MACHINE LEARNING FOR SUSTAINABLE LAND MANAGEMENT: A FOCUS ON ITALY

Matteo Dalle Vaglie, Federico Martellozzo

Abstract: Soil salinization poses a multifaceted challenge demanding a comprehensive approach combining environmental science, machine learning, geography, and socio-economic analysis. Our study integrates these disciplines to unravel the complexities of soil salinization and devise effective mitigation strategies. We ground our investigation in understanding the geological and climatic fundamentals governing soil properties and processes, with a focus on the Mediterranean coastal areas. By harnessing the power of machine learning, we navigate the high-dimensionality and non-linearity of soil salinization, incorporating a comprehensive set of variables spanning geological, climatic, human activity, and socio-economic dimensions. Our models, trained on extensive datasets, are robust and capable of capturing intricate patterns associated with soil salinization. The Mediterranean coastal areas, with their unique ecological, climatic, and anthropogenic interactions, serve as a valuable case study for exploring the dynamics of soil salinization. Our approach integrates data on historical geological changes with current climatic and anthropogenic variables, creating a comprehensive model that encapsulates the temporal and spatial dimensions of soil salinization. This study aims to contribute meaningfully to global efforts in sustainable land management and environmental preservation.

Keywords: salinization, land monitoring, remote sensing, soil management

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Introduction

Soil salinization poses a multifaceted challenge that demands a comprehensive and integrated approach, combining diverse disciplines and methodologies to unravel its complexities and devise effective mitigation strategies ((Sparks, 2003; Szabolcs, 1989). Our study nestles within this intricate tapestry, adopting a holistic framework that intertwines environmental science, machine learning, geography, and socio-economic analysis.

We start by grounding our investigation in a robust understanding of the geological and climatic fundamentals that govern soil properties and processes. This involves delving into the morphology and evolution of coastlines and seabeds, as these features play a crucial role in shaping the distribution and dynamics of saline soils (Doula & Sarris, 2016). Coastal areas, with their unique geomorphological characteristics, are particularly susceptible to salinization due to factors such as tidal movements, sea spray, and the intrusion of saline water into freshwater aquifers (Wong et al., 2010). The seabed's topography and composition further influence underwater currents and the transportation of saline water, impacting coastal salinity levels. A nuanced understanding of these geological processes is vital for accurately predicting and mitigating soil salinization in coastal regions (Corwin, 2021). Simultaneously, we extend our analytical lens to incorporate the socio-economic dimensions of soil salinization, recognizing that its impacts ripple far beyond the environmental sphere. This is particularly evident in the Mediterranean coastal areas, where agriculture forms the backbone of many local economies, and the delicate balance of the ecosystem is intricately linked with community well-being (Aung Naing Oo et al., 2013). In these regions, salinization not only degrades soil health but also threatens the livelihoods of farmers, disrupts local food supplies, and exacerbates socio-economic disparities. Our framework, therefore, integrates socio-economic variables and aims to uncover the complex interplay between environmental degradation and social outcomes, providing a holistic perspective on the challenge at hand.

Building on this foundation, we harness the power of machine learning to navigate the high-dimensionality and non-linearity of soil salinization. Our approach is grounded in a thorough understanding of the various factors that contribute to salinization, as well as the intricate ways in which they interact. By incorporating a comprehensive set of variables spanning geological, climatic, human activity, and socio-economic dimensions, we strive to capture the full complexity of the phenomenon (Blum, 2005; Erkin et al., 2019). This not only enhances the accuracy and reliability of our predictions but also enables us to draw nuanced insights that can inform targeted and effective mitigation strategies. The machine learning models serve as a crucial bridge, translating raw data and theoretical knowledge into actionable intelligence. By training our models on extensive datasets, encompassing a wide array of variables and field measurements, we ensure that they are robust and capable of capturing the intricate patterns associated with soil salinization (Hassani et al., 2020). This is particularly crucial for addressing the challenge in Mediterranean coastal areas, where the interplay of natural and human factors creates a unique and complex landscape of soil salinity (Metternicht, 2017). In further enriching our framework, we place a pronounced emphasis on the Mediterranean coastal areas, an epicenter of diverse ecological, climatic, and anthropogenic interactions. The unique characteristics of the Mediterranean climate, marked by hot, dry summers and mild, wet winters, create a distinct environment that is simultaneously rich in biodiversity and vulnerable to soil salinization (Khamidov et al., 2022). The complex interplay of natural elements and human activities in these regions requires a tailored approach, acknowledging the specific challenges and opportunities they present. The Mediterranean basin, with its extensive coastline and intricate seabed morphology, serves as a valuable case study for exploring the dynamics of soil salinization. The region's coastlines have undergone significant changes over geological time scales, shaped by tectonic activities, sea level fluctuations, and sedimentary processes. (Eswar et al., 2021a)These historical transformations have left an indelible mark on the present-day landscape, influencing soil characteristics and salinity patterns. Understanding the evolution of coastlines and seabeds is pivotal in deciphering the spatial distribution of saline soils and predicting their future trends.

