Salt-affected soils: a sustainability challenge in a changing world

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Highlights

- *Natural salt-affected ecosystems are valuable environments supporting life under extreme conditions, holding a genomic wealth from which to learn.*
- *Soils and groundwater secondary salinization are an increasing problem worldwide, enhanced under global warming and particular climate change scenarios.*
- *Modern approaches and tools enable better management of Salt-Affected Soils (SAS) and the survey of associated environment impacts.*
- *Saline agriculture offers an option for food and biomass production in SAS.*
- *The INSAS is a FAO-GSP technical network intended to coordinate efforts in halting salinization and sodification while enhancing production in SAS.*

Introduction

Salt-affected soils (SAS) occur under different environmental conditions, at any latitude, with variations in their morphology and biology, as well as in chemical, physical and physicochemical properties (Gupta and Gupta, 2017). All types of SAS have in common the dominant role of soil solution electrolytes in the soil forming processes and soil properties, resulting in unfavourable medium for the normal growth of most plants (Szabolcs, 1989). In SAS originated by natural geomorphological processes, some plants with adapted physiology (halophytes) can grow and colonize these ecosystems. Halophytes are plant species capable of thriving and developing in habitats with high salinity levels by effectively managing the challenges posed by excessive salt.

Plants possess diverse adaptive mechanisms to withstand and manage salt levels, including specialized root structures, salt elimination or containment, and efficient absorption of water and nutrients (Flowers and Colmer, 2015). The primary SAS ecosystems usually present a low alpha-biodiversity but contribute to the beta-biodiversity, due to the specialization of organisms surviving in such harsh environments. Many naturally salt-affected ecosystems of high ecological value have been degraded across the world by different political decisions or economical interested actions, including: the destruction of mangroves in Thailand, Vietnam, Mexico, Ecuador and other intertropical countries (FAO, 2007) transformed into ponds for shrimp farming; the desiccation of sabkhas around the Mediterranean coast, due to overexploitation of the aquifers that fill them; the reduction of water flow towards closed drainage basins is caused by diverting water for irrigation purposes, as seen in the case of the expansion of cotton fields that led to the drying up of the Aral Sea. Furthermore, SAS wetlands have also been transformed into agricultural fields by drainage, along with numerous other unfortunate instances; the transformation of SAS of wetlands to agricultural fields by draining them, and several other sadly examples (Mitsch and Gosselink, 2007). In other cases, the intrinsic value of such valuable ecosystems has been despised: “wetland=wasteland”, due to a lack of economic/agricultural activity

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The development of human-induced, or secondary salinization, due to erroneous management practices, degrades the capability of the soil to produce high yields of normal crops, or even impedes the normal development of plants. Secondary soil salinization can be caused by: i) agricultural irrigation activities involving the use waters of medium to high solute concentration (even brackish or saline waters) under semiarid and arid climate; ii) irrigation of sediments and soils containing fossil salts that are subsequently dissolved and mobilized; iii) marine spray and dust storms causing deposition of dispersed particles containing salts; iv) a rise in the saline water table induced by the deforestation causing a reduction in deep water pumping through the evapotranspirative mechanism of deep rooting,(Zhang *et al.*, 2017). Due to the scarcity or unavailability of water with low concentrations of electrolytes that is the origin of the problem of soil salinity in many cases, the desalinization procedure by leaching of salts from the soil profile is difficult, especially in SAS with low permeability or with a soil structure that impedes drainage (Arora, 2017).

The removal of salts from the soil, either through deep drainage into groundwater layers or through collection by the farm drainage system, represents a process of salt mobilization outside the cultivated area. This process has the potential to extend the issue of salinization to other hydrologically interconnected regions.

Salt-affected soils and climate change

The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (AR6) (Mukherji *et al.*, 2023) summarises the state of knowledge of climate change, forecasted impacts, induced risks, and the possibilities of climate change mitigation and adaptation. It is clearly recognized that climate change is already affecting many weather and climate extremes in every region across the globe; including changes in extremes such as heatwaves, heavy precipitation and droughts that will be accentuated in the future, leading to unfavourable scenarios related to water availability and increase of droughts. Forecasts suggest that there will be a rise in the extent of soil-affected by salinity and a potential decline in crop yields associated with salinity under specific circumstances.

