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ORIGINAL RESEARCH ARTICLE

Effects of climate change on the food security of Morocco: A case study of the Bouregreg watershed

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ABSTRACT

This study examines the impact of climate variability on agricultural systems in Morocco, with particular attention to wheat production and vegetation dynamics in a context of increasing temperature, decreasing and irregular rainfall, and heightened exposure to droughts and floods. This work aims to evaluate the magnitude and spatial extent of the combined effects of climate variability and agricultural and pastoral activities on the surface condition of the Bouregreg watershed. The specific objectives are to analyze recent climatic changes, assess their influence on plant-level alterations, and examine how agricultural and pastoral practices interact with climatic constraints to affect agricultural productivity. The study is based on an evaluation of climatic variability, including changes in temperature and rainfall patterns, alongside an analysis of vegetation dynamics as indicators of agricultural and environmental conditions within the Bouregreg watershed. Particular attention is given to inter-annual variability in agricultural yields and to the role of agricultural and pastoral activities in shaping vegetation responses to climatic stress. The analysis highlights a decline and increasing irregularity of rainfall, rising temperatures, and a high frequency of extreme climatic events, which collectively contribute to low average wheat yields and strong inter-annual variability in Morocco. Compared with other Mediterranean countries, Morocco exhibits limited technological progress in wheat production, which amplifies the sensitivity of agricultural output to climatic fluctuations. The findings indicate that national agriculture, particularly wheat production, is highly vulnerable to ongoing climatic changes. The strong dependence of agricultural performance on climate variability and land use practices suggests significant risks for the sustainability of agricultural systems and underscores the need for improved adaptation strategies to mitigate future impacts on food security.

Keywords: food security; climate change; agriculture; Bouregreg basin; Morocco

1. Introduction

Morocco's agricultural policy since 1960 has been based on a dual observation: The traditional nature of Moroccan agriculture and the weight of climatic constraints weighing on it[1]. Also, to modernize the agricultural sector and reduce the impact of climatic hazards on it, an irrigation policy is initiated by the construction of dams. This policy officially launched in March 1967[2,3].

The World Food Summit in Rome in 1995 defined food security as: "Food security exists when people, at all times, have economic, social and physical access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Food availability, accessibility, safety, and quality are the four aspects of food security. (FAO, 1996). Numerous studies on the evolution of surface conditions in Morocco and in the Bouregreg watershed in particular have been carried out[4-7]. However, these studies carried out at the level of this basin were limited to sub-areas (micro-basin) or regional areas. Previous studies thus suffer from a problem of scale of analysis both at the spatial level, but also at the temporal level concerning the study of the environmental dynamics of the Bouregreg basin. Indeed, at the spatial level, studies on micro-basins do not make it possible to understand all the dynamics of the interaction between climate, agro-pastoral activities, and their impacts on the natural environment. The studies carried out by[4,6] for example took a socio-cultural space (the Sehoul country) as their geographic framework. Also, although this space is homogeneous, at the cultural level, the research carried out is difficult to generalize to the entire basin because the physical (at the hydro-climatological, pedological, and topographical level) and socio-cultural realities often differ considerably. Research carried out on more restricted areas, such as sub-basins or homogeneous cultural areas, is a response to the need to work on a territory that is sufficiently homogeneous in both physical and human terms. This is particularly true given that remote sensing and GIS methods used to highlight the degradation of a given environment based on the temporal dynamics of the interaction between the physical environment and human actions provide much more satisfactory results for homogeneous areas than for large, heterogeneous regions. This is the case for models designed to study soil erosion, which incorporate variables related to both the physical environment and human activities[8-10]. In addition, these studies are, in many cases, interested in priority sites requiring emergency intervention, or sites with sufficiently rugged topography[11-14].

Developing regions, especially arid and semi-arid areas, face more severe consequences from climate-related disasters. The impacts particularly affect the most vulnerable communities and households in these environments, especially smallholder farmers. The negative consequences of CC on agricultural production can result in problems such as food insecurity, lower living standards, reduced well-being, and increased poverty. Furthermore, the impact of climate variability on food security manifests itself in disruptions to farmers' production and incomes, thereby hampering aspects of food availability, access, utilization, and stability[15]. The FAO (2020) estimates that between 83 and 132 million more people are undernourished globally, and by 2030, that figure could rise to 840 million (9.8%). According to UNFAO (2023), economic shocks, geopolitical situations, climate change, and extreme weather events all contributed to the worsening of the global food crisis and acute food insecurity in 2022[16].

The Bouregreg watershed is topographically made up of plains and moderately rugged plateaus (**Figure 1**). Also, the study of the degradation of the natural environment due to the combined action of human activities and the natural dynamics of the physical environment on the scale of the geographical unit of the Bouregreg watershed as a whole has never been accomplished. In addition, even if, at the regional level, the Bouregreg watershed is in the same climatic space as other humid basins such as that of the Sebou and for which certain regional studies classify them in the same agro-climatic unit[17-21]. The Bouregreg basin remains disadvantaged by its hydrogeological conditions (basin made up of impermeable formations of primary age). This geological structure does not favor the development of irrigated agriculture. Thus, the studies carried out at the level of the Bouregreg watershed, intending to make a diagnosis of the interaction between agricultural activities and their physical setting in the social, historical, and cultural environment of the basin, have paid very little attention taking into account the interweaving of several spatial levels. Remote sensing and Geographic Information Systems (GIS) offer the ability to take into account different spatial and temporal scales. It, therefore, appears that, for the study of the impact of human activities and climatic variability on vegetation and land use in the Bouregreg watershed (about 10,000 km2), it is important to adopt a multi-scale approach using images of different spatial and temporal resolution[21]. It is a question of apprehending the natural environment and the anthropized environment as elements of a dynamic system at several scales (spatial scales and temporal scales). How did the dynamic interaction between agro-pastoral activities and climatic variability impact the surface condition in the Bouregreg watershed from 1980 to 2009 and how is the temporal dynamic of this interaction expressed spatially?

