

Mapping soil salinization in the Shirvan plain based on Sentinel-2 data

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Abstract

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In this study, we used topographic indices derived from digital elevation model (DEM), SAR and vegetation indices generated by Sentinel-2 to map soil salinization in the Kurdamir, located in the central and northern Shirvan plain of Azerbaijan Republic, and evaluated the potential of multi-source sensors to predict soil salinity. This paper reflects the results of assessing the degree of salinity of Kurdamir soils based on remote sensing technologies. Classification of soils by salinity degree was performed using indices calculated from data in Sentinel-2 spectral channels. Based on a comparative analysis of machine learning and remote sensing methods, it was found that they provide similar results for soil salinity assessment, when the study area does not cover a large area of land. Using the soil electrical conductivity (EC) values of soil sampling sites as the target variable, and the optimal environmental factors as the predictive variable, we constructed three soil salinity inversion models based on classification and regression tree (CART), and extreme gradient boosting (XGBoost). This work has important implications for understanding soil salinity dynamics, and could be used in further research on land and agricultural management at the regional level.

Keywords: Sentinel-2; remote sensing; ground-based observations; digital soil mapping salinization

Introduction

Saline soils occupy about 20% of the agricultural land area of Azerbaijan Republic. Salinization, the most important determinant of agricultural productivity, poses serious challenges to sustainable land management in arid and semi-arid regions. Regions of Azerbaijan, characterized by diverse ecological landscapes, are particularly prone to soil salinization, which affects crop yields and ecosystem health. The territory of Azerbaijan is an ancient agricultural region, because

of the thousand-year influence of anthropogenic factors, salinization of soils of irrigated lands has become widespread.

Soil protection and its rational use for arable land is one of the important tasks in agriculture. Remote sensing technologies, such as Sentinel-2 satellite imagery, offer promising opportunities for monitoring and mapping soil salinity at large spatial scales with high temporal resolution (Chaves et al., 2020). The peculiarities of each region are manifested in the characteristic optical properties of the landscape, which form its external appearance. By identifying homogeneous

areas by their optical characteristics, we can solve the problems of physical and geographical zoning. Thus, when photographing the earth from space, we record its instantaneous state (Gorji et al., 2020; Hasanova and Abasova, 2024). This work aims to use remote sensing techniques to map soil salinity levels in the southern territories of Azerbaijan, focusing on the synergy between spectral reflectance data and ground truth measurements. Using multispectral capabilities of Sentinel-2 satellites, the spatial distribution of soil salinization is analyzed, clarifying the main environmental factors determining salinization processes. Methodologically, a combination of spectral indices, machine learning algorithms and geographic information systems were used to produce accurate and spatially detailed soil salinity maps (Hasanova and Asgarova, 2021; Hasanova et al., 2021).

The results of this study provide valuable information on the spatial variability of soil salinity, facilitating targeted land management strategies and mitigation measures. The application of remote sensing technologies to soil salinity mapping offers a cost-effective and scalable approach to monitoring environmental change and supporting decision-making processes (He et al., 2021; Ismayilov et al., 2025). This study contributes to the broader goal of improving agricultural sustainability and land management in the context of saline soils in the southern regions of Azerbaijan.

Material and Methods

Field sampling and analysis

The research focused on Kurdamir district (Shirvan plain). Indices calculated from data in spectral channels of Sentinel-2 satellite were used to classify soils by salinity degree. Remote sensing has become a valuable tool for mapping soil salinity on a regional scale. The research paper explores the application of remote sensing technology, specifically the combination of Sentinel-2 (Moussa et al., 2020; Macnunlu et al., 2025). Used the five-point sampling method to collect 5 soil samples at each sampling site (30 m*30 m), and mixed them on site to create a representative composite sample (0–20 cm soil depth), placed each soil sample in a sealed bag (to prevent soil moisture loss) and made a mark, then brought these samples back to the laboratory for further chemical analyses. All soil samples were air-dried, ground, homogenized, and sieved to ≥ 2 mm particle size. Added 100 mL of distilled water to each 25 g soil sample and mixed thoroughly (1:5 soil-water extraction solution), and then, we extracted the percolate through a multiparameter measuring device (Multi 3420 Set B), equipped with a composite electrode (TetraCon 925), at room temperature of 24 °C to measure electrical conductivity (EC). The PHS-3C was used

to measure pH value, and the oven dry weighing method (105 °C constant temperature box, 24 h) was used to measure the soil moisture content (SMC).