Our approach integrates data on historical geological changes with current climatic and anthropogenic variables, creating a comprehensive model that encapsulates the temporal and spatial dimensions of soil salinization. This allows us to identify areas at risk, anticipate potential changes, and formulate proactive mitigation strategies. The Mediterranean coastal areas, with their complex interplay of natural and human-induced factors, offer a valuable context for testing and refining our models, ensuring their robustness and applicability across diverse settings. Human activities, particularly agriculture, urbanization, and tourism, have exerted substantial pressure on the Mediterranean region's natural resources, exacerbating soil salinization. Intensive agricultural practices, relying heavily on irrigation, have led to the mobilization of salts and their accumulation in the soil. Urban sprawl and tourism-related infrastructures have altered natural drainage patterns, further contributing to the salinity issue (Parihar et al., 2015).Our framework explicitly accounts for these human-induced factors, recognizing their critical role in shaping soil conditions and their potential as leverage points for intervention. In encapsulating these diverse elements, our framework adopts a multidisciplinary and multiscale perspective, recognizing that soil salinization is a complex phenomenon influenced by an array of factors operating at different spatial and temporal scales. By integrating geological, climatic, anthropogenic, and socio-economic data, we create a rich and nuanced understanding of the phenomenon, enabling us to capture its multifaceted nature and devise effective mitigation strategies (Tran et al., 2021).

Our holistic and integrative approach, grounded in a deep understanding of the natural environment and enriched by socio-economic insights, positions us to tackle soil salinization in all its complexity. The Mediterranean coastal areas, with their unique challenges and opportunities, serve as a valuable laboratory for refining our models and strategies, ensuring their relevance and effectiveness in diverse settings. Through this comprehensive framework, we aspire to contribute meaningfully to global efforts in sustainable land management and environmental preservation, safeguarding the soil that sustains us all.

Materials and Methods

This study employed a comprehensive and robust dataset, totalling 43594 observations, drawn from the ISRIC-WISE Harmonised Global Soil Profile Dataset (WISE version 3.1). To ensure the reliability and uniformity of the data, stringent inclusion criteria were applied. Only measurements of electrical conductivity in saturated paste were considered, while observations under different dilution ratios (1:1, 1:2, 1:5, and 1:10) were excluded due to their potential to alter the ionic strength and composition of the soil solution (Wong et al., 2010).

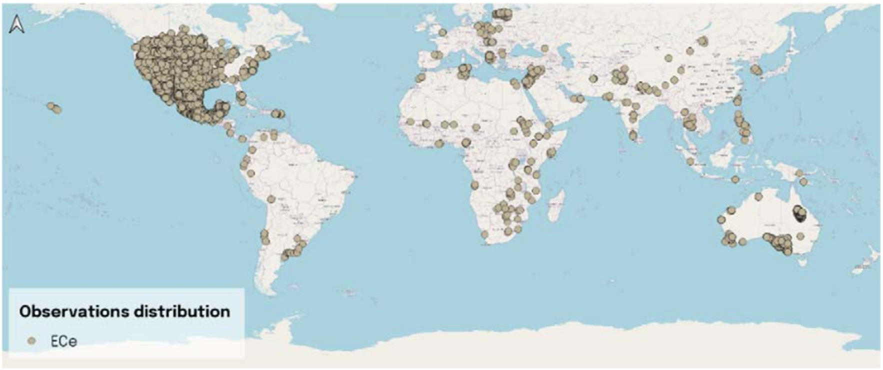

Figure 1 – Geographic Distribution of Ece Input Observation

Each observation included information on the year, exact location, and upper and lower depths of the soil sample. Observations with missing data were excluded, and data collected before January 1980 were disregarded to ensure consistency with environmental data collection standards and predictor availability. The dataset encompassed 44 environmental predictors, reflecting a broad range of factors essential to understanding the intricate process of soil salinization. These predictors included geomorphological, hydrogeological, meteorological, soil composition, land use patterns, and variables related to sea level rise and drought prevalence (Corwin, 2021).