This study aims to improve our understanding of how agricultural and pastoral activities interact with climate variability to degrade agro-pastoral areas within the Bouregreg watershed. Although climatic constraints and land use dynamics are frequently studied independently, the combined impact of these factors on the basin's surface conditions, particularly the intensity and spatial extent of degradation processes, remains inadequately quantified. In response to this gap, the present study examines how agro-pastoral practices influence the rate and spatial distribution of land degradation under increasingly unfavorable climatic conditions. To this end, the study investigates whether quantitative, spatially explicit analyses integrating remote sensing, geographic information systems, and statistical methods can effectively capture the relationships between changes in physical variables (e.g., climate, soil, and vegetation) and socioeconomic and demographic dynamics related to agricultural and pastoral activities, technical itineraries, and rangeland use.

2. Materials and methods

2.1. Study area

The Bouregreg watershed is located in the north-west center of Morocco. It belongs to the favorable rainfed agro-ecological zone of the Kingdom. 78% of Morocco's territory is made up of arid and Saharan areas, and only 15% of the country has semi-arid characteristics (**Figure 1**). This bioclimatic spatial distribution constitutes the basis of all the issues related to the agro-sylvo-pastoral dynamics of the country.

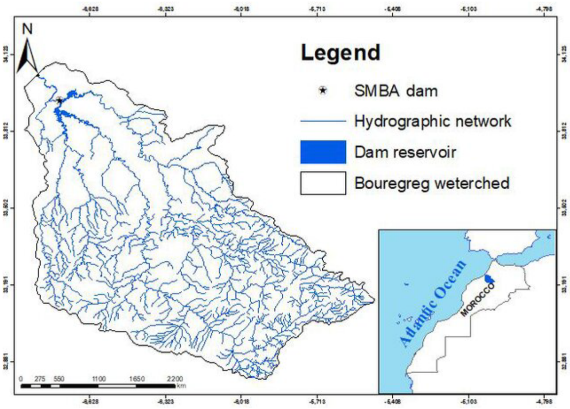

Figure 1. Geographical location of the Bouregreg watershed.

2.2. Research data

The Moroccan climate is characterized by great spatial and temporal variability of precipitation and temperature. The Bouregreg watershed, although belonging to the wet areas of the country, does not escape this climatic variability. The length of the summer drought is more accentuated. The seasonal evolution of temperatures also experiences notable variations. Rising trends mark summer minimum and maximum temperatures. As for minimum winter temperatures, they show a downward trend[22]. To summarize these variations, Moussa et al.[23] conclude that the importance of spring and autumn has diminished. The Moroccan climate tends towards a bi-seasonal climate: winter-summer. The analysis of the interannual evolution of the climate of Morocco obeys the general evolution observed in the African climate: that of a substantial drop in precipitation since the 1970s or 1980s and a rise in temperatures.

The low spatial resolution images used for this study are NDVI (Normalized Difference Vegetation Index) vegetation index images and surface temperature images. These images are provided by AVHRR (Advanced Very High-Resolution Radiometer) sensors from NOAA and Terra from MODIS (**Figure 2**). Low-resolution images have the advantage of making it possible to analyze, at a fine temporal rate, the seasonal and interannual dynamics of plant cover or the evolution of climatic or water conditions for vegetation development. The NOAA images used for this study are images of 8 km spatial resolution and 15 days of temporal resolution. They come from the GIMMS program (Global Inventory Modeling and Mapping Studies).

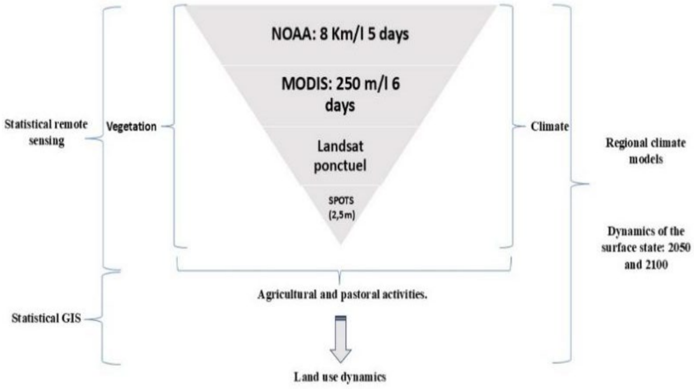

Figure 2. General methodological scheme.

3. Results

3.1. Water availability and agricultural activities

The agricultural sector remains one of the fundamental pillars of Morocco's economy. It represents 13 to 23% of the Gross Domestic Product. Analyzes of the evolution of the Moroccan economy show a strong correlation between the evolution of agricultural performance and that of GDP. Agricultural production is itself very influenced by the variation in rainfall quantities. The Bouregreg watershed is thus intended mainly for rain-fed agriculture. The autumn season, which corresponds to the beginning of the growing season and during which agricultural land is bare and prepared for annual crops (mainly cereals and legumes), is the period of greatest degradation linked to soil erosion. The dynamic interaction between agricultural activities and natural development conditions has led, in the Bouregreg basin, to significant degradation of the agronomic qualities of the soils by erosion and loss of their physico-chemical qualities. This ultimately leads to stagnation or even a significant drop in the yields of certain crops such as cereals and legumes.

