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Geostatistical Modelling of Soil Physicochemical Variability for Improved Irrigation Management in Béni-Amir, Morocco

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Abstract: Irrigated areas in Morocco are increasingly affected by climate change and the intensification of agricultural practices, particularly in arid and semi-arid zones. The Beni-Amir irrigation area, located in the Tadla plain (central Morocco), illustrates this degradation dynamic. This study analyzes the spatiotemporal variability of certain physicochemical properties of the soil at a depth of 0 to 20 cm, in particular organic matter (MO) (2015 and 2019), pH, and electrical conductivity (EC) (2013 and 2023), as indicators of soil quality. The geostatistical approach is an innovative method that allows data to be estimated taking into account their spatial dependence and uncertainty. The results show a moderate increase in organic matter content, from 2.89% (2015) to 3.58% (2019). The pH increased slightly to 8.32 in 2023, reflecting a trend towards alkalization. Electrical conductivity increased significantly, from 1.56 dS/m (2013) to 8.14 dS/m (2023), indicating an advanced process of salinization. The maps obtained by geostatistical interpolation reveal strong spatial heterogeneity, with localized areas of high salinity, particularly in the east and southeast of the perimeter. The spatial distributions of pH and organic matter also highlight different dynamics depending on the intensity of agricultural practices. These results highlight the combined effects of anthropogenic pressures and climatic hazards on soil quality in Beni-Amir. The sustainability of agricultural systems in this context depends on integrated and spatialized management of soil and water resources, the implementation of appropriate crop rotations, and targeted soil conservation and rehabilitation strategies.

Keywords: Physicochemical parameters, Spatial interpolation, Kriging, Irrigated Perimeter.

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1 Introduction

Climate change has emerged as a major driver of environmental change during the last two decades, contributing to greater exposure to natural hazards and placing increasing pressure on agricultural systems. These challenges are especially significant in countries where agricultural activities play a central role in ensuring food availability and supporting food security [1]. Alongside these climate challenges, soil degradation caused by unsustainable management has become a major environmental concern on a global scale [2], [3]. Morocco has experienced a substantial deterioration in its water resources over recent decades. Since the 1960s, the country's renewable water availability has decreased by approximately 70%, bringing per capita resources to less than 500 m^3 annually, a level commonly associated with severe water scarcity [4]. This growing water stress has also affected agricultural production, particularly cereal cultivation.

According to the Moroccan Ministry of Agriculture, cereal yields declined by nearly 40% during drought-affected years, including 2016 and 2020. Similarly, FAO estimates indicate that prolonged drought conditions have reduced cereal production by more than 40% relative to the long-term average [5]. Unsustainable agricultural practices, demographic pressure, and limited irrigation infrastructure exacerbate these difficulties. Irrigated agriculture constitutes a major component of Morocco's agricultural economy; however, the sector is increasingly affected by a range of constraints that may hinder the achievement of long-term and sustainable agricultural development [6]. Situated in central Morocco, the Tadla irrigated perimeter represents a historically established agricultural area and remains an important contributor to the country's agricultural production. It comprises an agricultural area of 300,000 hectares, of which 124,600 hectares are irrigated [7], [8]. Understanding the spatial heterogeneity of soil characteristics is fundamental to accurate soil mapping and efficient fertilizer management, while providing valuable information for a broad range of agricultural and environmental applications [9], [10], [11]. However, these properties vary over time and space [12]. These spatiotemporal variations result from a complex interaction of intrinsic and extrinsic factors. Intrinsic factors can be physical, chemical, or biological, while extrinsic factors are mainly related to human activities, such as the use of chemicals, tillage, and irrigation [10]. Analyzing the spatiotemporal variability of soil organic matter (OM), alkalinity (pH), and electrical conductivity (EC) is essential, but accurate measurements are often costly and time-consuming [13], [14]. As a result, sampling data are generally limited and do not always reflect total variability. Reliable estimation of soil attributes at locations where no direct observations are available is an important requirement for evaluating soil quality.