The predictors were sourced from various datasets, including detailed maps of soil and lithology, atmospheric reanalysis records, terrain elevation data, comprehensive climate datasets, and outputs from advanced hydrological models. This multifaceted approach allowed the development of a predictive model linking environmental factors with soil profile data. Data quality was rigorously screened, with 363 observations removed due to null values. In cases where null values resulted from geographical discrepancies, the closest predictor value within a two-cell radius was sampled to ensure spatial accuracy (Blum, 2005; Sparks, 2003).

Models	R2
Multiple Regression	0.23
Elastic Net	0.47
SVM	0.62
Random Forest	0.75
LightGBM	0.83
CatBoost	0.82
Neural Network	0.69

Figure 2 – R^2 of the different trained models.

The predictive model utilized 44 global predictors, categorized into static and dynamic types. Static predictors, which remain constant over the study period, included geomorphological factors and soil texture, derived from the Multi-Error-Removed Improved-Terrain (MERIT) DEM and the International Soil Reference and Information Centre (ISRIC) global gridded soil information. Dynamic predictors, which exhibit spatiotemporal variability, primarily comprised climatic, hydrologic, and surface vegetative variables from the CHELSA climatic reanalysis dataset. Non-autoregressive variables were aggregated into annual means and five-year moving averages, while autoregressive predictors considered yearly means due to their continuity over time (Erkin et al., 2019; Wang et al., 2020a). All raster predictors were reprojected in Mollweide Equal Area projection (EPSG:54009), and ECe observations were matched with corresponding predictor values by geographic coordinates and year. Missing values for remotely sensed variables were filled using five-year moving averages of the closest available years, while other variables, produced only in certain years, were matched with the nearest year available (Hassani et al., 2020; Metternicht, 2017). The regression and classification models for predicting ECe values were trained in Python using Pandas, Geopandas, Scipy, Sklearn, LightGBM, and XGBoost libraries. Models were trained using RandomizedSearchCV, evaluating 20 different hyperparameter combinations with 2-fold cross-validation. This method balanced computational speed and efficiency, capturing the variance of the phenomenon with larger datasets. Gradient Boosting trees, specifically CatBoost, LightGBM, and XGBoost, were found to outperform other frameworks in terms of speed, accuracy, and flexibility, with LightGBM ultimately selected for its overall effectiveness (Tran et al., 2021a).

To address the left skewness of the target variable, a natural logarithm transformation was applied to ECe, and a two-level model approach was adopted. This involved initially classifying soils as saline or non-saline and then applying separate regression models to each class. The optimal threshold for classification was determined through extensive testing, with the highest R^2 value achieved at an ECe threshold of 2.

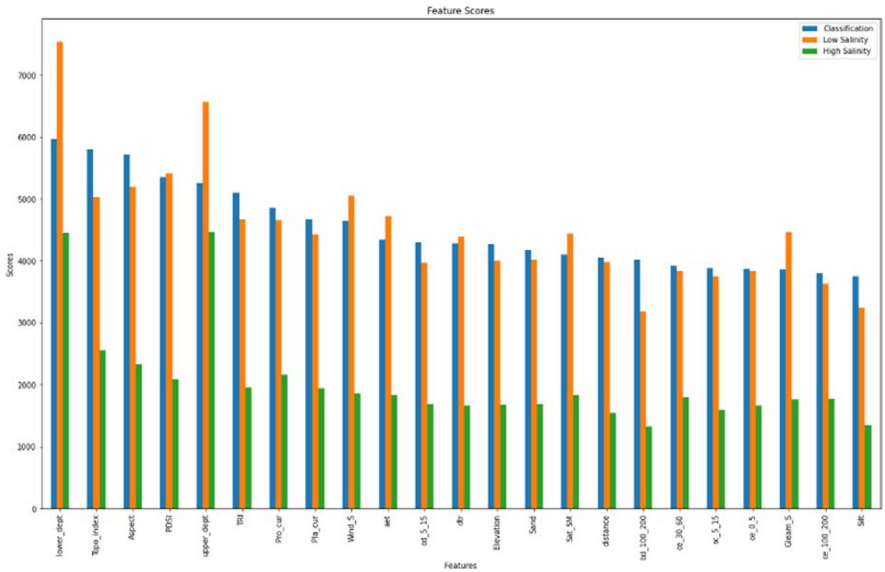

Figure 3 – Bar Chart of the 23 most important variables.

Feature selection was performed iteratively, removing the least significant variable at each step based on the cumulative feature score. This process reduced the predictors from 44 to 21, improving the model's R^2 to 88%. The final model, capable of predicting ECe values with high accuracy, was used to generate global high-resolution maps of soil salinity across various depths and time frames, demonstrating its utility in understanding and managing soil salinization (Eswar et al., 2021; Khamidov et al., 2022; Parihar et al., 2015).

