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First National Report on Soil Salinity Across Paraguay☆

Primer Informe Nacional sobre la Salinidad del Suelo en Paraguay

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Abstract

Assessing soil salinity on a national scale provides crucial information on soil fertility. Our objective was to map soil salinity in Paraguay at the topsoil layer (0-30 cm) using indicators such as Electrical Conductivity (EC), pH, and Exchangeable Sodium Percent (ESP). We employed a model with 80 data points for Electrical Conductivity (EC) and 204 points for pH and Exchangeable Sodium Percent (ESP). The statistical model used to map soil salinity properties was the "quantile random forest." For validation and accuracy calculation, we utilized "cross-validation" with all soil sampling sites and a "Random" selection parameter. To ensure result consistency, we repeated the validation five times, calculating the average of the results. Uncertainty was estimated using "predUncertain-quantile random forest," implemented in the R programming language. In general, Paraguayan soils at a depth of 0 to 30 cm exhibit low salt levels, with the soils in the Paraguayan Chaco region showing higher levels. Two primary factors contribute to soil salinity in Paraguay: natural factors, such as a dry climate, high temperatures, and high evapotranspiration, and secondary factors, including soil parent material with alluvial deposits and groundwater with significant salt content. It's worth noting that actual salinity values, both in Paraguayan Chaco and the eastern region, might surpass those mentioned in this study due to limited available data and the spatial resolution of the map. This study represents the first effort to develop a soil salinity map of Paraguay, providing the initial national baseline for the development of salinity/sodicity monitoring frameworks. It can be instrumental in addressing regional gaps in salinity/sodicity within South America.

Keywords: digital soil mapping, salinity, sodicity, Paraguay.

Resumen

Evaluar la salinidad del suelo a escala nacional proporciona información crucial sobre la fertilidad del suelo. Nuestro objetivo fue mapear la salinidad del suelo en Paraguay en la capa superficial (0-30 cm) utilizando indicadores como la Conductividad Eléctrica (EC), el pH y el Porcentaje de Sodio Intercambiable (ESP). Empleamos un modelo con 80 puntos de datos para la Conductividad Eléctrica (EC) y 204 puntos para el pH y el Porcentaje de Sodio Intercambiable (ESP). El modelo estadístico utilizado para mapear las propiedades de salinidad del suelo fue el "quantile random forest". Para la validación y el cálculo de la precisión, utilizamos la "validación cruzadaçon todos los sitios de muestreo de suelo y un parámetro de selección Random". Para garantizar la consistencia de los resultados, repetimos la validación cinco veces, calculando el promedio de los resultados. La incertidumbre se estimó utilizando "predUncertain-quantile random forest", implementado en el lenguaje de programación R. En general, los suelos paraguayos a una profundidad de 0 a 30 cm muestran niveles bajos de sal, siendo los suelos en la región del Chaco Paraguayo los que presentan niveles más altos. Dos factores principales contribuyen a la salinidad del suelo en Paraguay: factores naturales como un clima seco, altas temperaturas y una alta evapotranspiración, y factores secundarios que incluyen el material parental del suelo con depósitos aluviales y agua subterránea con un contenido significativo de sal. Es importante señalar que los valores de salinidad, tanto en el Chaco Paraguayo como en la región oriental, podrían superar los mencionados en este estudio debido a la limitación de datos disponibles y la resolución espacial del mapa. Este estudio representa el primer esfuerzo para desarrollar un mapa de salinidad del suelo de Paraguay, proporcionando la línea de base nacional inicial para el desarrollo de marcos de monitoreo de salinidad/sodicidad. Puede ser fundamental para abordar lagunas regionales en salinidad/sodicidad dentro de América del Sur.

Palabras clave: mapeo digital de suelos, salinidad, sodicidad, Paraguay

1. Introduction

Salinization stands as a significant form of soil degradation, exerting adverse effects on natural ecosystems, agroecosystems, and agricultural productivity in arid and semi-arid regions globally (Bas et al., 2017; Gebremedhin et al., 2018). It has repercussions on the functional health of ecosystems, habitat, and local biodiversity (Viglizzo and Ricard, 2021), exhibiting spatial and temporal variability influenced by factors such as groundwater fluctuation, water salinity, artificial irrigation, and human-induced alterations (Zhu et al., 2022).