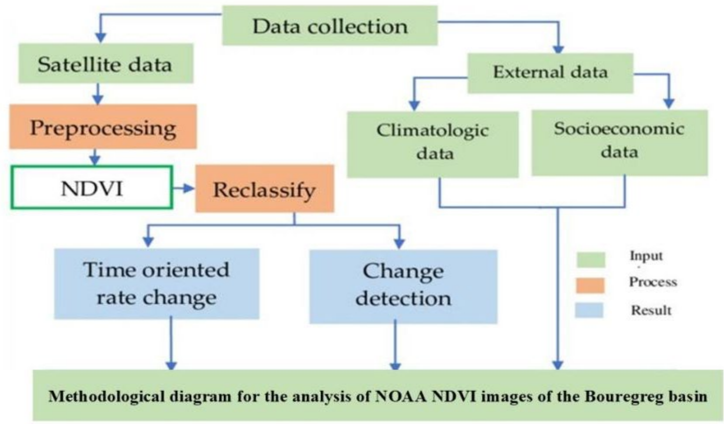

Figure 3. Methodological diagram for the analysis of NOAA NDVI images of the Bouregreg basin.

In this instance, we are examining the vegetation mass from 1982 to 2009 as well as the vegetation's phenological state from 2000 to 2009. This is accomplished by extracting the vegetation index photos that are compiled for this time series monthly as a text file and exporting it to an Excel spreadsheet (**Figure 3**). A table with 184 columns and 28 rows that shows the values of every pixel in an image at the same location every year is the result for a certain month. The dynamics of the vegetation in this 8 km2 area from 1982 to 2009 are then ascertained by using a trend test for each column. The Mann-Kendall test (with seasonality) was selected as the trend test. The tests show robustness serves as the driving force behind this decision.

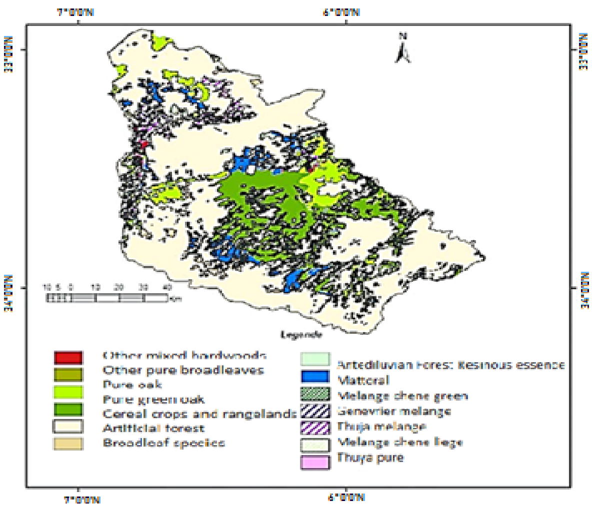

Figure 4. Main vegetation of the Bouregreg watershed[26].

The Bouregreg catchment area as illustrated in **Figure 4** is located in the centre-north-west of the Kingdom of Morocco. It is a Mediterranean basin located between parallels 32°50 and 34°30 N and meridians 5° and 7° W. With a surface area of 9,800 km2, it is bounded to the north and north-east by the Sébou basin, to the south and south-east by the Oum Er-Rbia basin, and the west and north-west by the Casablanca coastal basins and the Atlantic Ocean. The Bouregreg catchment area is drained by three main hydrological arteries: the Bouregreg wadi, the Grou wadi, and the Korifla wadi. The soil and climatic conditions in the Bouregreg basin give rise to predominantly sclerophyllous vegetation.

3.2. Agricultural calendar focused on cereal farming and extensive livestock

Wheat cereal growing remains the main agricultural activity in the Bouregreg basin. The agricultural calendar is therefore dominated by this crop. Other crops such as pulses and oilseeds occupy modest areas. In terms of cereals, the sowing period for wheat (soft or durum) extends from November 15 to December 15. The harvest is carried out between June 15 and July 10. Barley, which is the second cereal (in order of importance of cultivated area), has a longer sowing period: from November 1 to January 31. This cereal is harvested from June 01 to June 15. Maize remains a spring crop. It is sown from March 01 to March 15. The harvest of this cereal takes place from June 01 to June 30. Legumes (dry broad bean, dry common bean, lentil, chickpea) all follow the same agricultural calendar. They are sown from November 15 to December 15 and harvested from May 1 to May 20. Finally, oilseeds (peanuts, beets, soybeans, sesame) have a much less homogeneous calendar than the previous crops. Peanut and soybean are spring crops, sesame is a spring and summer crop, beet spans wider seasons (**Figure 5**). The global seasonal dynamics of cultivated plants is thus dominated by the cultivation of wheat. The pastoral calendar concerns two categories of animals: cattle and sheep and goats. In terms of cattle, the breeding system has three variants in Morocco: dairy farming in irrigated areas; the mixed system and beef cattle farming[24]. The Bouregreg watershed is affected by the last two systems and mainly the beef cattle system. The mixed livestock system is characterized by the absence (or very limited supply) of irrigated fodder crops. This system is also characterized by the marketing of milk. As for the beef cattle system, the milk is intended for family consumption[19].