Advances in digital soil mapping have made it possible to characterize and monitor the spatial and temporal variability of soil properties across different observation scales [15], [16], [17]. Among the available approaches, kriging is widely used as a geostatistical interpolation method because it can estimate soil attributes at unsampled locations from measurements collected at sampled sites. In addition to providing statistically optimized predictions, this approach enables the spatial characterization of prediction uncertainty and the associated estimation errors [18], [19]. Despite the potential of geostatistical approaches, the spatiotemporal characterization and prediction of soil properties in Morocco remain relatively underexplored, particularly in terms of their application to reliable spatial estimation [20].

Our study focuses on the irrigated area of Beni-Amir, covering 33,000 hectares in the Tadla plain in Morocco, which is under significant demographic pressure and agricultural intensification. These pressures intensify the unsustainable exploitation of natural resources, especially soil and water resources. Agricultural practices are largely based on soil cultivation and are mainly characterized by the cultivation of cereals, sugar beets, market gardening and fodder crops, fruit growing, and livestock farming. Agricultural production in the perimeter generally depends on the physical and chemical properties of the soil and climatic conditions. The present research applied kriging-based geostatistical analysis to characterize the spatial distribution and temporal evolution of selected soil physicochemical attributes within the 0–20 cm surface layer. The analysis focused on organic matter content for 2015 and 2019, as well as soil pH and electrical conductivity for 2013 and 2023. Based on these estimations, the study aimed to evaluate changes in soil quality over space and time and to delineate areas showing evidence of organic matter decline, increasing alkalinity, and salinity development.

2 Materials and methods

2.1 Study area

The Tadla Plain is located approximately 200 km southeast of Casablanca in the province of Fquih Ben Salah (Fig. 1). It covers a large area, estimated at 3,600 km^2, of the middle basin of the Oum-Er-Rbia between the High Atlas Mountains to the south and the Phosphate Plateau to the north [21]. The study area, Beni-Amir, is an irrigated sub-perimeter of Tadla. It is irrigated by water from the Oued Oum Er Rbia. Groundwater has a salt concentration of 1 g/L, while the salinity of the river reaches 2.25 dS/m [22]. The Béni-Amir perimeter has a generally regular relief, with an average elevation of approximately 400 m. The regional climate is characterized by semi-arid Mediterranean conditions, with relatively cool and wet winters and hot, dry summers. Annual rainfall is limited and irregular, while summer precipitation is generally scarce. Recorded temperatures range from approximately 0–5 °C during winter to 38-42 °C during summer. Annual evaporation is high, reaching approximately 1796 mm, with values generally ranging between 1500 and 2000 mm [22]. The geological formations consist mainly of marl, sandstone, and limestone from the Paleozoic and Quaternary periods [23], [24], [25].

2.2 Measured data

A total of 13 agricultural soil samples were collected from the 0–20 cm surface layer within the Béni-Amir area of the Tadla Plain. These samples, taken during the winter, were analyzed for OM in 2015 and 2019. Measurements of soil pH and EC were taken in 2013 and 2023. The soil sampling points are shown in Fig. 2. After sampling, the analyses were carried out in the soil, water, and plant analysis laboratory at the ORMVAT environmental office (GIS and remote sensing).

