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Editorial

Salinity Monitoring and Modelling at Different Scales: An Editorial Overview

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1. Introduction

Soil salinization is a significant abiotic process affecting arid, semi-arid, and sub-humid regions worldwide. Estimates suggest that approximately 412 million ha of land are impacted by salinity, while sodicity affects about 618 million ha [1]. Most of these areas have a natural origin and play a crucial ecological role, significantly contributing to global biodiversity. However, estimates also indicate that around one-third of the world's irrigated land—approximately 70 million ha—is affected by soil salinization [1], with an annual expansion rate of about 1.0 to 2.0 million ha. This issue arises not only from human-induced processes but also poses a serious threat to global food production, potentially leading to hunger and exacerbating societal problems in salt-affected regions and beyond.

Due to the transient nature of the soil salinization process, which is influenced by various factors including meteorological conditions, soil properties, crop tolerance to salinity levels, and irrigation water management, effective monitoring is crucial for mitigating the harmful effects of soil salinity in agricultural areas, often unnoticed until it is too late. Conversely, in natural salt-affected regions, monitoring supports the characterization and conservation of ecosystems. Therefore, establishing monitoring frameworks for rapid, non-invasive, and cost-effective assessment of the spatial and temporal distribution of salt-affected areas at various scales has emerged as a top priority for research [2].

In this Special Issue titled "Salinity Monitoring and Modeling at Different Scales", we aimed to compile articles that showcase a diverse range of approaches and methods for monitoring soil salinity across various environments and scales. The 11 published articles illustrate a variety of applications for characterizing both natural and human-induced salt-affected areas. The articles focused on the characterization of natural salt-affected areas provide valuable insights into the importance of wetland conservation. Meanwhile, the articles addressing agricultural water management emphasize improving practices for soil conservation and the sustainability of soil and water resources. Overall, this Special Issue offers a wide range of perspectives on the theme of soil salinization.

2. Contributions to the Special Issue

The articles in this Special Issue come from researchers worldwide, presenting cutting-edge research on salinity monitoring and management in various salt-affected regions. The studies span work conducted in countries including Portugal, Spain, Italy, France, Hungary, Türkiye, Tunisia, China, the USA, Australia, and Sudan. Collectively, these articles offer a comprehensive overview of various techniques for soil salinity monitoring and management, ranging from traditional sampling campaigns to advanced methods like proximal and remote sensing for soil salinity mapping, as well as the application of process-based modeling tools to predict salt transport in soil profiles and its impact on crops and yields.

Citation: Farzamian, M.; Gonçalves, M.C.; Ramos, T.B. Salinity Monitoring and Modelling at Different Scales: An Editorial Overview. *Land* **2024**, *13*, 1890. https://doi.org/10.3390/land13111890

Received: 26 October 2024
Accepted: 4 November 2024
Published: 12 November 2024

Three contributions utilize traditional sampling campaigns to characterize landscape soil salinity and its relationship with ecological status. Herrero and Castañeda (List of Contributions) focus on small, ecologically significant wetlands in the Ebro Basin of northeastern Spain. They conducted soil monitoring to collect samples and assess key parameters, including percent water saturation, equivalent calcium carbonate, gypsum content, soil cations and anions, and soil salinity. Salinity was measured as electrical conductivity using both a 1:5 soil-to-water ratio and saturation extracts in the laboratory. The article examines critical factors limiting life in two inland saline marshes and provides baseline data for guiding biodiversity protection. The findings emphasize the importance of comparing these conditions with other wetlands to better understand species-specific environmental requirements. Additionally, the article highlights the necessity of using appropriate analytical techniques for gypsum-rich soils to ensure accurate monitoring and effective conservation.

Similarly, Jiménez-Ballesta et al. (List of Contributions) investigate the relationship between soil properties and the presence and abundance of sub-communities within a saline pond in Castilla La Mancha, Spain. The authors characterized various top and subsoil layers from several soil profiles in the region, focusing on properties such as soil texture, electrical conductivity at a 1:5 soil-to-water ratio, and the concentrations of soil cations and anions, among other characteristics. They present baseline data essential for the conservation of local habitats, which include halophilous and gypsophilous vegetation.

In another study, Zhang et al. (List of Contributions) examine the impacts of agricultural water management on soil conservation by analyzing the spatial variation in soil salinity following autumn irrigation in the Hetao irrigation district of northern China. This region experiences widespread soil salinization due to excessive irrigation and challenging hydrogeological conditions. Autumn irrigation plays a crucial role in managing soil salinity levels; however, its effectiveness is significantly influenced by the shallow depth of the groundwater table in some areas. The study explored the distribution and variation in soil moisture and salinity in locations that received autumn irrigation compared to those that were not irrigated. Results indicated that autumn irrigation improved the uniform distribution of soil water and salt profiles compared to non-irrigated fields, resulting in higher leaching. However, unreasonable autumn irrigation raised groundwater levels, increasing the risk of salt movement to the surface during freeze–thaw cycles, which could negatively impact spring crop growth. These findings emphasize the need for effective water resource management to mitigate soil salinization in cold, dry areas.

Three other contributions to this Special Issue underscore the growing importance of electromagnetic induction (EMI) in soil salinity mapping and monitoring, highlighting advancements in both technology and its applications. EMI is a non-invasive method that measures apparent electrical conductivity without physical contact, making it ideal for mapping and monitoring soil salinity at depth on a field scale. Petsetidi and Kargas (List of Contributions) provide a comprehensive review of EM38 and EM38MK2 sensors, emphasizing their effectiveness in assessing soil salinity across various scales. By integrating these sensors with machine learning and remote sensing, the authors propose a method to more accurately predict spatiotemporal salinity variations, showcasing the potential of these sensors for large-scale agricultural management and environmental sustainability.