Soil salinization and sodification are major threats to global food security and to the achievement of the Sustainable Development Goals (SDGs) as identified in the Status of the World Soil Resources report (FAO and ITPS, 2015). Climate change can have significant implications for salt-affected soils (Mukhopadhyay *et al.*, 2021). Some aspects on how climate change can impact salt-affected soils are:

- Sea-level rise and coastal marine intrusion: rising sea levels due to climate change lead to increased coastal intrusion, where saltwater floods inland areas and salinizes the coastal aquifers. This intrusion can contribute to the salinization of soils in coastal regions, making them unsuitable for traditional agriculture.
- Changes in precipitation patterns: climate change can alter precipitation patterns, resulting in changes in the amount, intensity, and distribution of rainfall. This can affect the leaching of salts from soils. Reduced rainfall and increased evaporation can lead to higher concentrations of salts in the soil, exacerbating salinization.
- Increased soil and air temperatures: higher temperatures associated with climate change can accelerate the evaporation of water from soils. This increased evaporation can concentrate salts in the root zone, leading to the accumulation of salts and increased soil salinity.
- Altered hydrological cycles: climate change can disrupt natural hydrological cycles, impacting the availability and quality of water resources. Changes in river flows, groundwater levels, and irrigation practices influence the movement and accumulation of salts in soils.
- Impact on vegetation and ecosystem dynamics: salt-affected soils already pose challenges for plant growth and ecosystem function. Climate change can further stress vegetation in salt-affected areas, leading to reduced plant productivity, changes in species composition, and altered ecosystem dynamics.
- Feedback loops and amplification: saline soils contribute to climate change through the release of greenhouse gases, such as carbon dioxide and nitrous oxide, from microbial activity. Climate change-induced changes in soil salinity affects these feedback loops, potentially amplifying greenhouse gas emissions.

What can saline agriculture offer?

Saline agriculture, also known as saltwater agriculture or halophyte agriculture, refers to the cultivation of plants in saline or salt-affected soils, or the use of saline water for irrigation, in areas where freshwater resources are limited or where the soil has a high salt content, making it unsuitable for conventional agriculture (Negacz *et al.*, 2022). High salt levels in the soil can be detrimental to most crops, as they hinder the ability of plants to absorb water and nutrients effectively, affecting photosynthesis, transpiration, causing plant growth inhibition, wilting and death of entire organs of most plants. However, saline agriculture focuses on utilizing plants that are naturally tolerant or adapted to high salt conditions (Santos *et al.*, 2016), known as halophytes, including sometimes the use of Technosols (Navarro-Torre *et al.*, 2023).

Saline agriculture can be beneficial in several ways:

- Utilization of marginal lands: saline agriculture allows for the cultivation of crops in areas that are not suitable for traditional agriculture due to soil salinity. This helps utilize otherwise unproductive land and expand agricultural possibilities.
- Conservation of freshwater resources: by using saline water for irrigation, saline agriculture reduces the demand for freshwater resources, which are often scarce in arid or coastal regions.
- Sustainable agriculture: saline agriculture can contribute to sustainable agricultural practices by reducing pressure on freshwater sources, preventing soil degradation, improving soil properties such as porosity and organic carbon content and increasing food production in challenging environments.
- Bioenergy production: some halophytes can be used for bioenergy production, such as the production of biofuels or biomass for energy generation, providing an alternative renewable energy source.

Despite the potential advantages offered by saline agriculture, it encounters obstacles such as limited crop choices, lower yields compared to conventional agriculture, potential environmental consequences, and the requirement for additional research and development to enhance both crop productivity and economic feasibility.