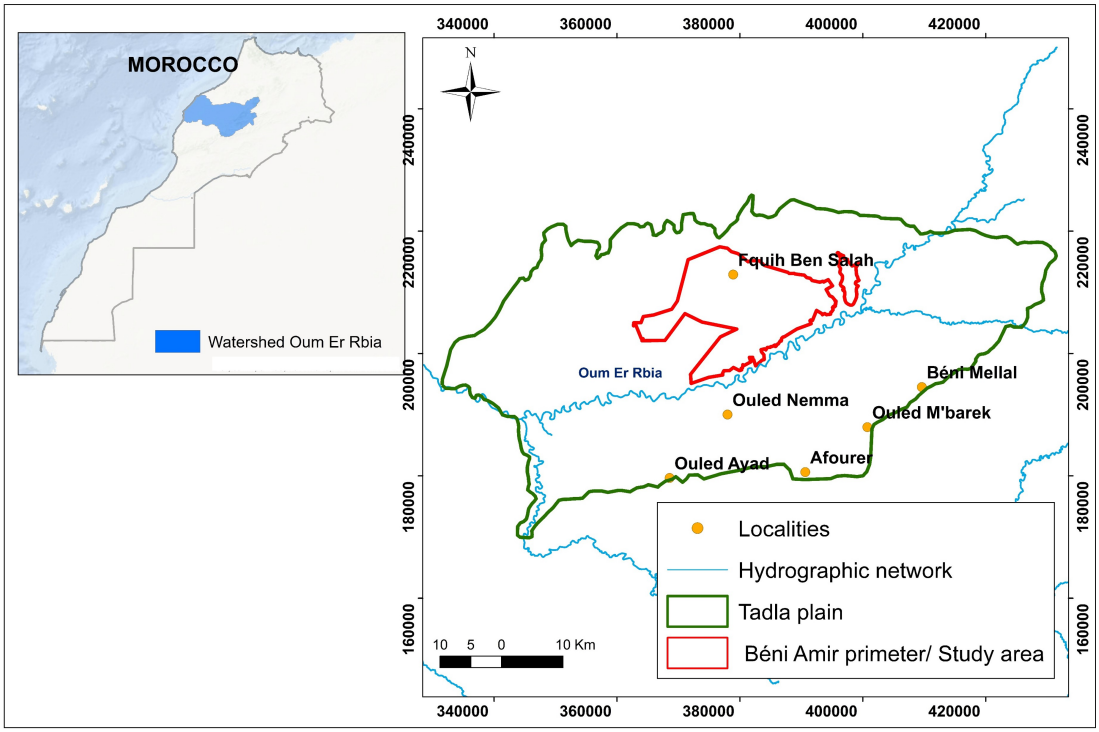


Fig. 1. Study area geographical location.

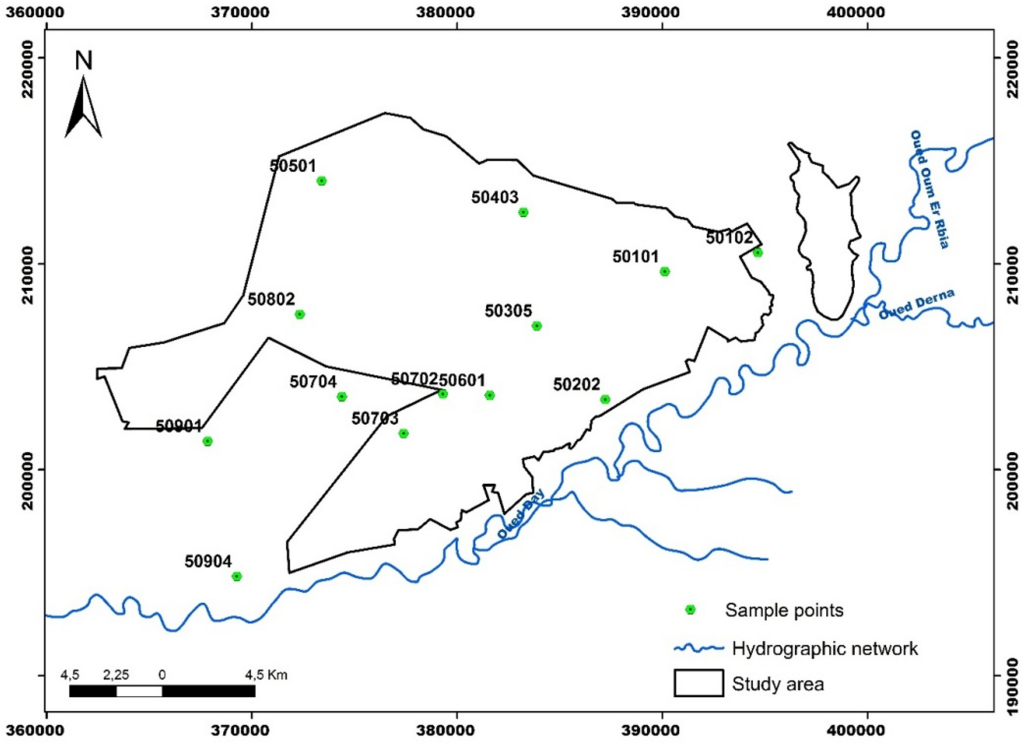


Fig. 2. Spatial distribution of soil sampling sites within the study area.