The study combines data from several sources, including SAR and multispectral imagery, as well as digital elevation models (DEMs), to develop a robust soil salinity prediction model. The results demonstrate that the inclusion of SAR indices along with traditional terrain and vegetation indices significantly improves the prediction accuracy of the models (Nasirova et al., 2022; Nasirova et al., 2025). Although the study utilizes ground-sampling sites for model validation, the number of sampling sites was relatively small to accurately validate predictive models over the entire study area. The paper investigates the application of remote sensing methods using Sentinel-2 satellite images for predicting soil salinization in arid conditions. The most important problem of soil salinization is considered, especially in arid and semi-arid regions, where it contributes to land degradation and desertification. Using high-resolution Sentinel-2 and Landsat-8 satellite images and remote sensing techniques, the study aims to assess soil salinization by producing soil electrical conductivity (EC) maps. Two different regression approaches, MLP and SVR, were used. In addition, two feature selection algorithms, GA and SFS, were implemented on the data to improve model performance.

Through a combination of field studies and different modeling approaches including regression and feature selection algorithms, the study demonstrates the effectiveness of the proposed soil salinity monitoring method (Sahbeni, 2021). Using Sentinel-2 satellite imagery and ground data, researchers are developing a method to detect salinity-prone soils using two complementary approaches: assessing salinity in bare soils using the salinity index (SI), and monitoring the indirect effects of salinity on rice growth using time-series vegetation index (NDVI). Correlations between NDVI, soil electrical conductivity and crop yields provide valuable information on soil salinity dynamics. The classification approach of the study based on NDVI models shows promise in identifying areas with different levels of salinization, while further research is needed to confirm its effectiveness in identifying moderate soil salinity limitations over large areas. The study addresses the critical need for accurate prediction of agricultural soil salinization, especially in arid and semi-arid regions, using Sentinel-2A (S2) satellite data.

Using multiple linear regression analysis, the study found significant correlations between soil salinity (EC_e) values and various S2 data parameters, including individual bands, band ratios, and spectral indices. By combining Sentinel-2 optical data, the study develops an innovative approach to predict soil salinity using integrated radar and optical sensor

variables. The study focuses on feature selection strategies and regression learning methods, using various machine-learning models such as random forest, linear regression, back propagation neural network and support vector regres-

sion. The results showed that salinity indices could be used for soil salinity mapping and represent a valuable tool to assess soil salinity in rice growing areas affected by salinity problems (Shukurov et al., 2025; Taghadosi et al., 2019).