Sustainable management of salt-affected soils

Agriculture in soils under risk of salinization requires careful management practices to mitigate the adverse effects of high soil salinity. Hundreds of publications have developed approaches to sustainable management of SAS, for example Chhabra (2021), considering different aspects such as the environmental impact of the reclamation of SAS and the use of wastewaters as a non-conventional source of irrigation water. Several methodologies have reached maturity in terms of optimizing the sustainable use of agricultural fields under the risk of salinization:

- Methodologies of precision agriculture that allow mapping of soil salinity at high resolution or at a regional scale in quasi-real time, permitting the periodical survey of salinity changes and crop yield prediction; electromagnetic induction, drones and satellite multispectral images, instruments for proximal sensing, development of soils and vegetation spectral signatures, development of GIS driven by machine learning and neural networks.
- Mechanistic models simulating solute reactive transport through the soil, with atmospheric interaction, plant growth with water and nutrients uptake, and drainage to aquifers and artificial drainage systems. These models allow for optimization of irrigation water taking into account its chemical composition, computing drainage fraction and its composition, as well as salinity distribution into the profile along the time.
- Databases of plant species tolerance to salinity and water

requirements, of halophytes proteomics for adaptation of normal plants to salinity stress. Cataloguing of soil amendments to improve soil conditions.
- Increasing soil, climate, waters, and crops databases suitable for analysis using Big Data processing.
- Development of water desalinization technologies, such as reverse osmosis, and renewable energy sources (wind, solar).
- Technologies for saving water (drip irrigation, under plastic cropping) and optimization of fertilization (fertirrigation).

The adoption of those methodologies and exploitation of the multiple possibilities they offer, encounters several access barriers: lack of scientists and technicians, later acting as advisors, familiar with these approaches; economic barriers to acquire instruments, laboratory, field equipment and fungible materials; difficulties for translating the knowledge to farmers and stakeholders in an operative manner.

Government policies and support programs can play a crucial role in overcoming these barriers and promoting sustainable agriculture in salt-affected areas. Policies and supportive initiatives have a vital role to play in fostering sustainable agriculture in regions affected by salinity. Providing farmers with access to information, training, financial incentives, and technical assistance can aid in adopting appropriate practices for managing soil salinity. It is worth noting that the specific strategies and practices for managing agriculture in salt-affected soils may vary depending on the severity of salinization, local conditions, and available resources. Seeking guidance from local agricultural extension services or soil experts can provide valuable insights tailored to the specific region or farm.

The holistic approach to the management of salt-affected lands

"Land" concept is the basic element for agriculture and other rural land uses, encompassing soils, climate, vegetation, topography and other natural resources; hence this involves elements other than the soil, and is used as a basic processfor management and resources planning (FAO, 2022). The United Nations extended the concept, including plant and animal populations, the human settlement pattern and physical results of past and present human activities. Several classifications appeared trying to categorize lands according to their capacity to support different uses, among the best known are the "Land Capability Classification", presented by the USDA (USDA, 1961) and the Land Use/Land Cover classification system proposed by the US Geological Service for allowing land monitoring by remote sensing. The European Union has adopted the Land use/cover area frame statistical survey, abbreviated as LUCAS (JRC, ESDAC), supported by EUROSTAT for environmental management. Indicators constitute an interface between science and policy (Heink and Kowarik, 2010), and their correct selection plays a decisive role in the support for taking correct environmental management decisions. According to the OECD ('Environment at a Glance', 2005) an indicator is a parameter, or value derived from other parameters, that provides information and describes the state of a phenomenon with an added meaning greater than that directly associated with its own value.

Often, the management of affected lands is focused on a project or farm level, without considering the external factors or the intricate interconnections with the water cycle, biodiversity, and potential environmental consequences of the activity. New plans and projects should be evaluated within the framework of "Environmental Evaluation" and/or of "Environmental Impact Assessment" on the basis of a detailed conceptual model, structured according the DPSIR approach (Kristensen, 2004) that takes into account the Status of the land system "S", the Pressures over the system "P", the Impacts likely to occur "I", the possible Responses "R" and the Driving forces regulating the pressures "D". To make this possible a set of indicators for D, P, S, I, and R specially suited to salt-affected soils and lands has to be established, to optimize their management. Several authors have proposed general schemes of indicators, such as the Doran and Parkin's (1994) Soil Quality concept, or Costantini and Priory's (2023) expansion of the concept of Soil Quality to Soil Health. These kinds of proposals focused on soil properties, but a system with a holistic approach is needed to reflect the complex interactions between nature and society. An interesting approach is presented by Bergez et al. (2022) integrating agri-environmental indicators, ecosystem services assessment, life cycle assessment and yield gap analysis to assess the environmental sustainability of agriculture.