2.3 Soils quality analysis

A total of 13 soil samples were collected at a depth of 0 to 20 cm, using a reasoned sampling approach. This method made it possible to compare data from two distinct periods in order to assess the long-term effects of agricultural management and climatic variations, such as droughts or rainfall, on soil quality. It is crucial that all parameters be measured during the same sampling period to ensure data consistency, using a reasoned sampling approach between two different periods. The points were distributed to cover the main agricultural units in the irrigated area, including field crops, market gardening, and arboriculture,while taking into account logistical and accessibility constraints. Although the number of points is limited, this strategy makes it possible to capture major spatial trends and test the relevance of geostatistical modelling.

2.4 Geostatistical interpolation and evaluation

To analyse the spatial patterns of soil organic matter, pH and electrical conductivity, we applied a geostatistical approach adapted to the limited dataset (13 samples collected at 0–20 cm). An exploratory spatial data analysis was first conducted to verify the distribution of variables and to evaluate spatial continuity. Spatial dependence was examined through the empirical semivariogram, computed using Eq. (1):

$$\gamma(h) = \frac{1}{2N(h)} \sum [z(x_i) - z(x_i + h)]^2 \tag{1}$$

where h is the separation distance. The presence of structured variability justified the use of ordinary kriging. Ordinary kriging (OK) was applied separately for each parameter and each year, using a manually adjusted variogram model consistent with the empirical structure. A spherical model was selected based on visual agreement between the empirical semivariogram and the theoretical curve, and its nugget, sill and range parameters were tuned iteratively to stabilize the kriging system.
Kriging estimates were computed as a weighted linear combination of observations:

$$\hat{z}(x_0) = \sum_i \lambda_i z(x_i) \tag{2}$$

with weights constrained so that:

$$\sum_i \lambda_i = 1 \tag{3}$$

This approach is widely used in soil mapping under sparse sampling conditions [12], [17]. For comparison, the Inverse Distance Weighting (IDW) method was also applied using the classical distance-decay rule:

$$\hat{z}(x_0) = \frac{\sum_i z(x_i)/d_i^p}{\sum_i 1/d_i^p} \tag{4}$$

where d_i is the distance between the prediction location and each sampled point. The predictive performance of both methods was assessed through leave-one-out cross-validation (LOOCV). For each location, the observed value was compared with the prediction obtained using the remaining points. Prediction accuracy was expressed using the mean error (ME):

$$ME = \frac{1}{n}\sum_{i=1}^{n}[z(x_i) - \hat{z}(x_i)] \tag{5}$$

and the root mean square error (RMSE):

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}[z(x_i) - \hat{z}(x_i)]^2} \tag{6}$$

For example, the semivariogram equation can be referenced as Equation (1), while the kriging estimator can be referenced as Equation (2). The IDW estimator is given in Equation (4), whereas the prediction error and RMSE are given in Equations (5) and (6), respectively. In addition to the prediction maps, a kriging variance surface was generated to visualise the spatial distribution of uncertainty. Given the small number of soil samples ($n = 13$), kriging predictions and cross-validation metrics must be interpreted cautiously, and the variogram model should be understood as an approximate representation of spatial dependence rather than a fully optimized structure.

3 Results and Discussion

In order to study the distribution and spatiotemporal variation of soil properties throughout the irrigated perimeter of Beni-Amir, spatial interpolations based on mathematical (empirical) and geostatistical methods were chosen. To this end, two different approaches were tested: kriging [26] and the IDW (Inverse Distance Weighted) method [27]. The study of the spatiotemporal variation of the physicochemical properties of soils in the Beni-Amir region has revealed significant changes over the last few decades. The results are presented in the form of maps illustrating the geostatistical analysis of the spatiotemporal variability of physicochemical parameters, in particular OM (2015 and 2019), pH, and EC (2013 and 2023). The values reported in Table 1 provide a comparison of the cross-validation results obtained using the two interpolation approaches.

Table 1. Comparison of Spatial Interpolation Methods.

Performance Criteria	**IDW**	**Kriging**
Samples	13 out of 13	13 out of 13
Mean Error (ME)	0.291	0.011
Root-Mean-Square Error (RMSE)	2.129	1.834

3.1 Soil OM status and dynamics

Figure 3 shows the spatial and temporal variation in OM content reveal an increase moving from east to west across the irrigated area. It ranged from 2.89% to 2.98% in 2015 and reached values ranging from 3.50% to 3.58% in 2019. Intensive agricultural practices in the eastern part, with heavy use of chemical fertilizers and poorly controlled irrigation, appear to have a negative impact on soil organic matter content, unlike in the western part, where arboriculture better preserves this indicator of fertility.