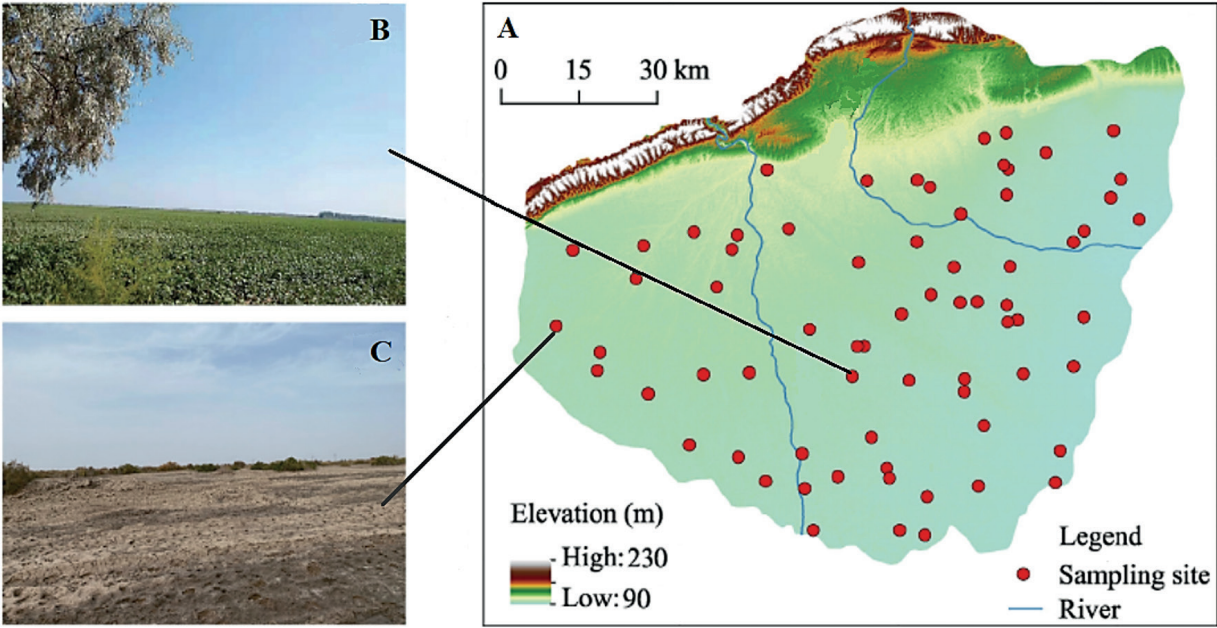


Fig. 1. A. Location of sampling sites (with Main Shirvan collector and Girdiman River), and demonstration of the landscape of sampling sites in B and C
Source: Authors' own elaboration

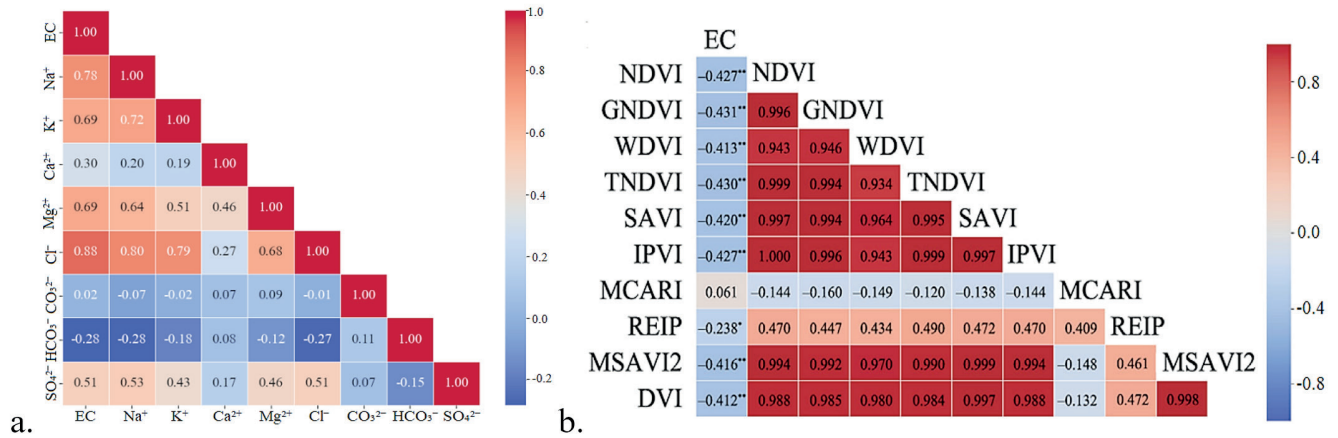


Fig. 2. a. Correlation of electrical conductivity with cations and anions; b. Correlation coefficients between measured electrical conductivity (EC) values and vegetation indices
*Note: **, significance at the 0.01 probability level; *, significance at the 0.05 probability level. NDVI, Normalized Difference Vegetation Index; GNDVI, Green Normalized Difference Vegetation Index; WDVI, Weighted Difference Vegetation Index; TNDVI, Transformed Normalized Difference Vegetation Index; SAVI, Soil Adjusted Vegetation Index; IPVI, Infrared Percentage Vegetation Index; MCARI, Modified Chlorophyll Absorption Ratio Index; REIP, Red Edge In-flection Point; MSAVI2, Modified Soil Adjusted Vegetation Index 2; DVI, Difference Vegetation Index*
Source: Authors' own elaboration