Increased soil salinity adversely affects the community's social structure, diminishing the landscape's aesthetic value, reducing agricultural revenue, and lowering commercial property value due to soil degradation and a lack of agricultural jobs (Da Silva Dias et al., 2021). Salinity arises from natural, human, or combined actions on the Earth's dynamic system (Gebremedhin et al., 2018), with variations influenced by climate, soil texture, vegetation type, soil depth, and land use changes.

Estimating soil salinity through electrical conductivity is a common practice, with Bas et al. (2017) noting that electrical conductivity increases with salinity. In dry climate zones, expanding cultivated land contributes to soil salinization. Despite the importance of understanding and managing soil salinity, estimates of salt-affected soils in Latin America are often imprecise and outdated, relying partially on expert judgment (Taleisnik, 2021).

Changes in land use and vegetation can alter water fluxes, affecting salt retention mechanisms (Jobbágy et al., 2021). Secondary salt-affected soils in Latin America, often developed under irrigation, result from low irrigation water quality and inefficient water management (Taleisnik, 2021). Studies in the region indicate that soil salinity problems are linked to high water tables in certain sectors, impacting Exchangeable Sodium Percentage (ESP) levels during the irrigation season (Torres Duggan et al., 2017).

Identifying salinization-vulnerable ecosystems is crucial for developing adaptation policies and mitigating the negative impacts on food production and security (Battle, 2011). Beyond land degradation, a changing climate poses significant challenges to soil properties, natural vegetation, land use practices, and food production security (Várallyay, 2010). Different plant species exhibit varying levels of adaptability or vulnerability based on soil salt content, highlighting the importance of recognizing temporal and spatial responses to salinization episodes caused by climate change (Jobbágy et al., 2017).

Soil salinity's socioeconomic impacts include reduced crop yields, leading to the loss of commercial value of agricultural land (Da Silva Dias et al., 2021). Salinization diminishes plant growth, agricultural productivity, and fruit quality (Machado and Serralheiro, 2017; Ferreira et al., 2019), categorizing all soils with salt-related issues as "salt-affected soils" (Pla Sentís, 1983). Such soils, whether saline or sodic, negatively impact physical and chemical soil properties, crop production, and animal and human health under both dryland and irrigated conditions (Pla Sentís, 2014a; Pla Sentís, 2014b).

Salinization in irrigated areas is a significant concern for farmers in arid and semiarid zones worldwide, accelerated by human activities such as deforestation and poorly managed irrigation (Da Silva Dias et al., 2021). Water sources with high salt concentrations can compromise irrigated areas and agricultural production, exacerbated by edaphoclimatic conditions and improper management practices (Medeiros et al., 2017; Brito et al., 2017), leading to a decline in soil biodiversity (Bui, 2013).

In Paraguay, the relationship between topography, land cover, precipitation, groundwater salinity, and surface salinization is evident. The Paraguayan Chaco region experiences the highest concentrations of salts, attributed to both natural causes like dry climate and saline aquifers and anthropogenic factors due to changes in land cover (Glatzle et al., 2020). Deforestation, replacing natural forests with shallow-rooted crops and pastures, has brought saline groundwater closer to the soil surface, causing salinization. This necessitates the substitution of actual crops with more salt-tolerant varieties over time (Glatzle et al., 2020).

Paraguay comprises two distinct regions with different climates and soil properties: the dry Paraguayan Chaco (western region), characterized by significant salinity and sodicity, and the eastern region with a humid climate and low salt levels (Grassi, 2020; López et al., 1995). Despite this diversity, there is a lack of salinity or sodium maps for these regions. The present study, in collaboration with FAO, aims to fill this gap by creating salinity risk maps based on FAO's methodology (FAO, 2020). This work marks the first systematic attempt to map soil salinity at the national level in Paraguay, utilizing soil profile data and digital soil mapping methods. The generated digital maps encompass electrical conductivity (EC), pH, and Exchangeable Sodium Percentage in the soil (ESP), along with a comprehensive summary map titled "Soils affected by salts" at a depth of 0 to 30 cm. Given the severe concentration of salts and sodium in the Paraguayan Chaco, and minimal presence in the eastern region, this study contributes valuable information for land-use planning, particularly in regions prone to dryland salinity. With a focus on generating new knowledge and threat monitoring, this research addresses the critical need for understanding soil salinity in Paraguay. The ultimate goal is to mitigate the potential impact of high soil salinization on food production in the country.