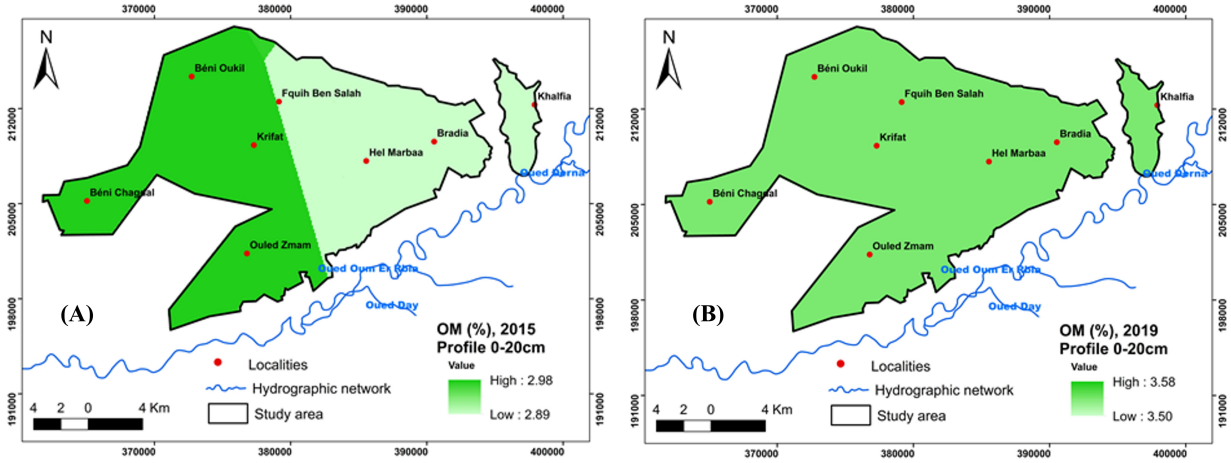


Fig. 3. Spatial distribution of soil organic matter in (A) 2015 and (B) 2019.

3.2 Soil pH status and dynamics

Soil pH analyses (Fig. 4) carried out in 2013 and 2023 in Beni-Amir show that the soil is naturally alkaline. With a pH ranging from 8.24 to 8.28 in 2013, then reaching 8.32 in 2023, a slight alkalization can be observed over time. This trend is probably due to factors such as irrigation in a semi-arid climate, which promotes the accumulation of salts. These salts can increase the pH and, over time, lead to soil salinization. Other factors such as limestone bedrock, loss of organic matter, or the use of basic fertilizers may also contribute to this increase in pH. In addition, the spatial variation in pH, which increases from southwest to east, suggests an uneven distribution of these processes within the irrigated area. High pH can have negative consequences on the availability of certain nutrients essential for crops, such as iron and phosphorus.

3.3 Soil EC status and dynamics

The spatial and temporal variation in EC reveal an increase moving from east to west across the irrigated area (Fig. 5). In 2013, soil salinity measurements revealed values between 1.55 and 1.73 dS/m. In 2023, measurements showed high salinization, with a maximum value of 8.14 dS/m recorded in the southern part. The findings indicate that soil salinization is a significant issue in the Béni-Amir area, in agreement with previous studies reported by Badraoui (2002) [28], Chaaou (2020) [29], and El Hamdi (2022) [22]. Salinity levels are