Results

The results of our comprehensive study on soil salinization, particularly focusing on global landscapes with an emphasis on the Mediterranean coastal areas, unveil a nuanced and multifaceted understanding of the phenomenon. By leveraging advanced machine learning algorithms and incorporating a diverse set of variables encompassing geological, morphological, climatic, and human-induced factors, our research provides unparalleled insight into the patterns and drivers of soil salinity. One of the pivotal findings of our research is the identification of key variables and their interactions that significantly influence soil salinity levels. Geological and morphological factors such as soil type, topography, and historical shifts in coastlines and seabeds emerged as crucial determinants (Doula & Sarris, 2016).These factors, deeply rooted in the region's geological history, have set the stage for the current distribution of saline soils. The Mediterranean's unique climate, characterized by distinct wet and dry seasons, further exacerbates soil salinity, particularly in coastal areas where evaporation rates are high, and freshwater inputs are limited (Corwin, 2021). The study also sheds light on the significant role of human-induced activities in shaping soil salinity patterns. Agricultural practices, urbanization, and tourism have been identified as major contributors, with irrigation practices in agriculture being a double-edged sword. While essential for crop production in arid and semi-arid regions, improper management can lead to waterlogging and the mobilization of salts, exacerbating soil salinity (Parihar et al., 2015). Our findings indicate a pressing need for sustainable land management practices that balance agricultural productivity with soil conservation.

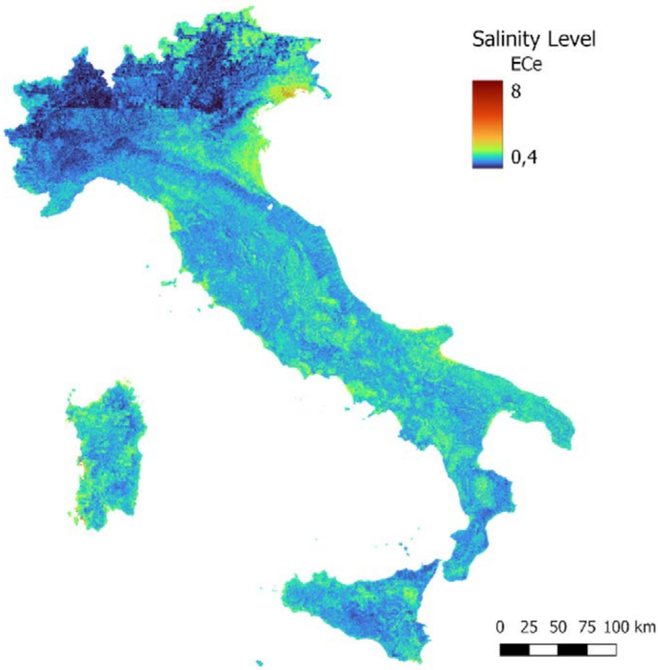

Figure 4 – Soil Salinity Map for Italy (dS/m).

In terms of spatial distribution, our research reveals a heterogeneous pattern of soil salinity across the Mediterranean region, influenced by a combination of natural and human-induced factors. Coastal areas and river deltas were identified as hotspots, bearing the brunt of salinity stress (Eswar et al., 2021a). These findings underscore the importance of targeted interventions and tailored strategies to address soil salinity in these vulnerable regions.

The temporal analysis of soil salinity trends reveals a concerning escalation of the phenomenon correlated with climatic changes and intensified human activities. The increase in global temperatures and changes in precipitation patterns due to climate change have led to an amplification of soil salinity levels, particularly in arid and semi-arid regions (Hassani et al., 2020; Khamidov et al., 2022). This has significant implications for agricultural productivity, biodiversity, and the overall resilience of ecosystems. Our machine learning models proved to be highly efficient and accurate in predicting soil salinity levels, demonstrating their potential as valuable tools for policymakers and land managers. These models facilitate the anticipation of salinity trends, enabling proactive measures and informed decision-making. For instance, the model's ability to predict soil salinity levels in Italy, as depicted in the figure below, highlights areas of high salinity risk that require immediate attention and intervention.