The calendar of the agro-pastoral system is structured as follows: - Grazing on rangelands and fallow land from January to May; -Stubble grazing from June to October; - Consumption of straw, cereals from September to March.

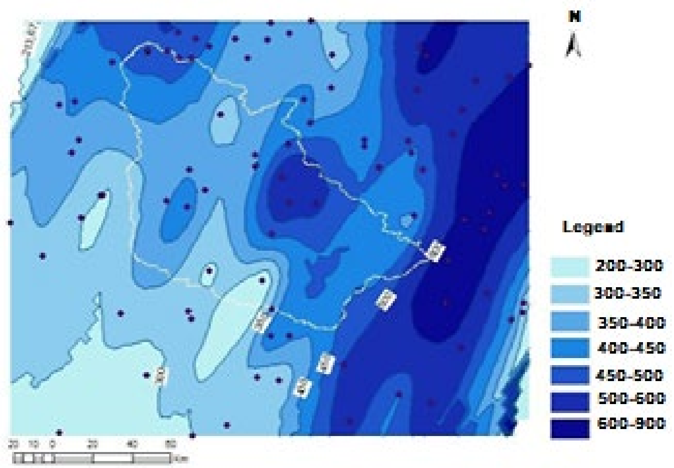

Figure 5. Spatial variation of average annual rainfall in the Bouregreg basin (average from 1980 to 1999)[26].

3.3. Climate

The region's climate is semi-arid. The average annual rainfall varies between 350 and 400 mm (**Figure 6**). The Bouregreg catchment has a semi-arid Mediterranean climate. Average rainfall is estimated at 440 mm. Generally, rainfall decreases with latitude, following a gentle gradient. Temperatures are also unimodal. The hot season corresponds to the period between April and October.

Table 1. Area of main agricultural production in the region (Average from 1995 to 2003) in (ha).

Production	Area	
	Ha	%
Cereals	244.550	66
Legumes	28.240	7.5
Fruit plantations	21.101	5.6
market gardening	7.151	1.9
Fodder crops	18.500	5
Industrial crops	2.420	0.6
Tropical crops	2190	0.6

The cold season is between November and March. The mountain zone has extreme temperatures, with over 33.8°C in summer and less than 3°C in winter. The coastal zone remains moderate, with an average temperature that does not fall below 12°C in winter and does not exceed 24°C in summer[25]. The average yields of the main crops obtained which are presented in (**Table 1** and **Table 2**) are low compared to the yields achieved in some pilot farms, indicating that the potential of the region is not exploited.

Table 2. Yields achieved for the main crops of the region in (Qx/ha) (DPA Khemisset, 2004).

Spices	Average of Yield
Cereals	
Soft wheat	11.11
Durum wheat	9.8
Barley	9.6
But	6.5
Triticale	19.0
Legumes	
Bean	7.3
Pea	7.3
Lens	7.5
Chickpea	7.7
Bean	7.1
Fodder crops	
oats	30
Feed barley	14.7
Rye	28.7
oat vetch	34.4
Lupine	33.6

3.4. Seasonal and multi-annual dynamic study of vegetation from 1980 to 2009 using low spatial resolution images

The spatiotemporal analysis of vegetation in 8 km2 grids reveals particular dynamics in certain areas, contrasting with the general dynamics of the basin as a whole (**Figure 7**). In fact, in the first fortnight of September, there is a certain balance between areas marked by negative trends (downstream, center and south of the basin) and areas marked by positive trends (upstream north of the basin)[20]. The weak negative trends in plant activity are located on the outskirts of the Rabat-Salé urban area. As for the strong negative trends marked by breaks, they are located in the agricultural and matorral zones to the south of Maaziz (center of the basin) and to the north of Boukhrisse (southeast of the basin)[21,24]. The breaks in the chronological series of these negative trends occurred in 1998 (with more or less one year). In contrast to these areas with negative plant dynamics, the interior of the cork oak and holm oak forests located on the high plateaux upstream of the basin is experiencing positive trends, with positive breaks in some places in 1990-1992. In October, there was a strengthening of the positive trend in plant activity in the previously marked areas upstream of the basin[22].

