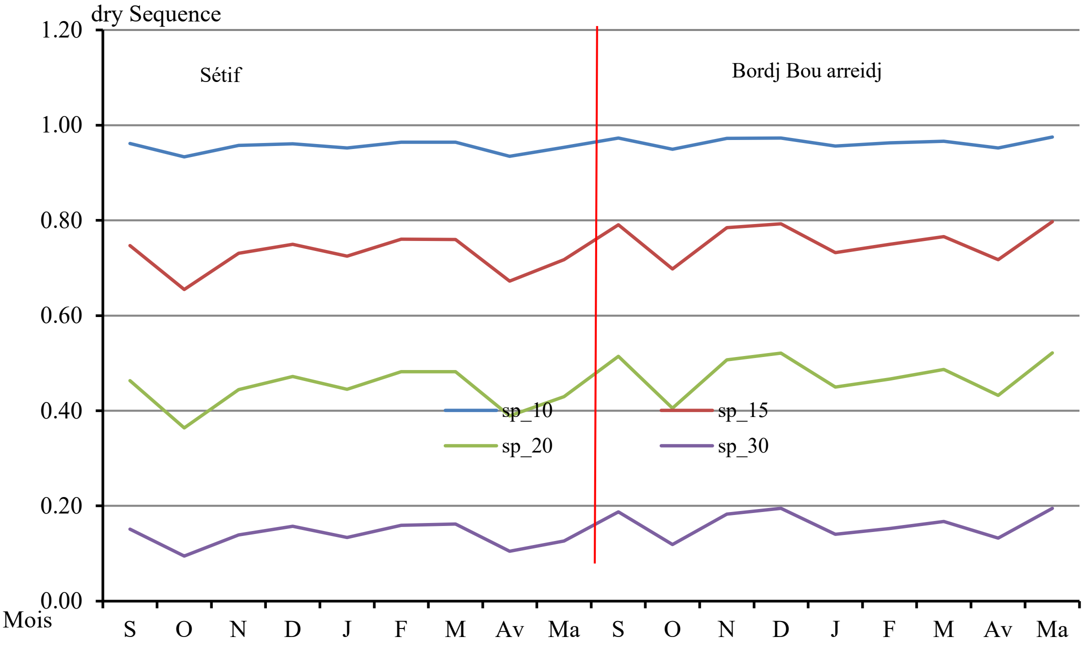

Figure 4 Probability of agricultural droughts in the semi-arid highlands of Sétif and semi-arid Bordj Bou Arreridj

3.3 Climatic and agroclimatic drought and vulnerability of cereal growing

Cereal growing in the high plains of Sétif and Bordj Bou Arreridj is predominantly rain-fed and extensive, synchronised with the rainy season. The main crops grown are durum wheat, common wheat, barley and oats, with areas varying from one crop to another. Over the last twenty years, the average area allocated to cereal growing has been 168,874 ha in Sétif and 83,094 ha in BBA.

Table 2 Distribution of average areas sown, production and yields

Agricultural factors	Sétif			Bordj Bou Arreridj		
Periodes	1940/1970	1970/2000	2000/2021	1940/1970	1970/2000	2000/2021
Surfaces (ha)	168802	168874	168833	82397	83094	82702
Productions (q)	1152166	1906257	1482081	533752	883895	686939
Yields (q ha^{-1})	7,1	11,1	8,9	6,4	10,5	8,2