Discussion

Our study's findings underscore the intricate interplay of natural and anthropogenic factors driving soil salinization, with significant implications for agriculture, especially in regions like the Mediterranean. The escalating soil salinity in these areas is a direct threat to agricultural productivity, food security, and socio-economic stability. The Mediterranean region, with its unique climatic conditions marked by hot, dry summers and mild, wet winters, is particularly vulnerable to soil salinization. The combination of high evaporation rates and limited freshwater input exacerbates salinity levels, severely impacting soil health and crop yields (Reed et al., 2022).This poses a critical challenge for local agriculture, which relies heavily on the delicate balance of these ecosystems. Salinization reduces soil fertility, hampers plant growth, and diminishes crop productivity, leading to substantial economic losses for farmers. Human activities further compound this issue. Intensive agricultural practices, especially those involving improper irrigation techniques, contribute significantly to soil salinity. The over-reliance on irrigation in arid and semi-arid regions mobilizes salts, which accumulate in the soil over time (de Ruig et al., 2019). This not only degrades soil quality but also affects water resources, as saline water leaches into freshwater systems. The economic repercussions are severe, with affected regions experiencing decreased agricultural output, increased costs for soil reclamation, and losses in farm income.

In the Mediterranean, agriculture is a cornerstone of local economies, and the impacts of soil salinization extend beyond the environmental sphere. The degradation of soil health threatens the livelihoods of farmers, disrupts local food supplies, and exacerbates socio-economic disparities. For instance, in areas like California, annual revenue losses due to soil salinization amount to approximately 1.0 to 1.2 billion $ (Welle & Mauter, 2017). Similarly, in Northeast Thailand, soil salinity severely impacts rice productivity, leading to food insecurity and economic stagnation in vulnerable communities (Katarzyna Negacz et al., 2022a). Our predictive models highlight the urgent need for sustainable land management practices. By identifying areas at high risk of salinization, our models can inform targeted interventions. Strategies such as improved irrigation management, the use of salt-tolerant crop varieties, and the implementation of crop rotation systems can mitigate the impacts of salinization. These measures not only enhance soil health but also ensure the long-term viability of agricultural lands.

Figure 5 – Salt Affected agricultural soil.

Moreover, the role of policy and governance is crucial in addressing soil salinization. Effective policies that promote sustainable agricultural practices, support research and innovation, and provide resources for soil reclamation are essential. Investing in education and training for farmers on best practices for soil and water management can further bolster these efforts (Ataie-Ashtiani et al., 2013). The integration of machine learning models in our study demonstrates their potential in providing actionable insights for policymakers and land managers. These models offer a robust framework for predicting soil salinity trends, enabling proactive measures to safeguard agricultural productivity. By translating complex environmental data into practical solutions, our approach contributes to the broader goal of sustainable land management and environmental preservation (Linke et al., 2019; Vousdoukas et al., 2016).

Conclusion

Our study on soil salinization underscores the urgent need for comprehensive strategies to address this escalating environmental challenge. The integration of advanced machine learning models with extensive datasets has provided deep insights into the complex interplay of natural and human-induced factors driving soil salinity. This multifaceted approach is crucial for developing effective mitigation strategies tailored to the unique characteristics of affected regions, particularly the Mediterranean coastal areas (Katarzyna Negacz et al., 2022b).

The findings reveal that both geological and climatic factors, along with human activities such as intensive agriculture, urbanization, and improper irrigation practices, significantly contribute to soil salinization. This poses a severe threat to agricultural productivity, food security, and socio-economic stability. The Mediterranean region, characterized by its distinct climatic conditions and high dependency on agriculture, is particularly vulnerable (Perri et al., 2020). Soil salinization in this area not only degrades soil health but also threatens the livelihoods of farmers and disrupts local economies. Our predictive models highlight the importance of targeted interventions to manage soil salinity. Sustainable land management practices, including improved irrigation techniques, the use of salt-tolerant crops, and crop rotation systems, are essential to mitigate the adverse impacts. Policymakers play a pivotal role in this process, requiring the development of robust policies that promote sustainable agricultural practices, support research and innovation, and provide resources for soil reclamation. Investing in education and training for farmers on best practices for soil and water management is also crucial (Eswar et al., 2021b; Haj-Amor et al., 2022). This not only enhances the effectiveness of mitigation strategies but also ensures the long-term viability of agricultural lands. Moreover, our study demonstrates the potential of machine learning models in providing actionable insights for land managers and policymakers. These models facilitate the prediction of soil salinity trends, enabling proactive and informed decision-making.

In conclusion, addressing soil salinization is a complex but essential task that demands a holistic and integrative approach. By combining scientific understanding with technological innovation and effective policy interventions, we can mitigate the detrimental effects of soil salinization. This will protect agricultural productivity, ensure food security, and enhance the resilience of ecosystems and communities, particularly in the Mediterranean region. Our comprehensive framework and findings contribute significantly to global efforts in sustainable land management and environmental preservation, paving the way for a more resilient and sustainable future (Tran et al., 2021b; Wang et al., 2020b).

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