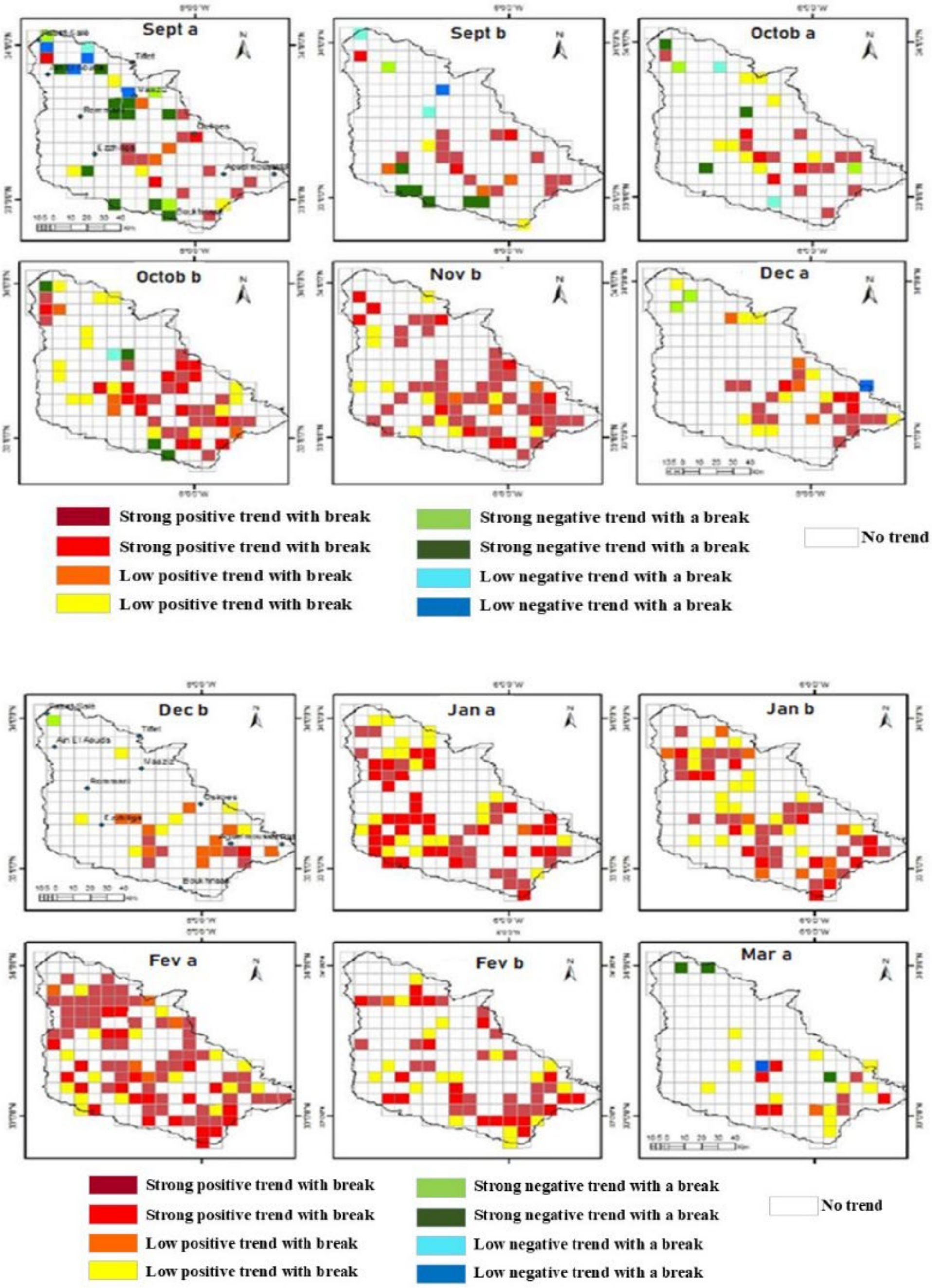

Figure 6. Spatio-temporal evolution of vegetation from the first half of September to the first half of March (NOAA 1982-2009)[26].

In the first half of October, vegetation trends in the south-east were still negative. In the second half of October, positive trends in vegetation activity spread across the whole basin. Strong positive trends with a break were observed upstream in the basin, but also downstream, around the town of Ain El Aouda. The centre of the basin continues to show weak positive trends. November appears to be the month at the start of the agricultural season that has seen the most positive growth in plant activity. Indeed, most of the basin is marked by strong upward trends in plant activity, with positive breaks in the time series for each 8 km2 grid cell[4].

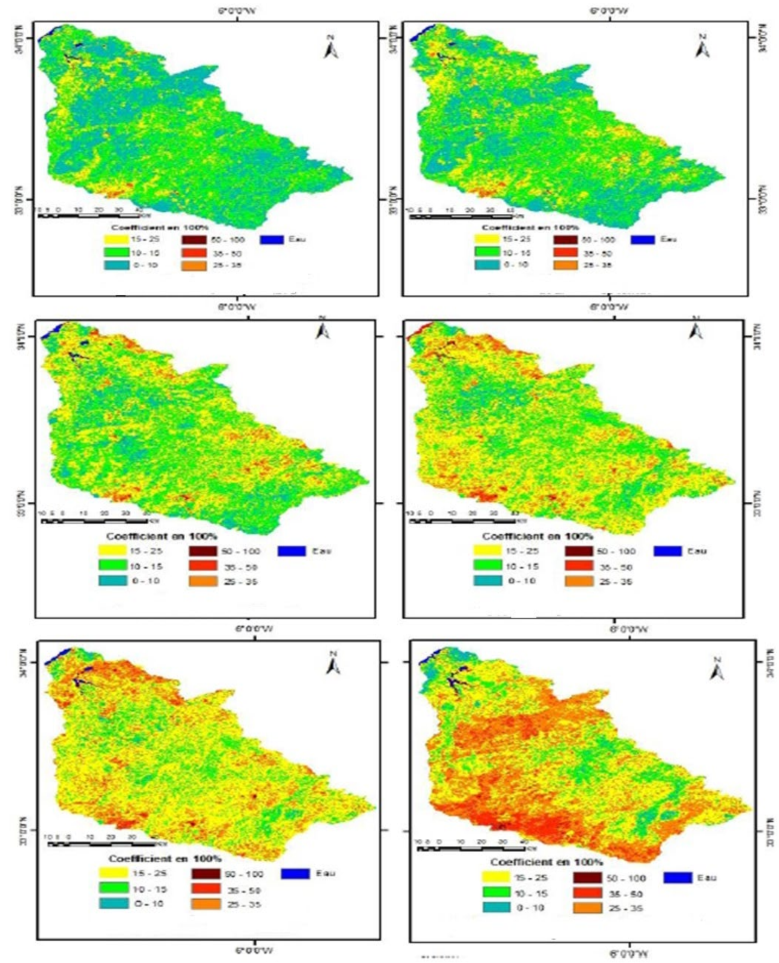

Figure 7. Variation in the vegetation cover of the Bouregreg basin at the start of the agricultural season (MODIS 2000-2009)[26].