The restoration of degraded lands and ecosystems is of particular interest to enable a sustainable future. Numerous saline wetlands have been transformed, desiccated or polluted. Many irrigation projects have been abandoned after wrong management and progressive degradation. It could be illustrative to perform post-hoc environmental impact studies at those sites, including not only biophysical variables, but also including life-cycle and other methodologies from economic disciplines to learn from past errors.

Convergence of efforts: the GSP and INSAS

A global map of SAS, with a ground resolution of 1 km^2 was published by FAO (FAO, 2021). Although still not complete, it contains the contribution of 118 Countries, with more than 250.000 points where EC, ESP and pH, were measured at two depth intervals (0-30 cm) and (30-100 cm). From examination of the map, it can be stated that SAS appear at any latitude, have different characteristics, can be found at the coasts and inside continents, and soils affected by secondary salinization. This synthetised information is directed to make the policy makers, researchers and students aware of the magnitude and extent of the salinization degradation process.

The 2002 recommendation of the International Union of Soil Sciences (IUSS) to devote an international day to celebrate Soils, led to the FAO, within the framework of the Global Soil Partnership (GSP), receiving the mandate to facilitate implementation of the World Soil Day. FAO Members and GSP partners at the 8th GSP Plenary Assembly agreed that the WSD 2021 has to be devoted to the theme "*Halt soil salinization, boost soil productivity*", ('About | World Soil Day, 5 December | Food and Agriculture Organization of the United Nations'), (Stanco, 2021). The aim of WSD 2021 was to focus the attention of the world's population on to the increasing environmental problem that imperils food production and leads to environmental degradation. Many informative, multimedia and didactic documents were produced, to be used at any educational level, from schools to universities to raise awareness of the nature of SAS, the environmental value of natural saline ecosystems and the risks of the degrading processes of salinization, giving recommendations of correct management of soils and waters.

After numerous symposia devoted to SAS and thousands of publications over decades, it became evident that research and extension efforts would benefit from convergence in a global Technical Network, integrating scientists, technicians, academics, decision makers, stakeholders and interested persons. In this way the International Network of Salt-Affected Soils (INSAS) (‘INSAS | Global Soil Partnership | Food and Agriculture Organization of the United Nations’) was established by the recommendation of the Intergovernmental Technical Panel on Soils (ITPS) under the coordination of the Global Soil Partnership (GSP). The launch of INSAS took place during the Global Forum on Innovations for Marginal Environments on 20-21 November 2019, in Dubai, and aimed to facilitate the sustainable and productive management of salt-affected soils for current and future generations. Since its start the INSAS has celebrated two plenary meetings, produced several documents, participated in the organization of the Global Symposium on Salt-affected Soils (GSAS21) and is very active in virtual modality meetings.

The establishment of this network has the following objectives:

- To promote the sustainable management of SAS .
- To develop a harmonized approach and indicators for the assessment, mapping and monitoring of salt-affected soils.
- To develop guidelines and manuals on good practices for the sustainable management of SAS .
- To provide a platform for countries with salt-affected soils to discuss common issues related to the most suitable methods for protection from deterioration and the sustainable management and reclamation of salt-affected soils, as well as establish a network of experts on salt-affected soils to share and develop further knowledge on the issue.
- To foster collaboration among INSAS member countries towards promoting the sustainable use and management of salt-affected soils, identify relevant knowledge and research gaps and promote regional and global joint research and development programs.
- To enhance collaboration between scientists, practitioners and policy-makers aimed at the sustainable management of salt-affected soils.
- To serve as a platform for capacity development, knowledge sharing and technical cooperation on salt-affected soils monitoring and management.
- To advocate towards the halting and reversal of the negative trends in the expansion of salt-affected soils through different instruments.

Conclusions

Soil and water salinization are experiencing a worldwide expansion in both scale and severity, with climate change expected to further exacerbate their environmental consequences. Such degradative process must be halted, and the SAS ecosystems and agricultural lands must be managed in a sustainable way and restored. To make this possible, there exists an impressive background of scientific/technical knowledge as well as modern technologies that can be used for suitable agricultural production, saving water, energy and other resources in an environmentally friendly way. GSP and the INSAS can play an active role in the coordinated joint work of scientists, stakeholders, farmers and decision makers through concentration and transmission of knowledge, capacity building, education, guidelines recommendation and other aspects related to salt-affected soils.

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