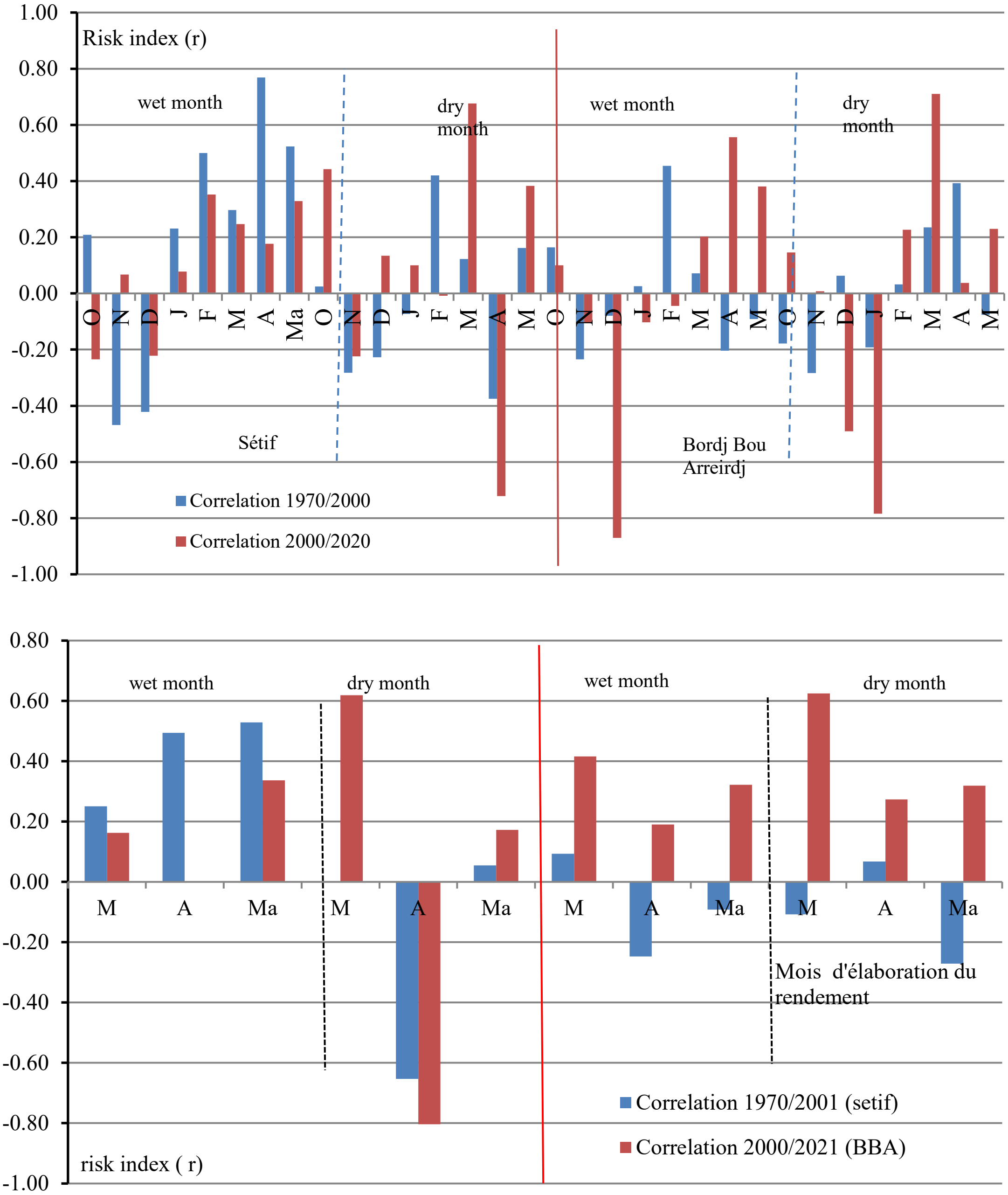

Figure 5 Impact of droughts and vulnerability of cereal crops to production in wet (wet months) and dry (dry months) conditions

The productions and yields obtained are often attributed to drought conditions, characterised by a lack of rain. The correlation matrices between the various drought, production and yield factors, evaluated on a monthly basis from September to May, are represented by both positive and negative values. These values, assimilated to risk indices 'r', are summarised in Figure 5. There is considerable variability in the indices, reflecting the years considered wet and those defined as dry (Figure 5).

In Sétif, during wet years (e.g. 1979/80; 1981/82; 1984/85; 1988/89; 1997/98; 1995/96; 1991/92; 1974/75; 1994/95; 92/93; 1999/00; etc.), the monthly risk indices at the start of the season (October to January) vary between 0.08 and 0.23, highlighting the vulnerability of the crop during the critical phases from sowing to tillering. This vulnerability tends to decrease between February and May, with values ranging from moderate (r=0.18) to high (r = 0.77), depending on the year and month in question. These indices highlight the crop's exposure to climatic hazards during key stages of its development: stem elongation and heading (February), tillering (March), fruiting (April) and grain filling/maturation (May).

In Bordj Bou Arreridj, during wet years (e.g. 1981/82, 1991/92, 1994/95, 2002/03, 2010/11, 2017/18, etc.), high vulnerability is observed throughout the growing season, although the months of March (r = 0.62), April (r = 0.27) and May (r = 0.32) play a decisive role in final yields.

On the other hand, during dry years, whether in Sétif or Bordj Bou Arreridj, most months have indices close to zero or negative, indicating high levels of water stress. This situation reflects unfavourable agroclimatic conditions, significantly compromising cereal production potential.

These results are consistent with similar findings in Tunisia (Slama et al., 2005), where the impact of droughts on cereal production has been documented, as well as in the Béja region, with projections of declining yields by 2030 if no adaptation measures are taken. These dynamics are comparable to other regions of the Mediterranean basin, where rainfall variability and increased spring droughts pose critical challenges for cereal farming (Iglesias et al., 2011; Olesen and Bindi, 2002).

The similarities between the dynamics observed in Algeria and those in neighbouring countries reinforce the value of shared regional adaptation strategies. Integrating a better understanding of risk indices and their monthly variability is a strategic lever for adapting agricultural practices to current semi-arid conditions, as recommended in several regional agricultural climate management frameworks.

4 Conclusion

The semi-arid high plains of Sétif and Bordj Bou Arreridj show marked disparities in terms of the number of rainy days and monthly precipitation volumes recorded over an 80-year period. These climatic characteristics are the cause of climatic (precipitation ⩾ 0.1 mm) and agroclimatic (precipitation ⩾ 5 mm) droughts affecting the key months of the cereal growing season.

Although fluctuating, droughts have shown relative stability in their frequency over the last 50 years. However, there has been a notable increase in their intensity over the last two decades. These intensities, ranging from standardised values of -1.49 to +1.95 (according to the SPI), have a differential impact on the vulnerability of cereal farming in this semi-arid environment.

The agroclimatic summary, which takes into account the duration, intensity and frequency of droughts (via the SPI), highlights a real threat to agricultural activity in the wilayas of Sétif and Bordj Bou Arreridj.

The risk indices thus established highlight the need to strengthen agricultural practices by introducing more resilient varieties, adjusting sowing dates and integrating the interactions between precipitation and temperatures to better define the duration of the rainfed cereal growth cycle. This integrated approach would be an appropriate response to mitigate the effects of drought hazards and guide decision-making strategies in the country's semi-arid areas.

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