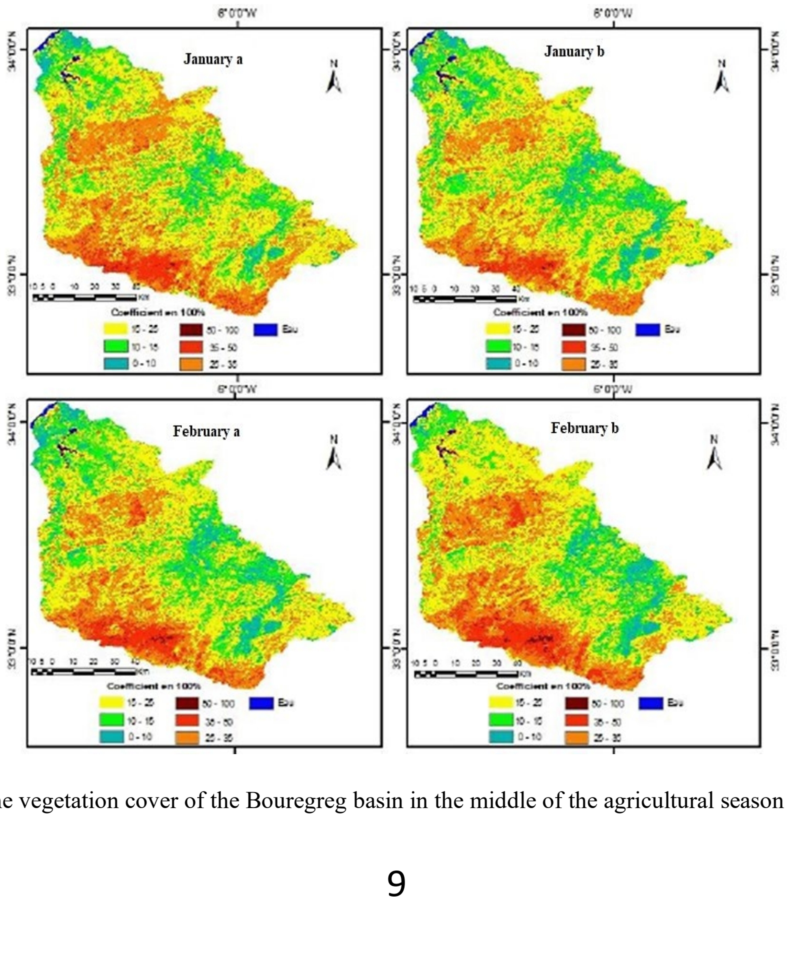

Figure 8. Variation in the vegetation cover of the Bouregreg basin in the middle of the agricultural season (MODIS 2000-2009)[26].

Analysis of the spatiotemporal variation in vegetation using MODIS NDVI images (2000-2009 period) gives a detailed idea of the dynamics observed between 1982 and 2009 using NOAA images. These images can also be used to highlight the dynamics of land use. For example, during the first two weeks of September, vegetation variations remain low across the whole basin[7]. The most significant vegetation activity (coefficient of variation greater than 15%) was observed mainly in forested areas, with agricultural areas still mostly bare (**Figure 8** and **Figure 9**). Variations in plant activity become increasingly significant as the agricultural season progresses. Thus, they are logically greater in October than in September. In the first half of October, the areas of moderate to strong variation (coefficient of variation greater than 35%) in vegetation from one year to the next are located in a few agricultural areas in the downstream north of the basin and in the upstream plateaux. In the second half, almost all the agricultural areas upstream and downstream are marked by significant variations. Only the centre of the basin and the forested areas experienced slight variations in vegetation over time (less than 15% coefficient). In November, the spatial and temporal variations in vegetation cover from one year to the next are significant and gradually extend to all agricultural areas[6,26].

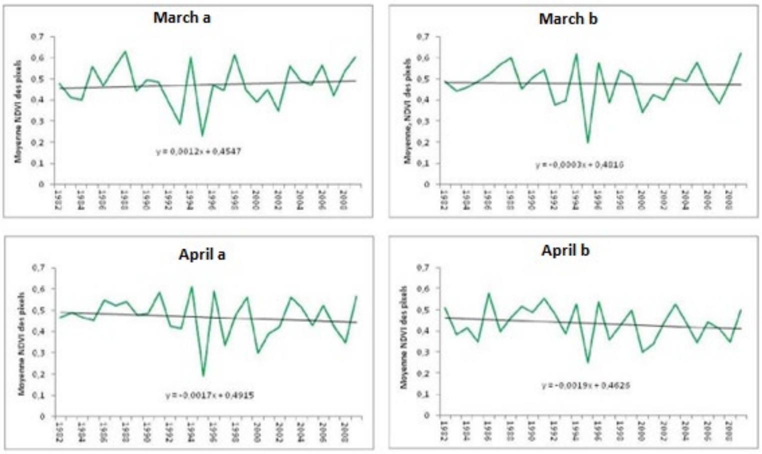

Figure 9. NDVI evolution curve: annual average of all pixels in March and April[26].