Paz et al. (List of Contributions) offer a comparative analysis between EMI and Electrical Resistivity Tomography (ERT) for predicting soil salinity in diverse environments. While ERT provides high-resolution images of the subsurface, its requirement for electrode installation and extensive cabling limits its application to field-scale investigations. Through field surveys conducted at four sites in Portugal with varying salinity levels, the study demonstrates that while ERT is more reliable in extreme salinity conditions, EMI offers a faster and sufficiently accurate alternative in most scenarios. This finding is very relevant for soil salinity management as it supports the practical implementation of EMI in large-scale soil salinity assessments.

De Carlo and Farzamian (List of Contributions) utilize time-lapse EMI measurements to monitor soil salinization under different irrigation strategies in tomato crops in Italy. By capturing changes in soil electrical conductivity over time, this study validates EMI as a robust tool for tracking salinization trends, particularly in response to brackish irrigation water. The ability to non-invasively collect data across extensive areas and in real-time further establishes EMI as an effective method for monitoring salinity dynamics and informing sustainable water management practices.

Three contributions to this Special Issue focused on remote sensing and the use of manned aerial vehicle (UAV) technology and machine learning. Pásztor et al. (List of Contributions) introduce an approach to indirectly assess salt-affected soil properties in protected salt meadows using UAV imagery. Through a machine learning model based on spectral indices and a digital elevation model, the researchers mapped soil indicators (total salt content, Na, and pH) in five habitat types across Hungarian salt meadows. This approach facilitates non-invasive environmental monitoring, allowing for the preservation of sensitive habitats while accurately estimating soil conditions.

Sulieman et al. (List of Contributions) apply machine learning techniques to map soil salinity in Sudan's arid regions, utilizing both optical and radar satellite data. By combining these data with digital elevation models as well as electrical conductivity measurements from the saturation extracts of soil samples, the study transfers soil salinity models across geographies with similar environmental conditions. The findings highlight model transferability for spatial salinity classification and demonstrate a framework for salinity assessment and land management planning in water-limited regions.

Offering a bibliometric overview, Yin et al. (List of Contributions) provide a comprehensive analysis of research trends in remote sensing applications for soil salinization from 2000 to 2023. The study tracks the field's evolution, highlighting the contributions of key authors, institutions, and nations. By detailing advancements in machine learning, UAV technology, and hyperspectral imaging, this review identifies trends and future directions of remote sensing applications for salinity management.

Lastly, two contributions to this Special Issue focused on using physical process-based modeling to enhance irrigation water management in salt-affected areas. Several modeling tools are now available to assess site-specific soil, water, and crop parameters while accounting for time-varying field conditions, including the timing and amount of irrigation as well as variable soil salinity. Among the available vadose zone models, the HYDRUS software package offers a range of state-of-the-art approaches for studying salinity dynamics in agricultural fields [3]. In this context, Phogat et al. (List of Contributions) use the HYDRUS (2D/3D) model to optimize irrigation management using brackish water in a vineyard in Southern Australia. After calibration and validation, the model evaluated the impact of irrigating with water of varying quality. The experiment involved blending and alternating the use of brackish waters with fresh waters, as well as testing spring irrigation as a viable method for salt leaching. The results indicate that leaching irrigation with high-quality river water at the beginning of the growing season enhances salt leaching efficiency and helps control salinity. Additionally, blending or alternating saline brackish water with non-saline surface water reduces salt deposition. The study advocates for early-season leaching irrigation as a strategic management option during droughts and emphasizes the need for ongoing monitoring to ensure long-term resilience in irrigated viticulture.

Similarly, Kanzari et al. (List of Contributions) use the HYDRUS-1D model to explore the combined effects of soil matric and osmotic potential stresses on water uptake by tomato roots grown in pots and in a field in Tunisia. The experiment involved irrigating with water of varying qualities, and the model played a crucial role in assessing how different salinity levels impacted tomato growth to varying degrees. However, incorporating crop growth models is necessary to expand the research to yield analysis.

3. Conclusions

The papers in this Special Issue offer a comprehensive overview of diverse methods and approaches for monitoring soil salinity, ranging from traditional sampling techniques to advanced methods such as proximal and remote sensing, which are used to characterize and map salt-affected areas across various global regions. Additionally, the articles showcase applications of process-based vadose zone models aimed at enhancing irrigation water management, particularly when using brackish waters.

By bringing together a wide array of studies, methodologies, and approaches related to soil salinity monitoring and management, this Special Issue highlights the critical importance of these practices in addressing one of the most pressing abiotic stresses worldwide. It is hoped that this collection will inspire more interdisciplinary research on soil salinity and motivate researchers to pursue effective solutions to manage this growing challenge in an increasingly water-scarce world.

Author Contributions: Conceptualization, T.B.R. and M.F.; writing—original draft preparation, T.B.R. and M.F.; writing—review and editing, T.B.R., M.F. and M.C.G. All authors have read and agreed to the published version of the manuscript.

Funding: The support of FCT—Fundação para a Ciência e a Tecnologia, I.P., through grant attributed to T.B. Ramos (CEECIND/01152/2017) is acknowledged.

Acknowledgments: We are grateful to the academic and managing editors and reviewers for the collaboration and support necessary to ensure the academic excellence of this Special Issue.

Conflicts of Interest: The authors declare no conflicts of interest.

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