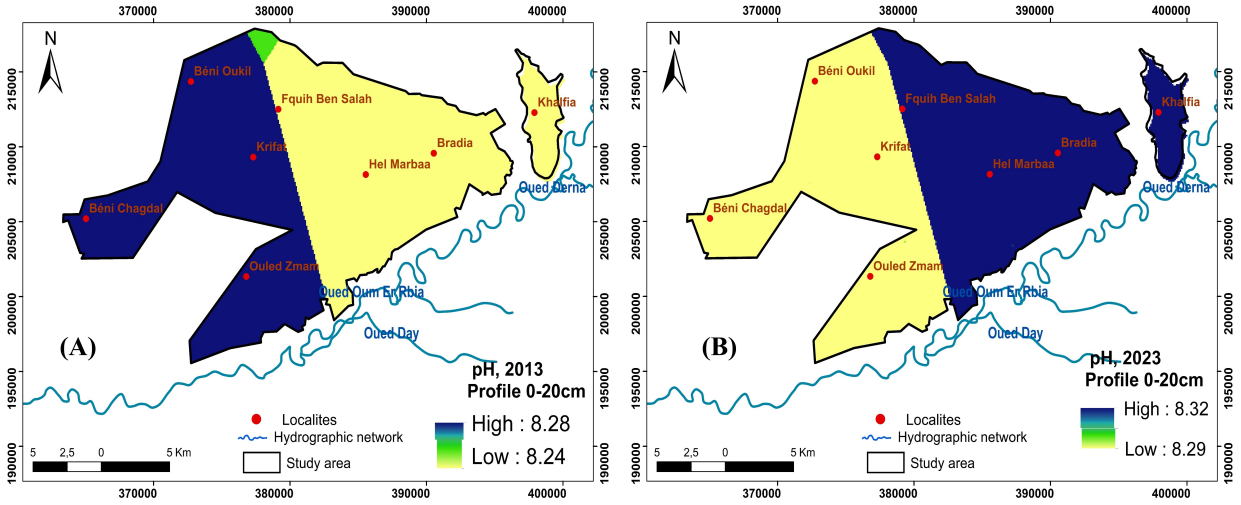


Fig. 4. Spatial distribution of soil pH in (A) 2013 and (B) 2023.

strongly influenced by groundwater behavior and the effectiveness of water management practices. Inadequate drainage, combined with excessive irrigation or the use of saline-quality water, can promote waterlogging and the accumulation of salts in downstream parts of irrigated areas, particularly under high evaporative conditions. In contrast, efficient drainage facilitates the removal and downward transport of substantial amounts of dissolved salts from the soil system [22]. This increase in salinity is caused by natural factors, including high salt content in irrigation water, salty groundwater, and decreased rainfall, and also by anthropogenic factors such as intensive agricultural practices.

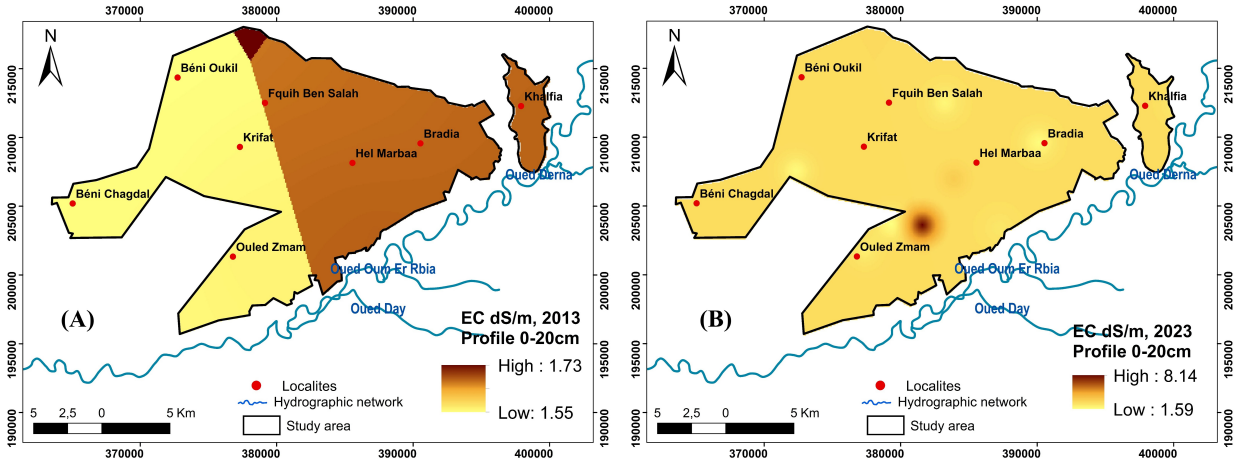


Fig. 5. Spatial distribution of soil CE (A) 2013 and (B) 2023

Soil pH, an important indicator of soil chemical conditions, showed a neutral reaction, with a mean value of 7.41. This parameter is known to influence both the mobility and retention of potentially toxic trace elements [25], [30], while values ranging from approximately 6 to 8 generally provide favorable conditions for plant development [31]. The organic matter content ranged from 4 to 6%, suggesting a relatively high level of soil fertility. These values