The months of January and February correspond to the optimum growth period for cultivated vegetation. The temporal dynamics of plant activity over the period 1982-2009 show the same pattern for this period. The temporal evolution of vegetation is characterized by three sequences: a positive sequence from 1982 to 1990, a negative sequence from 1990 to 1995 and a second positive sequence from 1995 to 2009 (**Figure 10**). The slopes of the vegetation change curve from 1982 to 2009 remain significantly positive overall. The change in vegetation during the 1982-1990 sequence compared with the start of the series (1982) is significant overall over this period. In January, the increase was 48% in the first fortnight and 41% in the second fortnight. In February, the sequence corresponds to an increase of 37% in plant activity in the first fortnight and 9% in the second fortnight[11,27-29].

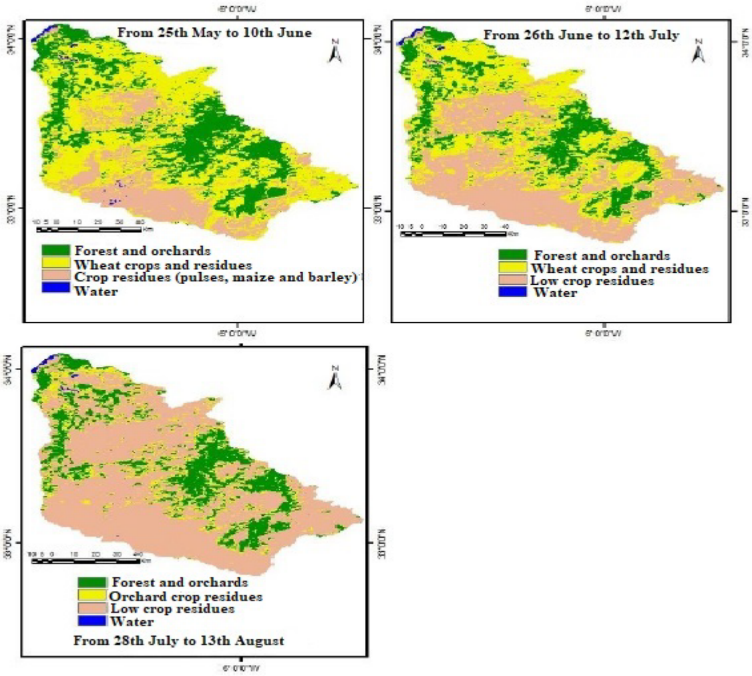

Figure 10. General land cover map at the end of the agricultural season (MODIS 2000 to 2009)[26].

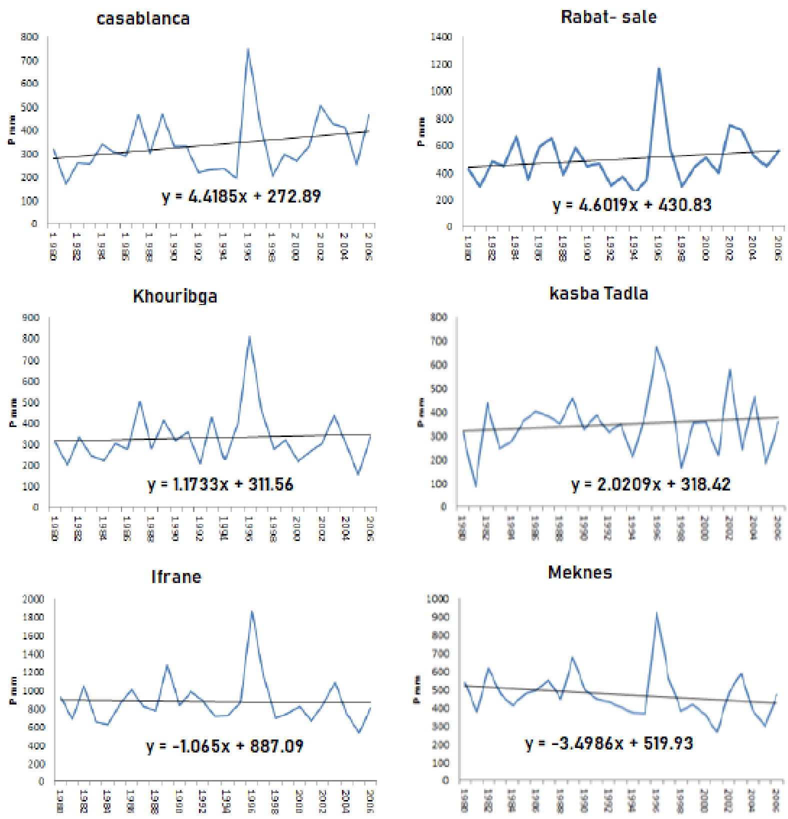

Figure 11. Curve of inter-annual evolution of rainfall in the space of the Bouregreg Basin[26].