Results and Discussion

The study addresses the problem of accurate soil salinity monitoring in bare soil areas using satellite remote sensing data. By Sentinel-2 multispectral images the study aims to improve the accuracy of soil salinity inversion, overcoming the limitations of sensor (Shukurov et al., 2025). Experiments, conducted in an irrigation district, demonstrate that fusion of VV and Sentinel-2 images yields higher accuracy compared to other fusion methods and individual images. Using machine learning models such as back propagation (BP), support vector machine (SVM), and random forest (RF), the study constructed a soil salinity inversion model, with RF achieving the most satisfactory results. The neighborhoods around Shirvan plain have less vegetation and sandy soil. The Kurdamir and Ujar areas are more agricultural, but the soil becomes alkaline in summer (Fig. 1).

Figure 1 shows the salinity map of Kurdamir region,

based on spectral index obtained from remote sensing data. The colored dots show the result of machine learning, where soil samples were obtained for salinity estimation. The study confirms that soil electrical conductivity (EC) is a reliable indicator of salinity, with chloride (Cl^-) and sodium (Na^+) being the main contributors. The secondary influence of potassium (K^+), magnesium (Mg^{2+}) and sulfate (SO_4^{2-}) further highlights the complex interactions between soil ions in shaping salinity patterns. The results show distinct spatial variability in soil EC associated with geomorphic processes and landform characteristics (Fig. 2a).

Figure 2a shows the soil cation and anion concentration, and vegetation indicators of the Kurdamir region. Principal component analysis was used to assess relationships between soil electrical conductivity (EC), and laboratory-measured cation and anion concentrations (Na^+ , K^+ , Ca^{2+} , Mg^{2+} , Cl^- , CO_3^{2-} , HCO_3^- , and SO_4^{2-}).