are consistent with those reported by Oumenskou et al., (2019) [10] for the Béni-Amir area, where an OM content of 5.72% was recorded. Beyond its contribution to soil fertility, organic matter plays an important role in controlling the mobility and uptake of metals,improving nutrient availability, and modifying several soil properties [32], [33], [34]. Electrical conductivity values ranged from 0.25 to 0.47 μS cm^{-1}, indicating that the investigated soils were not saline according to the threshold reported in the literature [35]. The observed deterioration of soil quality, characterized by increasing salinity and declining organic matter content, results from a combination of intrinsic soil conditions and external influences.

With regard to salinity, two main intrinsic factors can be identified:the limited effectiveness of drainage systems in certain parts of the region and differences in soil texture. In particular, soils with lower clay contents tend to contain less organic matter [13], [36], [37]. External drivers also contribute to soil salinization, alkalization,and the depletion of organic matter. Irrigation practices and climatic conditions are particularly important in this regard. The salt load introduced through irrigation water is substantial, with estimated inputs of approximately 130 kg ha^{-1} of sodium, 271 kg ha^{-1} of chloride, and 107 kg ha^{-1} of sulfate [38]. Continuous accumulation of these salts in the soil may progressively increase salinity, affect plant health through ionic toxicity, and ultimately reduce crop productivity [39]. The potential toxicity is particularly relevant under sprinkler irrigation, where sodium and chloride ions can be directly absorbed by plant foliage, unlike gravity irrigation systems [40]. Moreover, the downward movement of substantial amounts of dissolved salts may deteriorate groundwater quality [41], [42].

In parallel, the generally low organic matter content observed across most of the study area suggests an additional dimension of soil degradation associated with intensive agricultural practices and prevailing climatic conditions [13], [37]. In view of the worrying degradation of soils, sustainable management of agricultural land is essential. Accordingly, sustainable soil-management strategies should combine preventive measures for areas that remain unaffected by salinity with rehabilitation practices in degraded soils and actions aimed at restoring organic matter levels. Such approaches may include crop rotation [22], [43], the adoption of drought- and salinity-tolerant crop varieties [44], [45], the use of organic amendments [46], [47], and effective management of irrigation and soil conservation methods [48], [49].

4 Conclusions and Future Scope

This study highlights significant soil degradation, exacerbated by the nature of the water table in Beni-Amir, the nature of irrigation water, the geological substrate, climate change, and the intensification of agricultural practices. Spatiotemporal analysis of physicochemical properties reveals worrying changes. There has been a moderate increase in organic matter (from 2.89% to 3.58% between 2015 and 2019), a slight increase in pH to 8.32 in 2023, indicating a trend toward alkalization, and, above all, a marked increase in electrical conductivity, from 1.56 dS/m in 2013 to 8.14 dS/m in 2023, signaling advanced salinization. The geostatistical approach can be used to assess the spatial variability of soil properties for the management of irrigation, fertilizer use, and the selection of appropriate plant types. The findings of this study underscore the importance of examining aspects such as the spatial

resolution of soil sampling, the temporal coverage of the data from 2013 to 2023, and potential measurement uncertainties. Additionally, it is crucial to assess the generalizability of the results to other irrigated regions. An explicit discussion of these limitations would enhance the clarity,scientific rigor, and usefulness of the study for guiding future research. Therefore, future studies should incorporate these considerations to deepen our understanding of soil health dynamics.

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Author Contributions

All authors have similar contributions.

Conflict of Interest

The authors declare no conflict of interest.

Research Involving Human and/or Animals

Not Applicable.

Data Availability

The data used in this study were provided by the Regional Office for Agricultural Development of Tadla (ORMVAT) and were used for the analysis of soil and agricultural conditions within the Béni Amir irrigated perimeter.

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Use of AI Tools

Artificial intelligence (AI) tools, including ChatGPT, were used solely to assist with language editing, grammar correction, and improvement of the clarity and readability of the manuscript.

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