Average monthly rainfall variations from one year to the next are high (**Figure 11**). The Meknès and Ifrane stations show a negative balance in the evolution of rainfall quantities, while the coastal stations show the highest Kendall rates. At a significance level of 5%, only the Meknes station confirms a downward trend in interannual rainfall. Also, observation of the coefficients of variation shows that the downward or upward trends in rainfall are not linear. The coefficients of variation are significant from one year to the next. Except for Meknes, where the coefficient is less than 30% (28%), all the stations have coefficients of variation in rainfall between 30 and 40%. Deviations from annual averages are greater than 120 mm everywhere. This reflects the complexity of modeling these interannual rainfall dynamics. The Meknes and Ifrane stations show a function marked by a continuous decline, with a few exceptional years 88 characterized by significant increases[17,18,30-32].

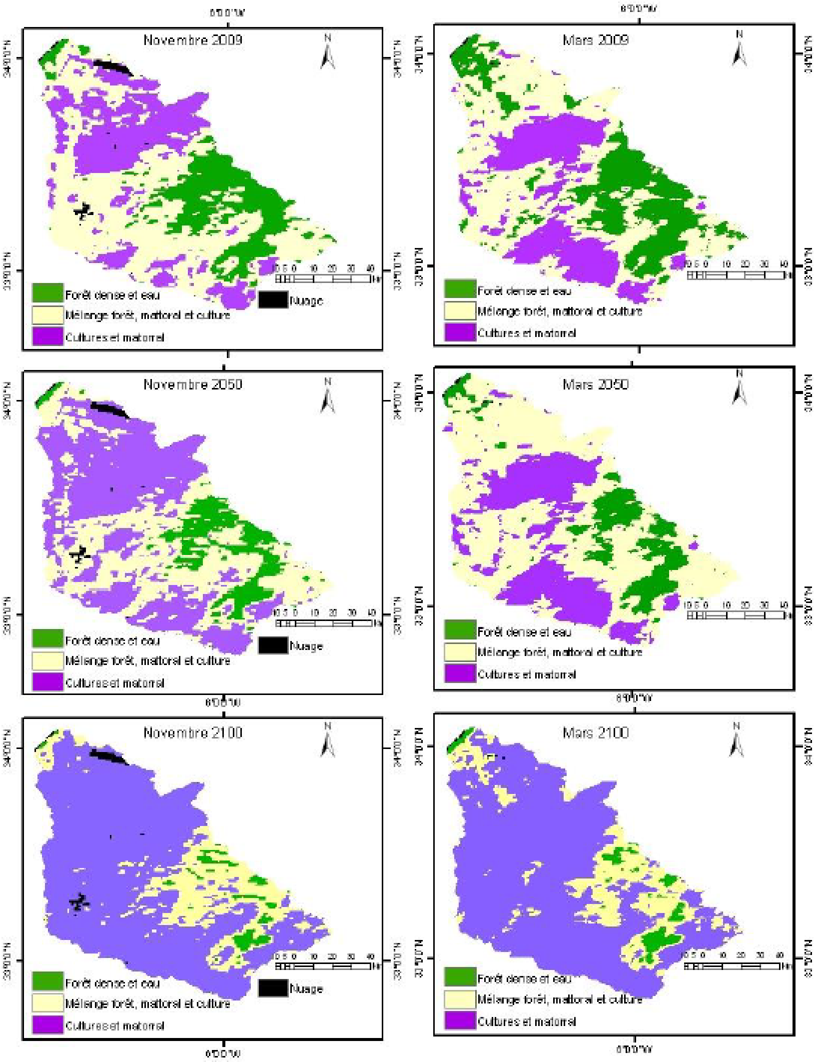

Figure 12. Evolution of vegetation determined from surface temperatures of MODIS and MCR-CNRM images (SIGMED, 2012)[26].

This difference is 14°C in March. This can be explained by the fact that, apart from the technical aspects of modelling, the area covered by the RCM is significantly larger than the basin. However, areas close to the Bouregreg basin, such as the mountainous areas to the east, are often snow-covered or have very low temperatures. Thus, the general observation that emerges from the future evolution of the vegetation cover is that the dense forest formations upstream and the cork oak forests downstream of the basin are likely to disappear or be considerably degraded (**Figure 12**). The rate of degradation is low until 2050. By 2100, the surface temperatures that used to be characteristic of woodland should be no more than residual patches, giving a degraded woodland landscape in an environment of matorral under agricultural and pastoral pressure.

4. Conclusion

The analysis of the Bouregreg watershed reveals significant spatial and temporal variability in rainfall, organized along north-south and east-west gradients. This variability directly impacts vegetation dynamics and agricultural productivity in an environment with fragile soils. The results reveal a clear correlation between interannual fluctuations in cereal yields and critical meteorological parameters, confirming the vulnerability of agro-pastoral systems to climatic hazards, especially drought and reduced crop growth periods. This vulnerability is further exacerbated by unsustainable agricultural practices that intensify vegetation stress and land degradation. Using remote sensing and GIS was effective in capturing these interactions across nested spatial scales and quantifying the links between climate variability, plant-level changes, and agricultural production. These findings underscore the necessity of continuous spatial and temporal monitoring, as well as the integration of agricultural simulation models. This integration would enhance the early detection of agricultural drought, facilitate the anticipatory planning of wheat imports, and bolster food security in the face of ongoing climate change.

Author contributions

Conceptualization, H. O. and K. EL.; methodology, J. M; software, A. A.; validation, Z. T., J. M. and H. O.; formal analysis, A. L.; investigation, H. O.; resources, H. O.; data curation, K. EL.; writing—original draft preparation, H. O.; writing—review and editing, K. EL.; visualization, Z. T.; supervision, J. M.; project administration, A. A.; funding acquisition, A. L. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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