Figure 3 presents a map of salinity in the Kurdamir re-

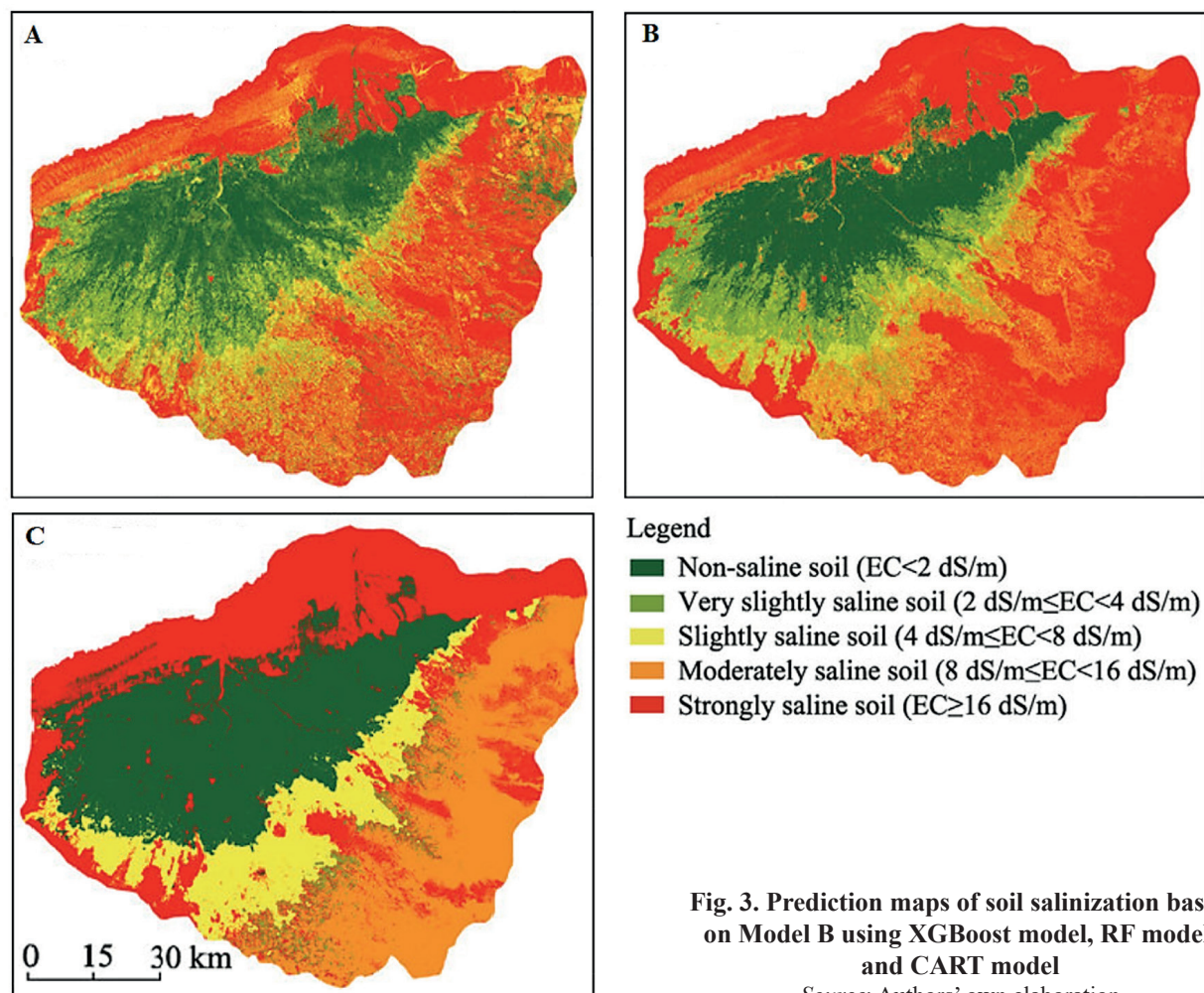


Fig. 3. Prediction maps of soil salinization based on Model B using XGBoost model, RF model, and CART model

Source: Authors' own elaboration

gion, based on the Model B using XGBoost model, RF model, and CART model derived from remote sensing data. Due to the dynamic changes in surface characteristics, Sentinel time series data will be taken into account in future studies to map soil salinity in different periods to further reduce uncertainty and improve the accuracy of predictions (Fig. 3).

The following conclusion can be drawn from Figures 2–3: when the area of interest does not cover a large part of the territory (in the example of Kurdamir), the accuracy of soil salinity estimation based on machine learning and using remote sensing, gives similar results. This is because the algorithm was trained specifically for local conditions and variations within a smaller area, resulting in predictions that are more accurate. In addition, large-scale areas often show significant spatial heterogeneity of soil salinity levels (Kurdamir is an example). The variability of soil properties, soil use and environmental conditions over a large area can make accurate collection and modeling using remotely sensed data and machine learning algorithms difficult. The research results showed that the combination of vegetation indices, SAR indices and topographic indices could effectively predict soil salinity, but further improvement is needed. In addition, our results have not yet achieved good prediction accuracy. The prediction accuracy of the optimal XGBoost model is only 0.68, which may be related to the study area, the type and quality of predictor variables, the accuracy of the prediction model and the variability of EC.

Conclusion

By comparing CART, RF, and XGBoost, used topographic indices derived from DEM, SAR indices, generated by vegetation indices generated by Sentinel-2, to study the spatial distribution of soil salinization in the Kurdamir region. This study presented the results of salinity assessment of Shirvan plain soils using Sentinel-2 satellite imagery. Indices calculated from data in spectral channels of Sentinel-2 satellite were used to classify soils by salinity degree. The dataset for training the machine-learning model consisted of 167 soil samples, of which 69 were selected for the training sample and 53 for the test sample. Based on the comparative analysis of machine learning and remote sensing methods, it was found that they provide similar results for soil salinity assessment when the study area is limited to a small-scale territory. This work has important implications for understanding soil salinity dynamics and could be used in further research on land and agricultural management at the regional level. Vegetation indices are the main explanatory variables for EC prediction, followed by topographic indices and SAR indices. The EC values in the whole study area varied great-

ly, ranging from 0.07 to 76.71 dS/m. The mean and median values were 13.76 and 6.25 dS/m, respectively, the SD was 18.25 dS/m, and the CV was 133.47%, indicating a strong variation. The SMC ranged from 0.53% to 20.21%, and the SD and CV were 5.14% and 53.87%, respectively, indicating a moderate variation. The soil pH values in the whole study area ranged from 7.95 to 9.22, with the mean and median values being 8.79 and 8.48.

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