2. Area of Study

This study encompasses the whole Paraguay, situated in the central region of South America and covering an area of 406,752

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km². The topography is predominantly characterized by plains, with elevations not exceeding 850 meters above sea level. Paraguay features two distinct climatic and soil regions: the Paraguayan Chaco and the Oriental or eastern region.

- Paraguayan Chaco (Western or Occidental Region):
  - Climate: Dry, with an average annual rainfall of 800 mm/year (Grassi, 2020).
  - Soil Properties: Significantly high levels of salinity and sodicity, as reported by Alvarenga et al., 1998.
  - Temperature: The average temperature ranges from 24 to 26°C (Devenish et al., 2009; MADES-DGPCB, 2019).
  - Dominant Soils: Predominantly Alfisols (80%), Entisols (15%), and Ultisols (5%).
  - Land Cover and Land Use: dominant land cover consists of 43% forest.
- Oriental or Eastern Region:
  - Climate: Humid, with an average annual rainfall of 1700 mm/year (Grassi, 2020).
  - Temperature: The average temperature ranges from 21 to 22°C.
  - Dominant Soils: Primarily Ultisols (37%), Alfisols (32%), Entisols (13%), Inceptisols (6%), Oxisols (6%), Vertisols (1%), Mollisols (1%), and 4% mixed soils (López Gorostiaga et al., 1995).
  - Land Cover and Land Use: forest covers 43% of the land, while agricultural and livestock activities occupy 33% (FFPRI. & UNA, 2011).

3. Data

3.1. Database Creation

The database employed in this study was generated by a team from the Facultad de Ciencias Agrarias, Universidad Nacional de Asunción. It comprises 204 observations derived from soil profiles and samples collected from the topsoil (first 30 cm) (Figure 1). The data originates from the projects "Study of Soil Recognition and Land Use Capacity of the Eastern Region of Paraguay" (López et al., 1993) and the "Chaco Environmental System Project" (Alvarenga et al., 1998). Additionally, data was sourced from private studies conducted in both the eastern and western regions of Paraguay. The data utilized in this study spans the years 1993 to 2018.

The distribution of the 204 soil sampling sites is depicted in Figure 1. These points encompass data on crucial properties such as electrical conductivity, pH, and the percentage of exchangeable sodium. Importantly, these sites are situated in cropland areas. Table 1 provides a summary of the main soil properties at a depth of 0 to 30 cm.

Table 1. Summary Statistics of 0 -30 cm depth soil properties / Table 1. Resumen de estadísticas de las propiedades del suelo de 0 a 30 cm de profundidad

Summary Statistics	EC	pH	ESP
Mean	0.400	6.31	5.23
Stándar Desviation	0.600	0.82	8.19
IQR	0.370	1.17	4.48
Variance	0.360	0.67	67.1
Range	3.154	4.38	55.50
Minimum	0.016	4.58	0.006
Maximum	3.170	8.96	55.51

Figure 1. Location of soil sampling sites in Paraguay, 0 – 30 cm depth. / Figura 1. Ubicación de los sitios de muestreo de suelos en Paraguay, 0 – 30 cm de profundidad.

3.2. Amount of data and Distribution

The map of salt-affected soils was created using data from 80 points for Electrical Conductivity (EC) and 204 points for pH and Exchangeable Sodium Percentage (ESP). These data were collected from soil analyses conducted throughout the country, complemented by information from the Paraguay Occidental Region Soil Map (Scale 1:750,000) and the Paraguay Oriental Region Soil Map (Scale 1:500,000).

3.3. Soil Depths

The soil depths considered for mapping range exclusively from 0 cm to 30 cm. It's worth noting that the majority of Paraguay's territory, approximately 90%, features very deep soils exceeding 150 cm in depth. Generally, soils in lowland areas and near hills and mountain ranges are shallow, typically less than 50 cm deep.

3.4. Soil Indicators of Salinity/Sodicity

The key indicators for salinity/sodicity are Electrical Conductivity (EC), pH, and Exchangeable Sodium Percent (ESP). These variables were chosen for their effectiveness in conveying information about soil salinity (FAO, 2020). EC data were obtained using a 1:5 solution, measured with an electrical conductivity meter, and expressed in dS/m. pH values were determined through dilution with distilled water at a soil/water ratio of 1:1, measured with a hydrogen ion concentration meter. ESP was estimated from Sodium Adsorption Ratio (NA) and Cation Exchange Capacity (CIC), with the formula for ESP being (NA / CIC (sum of bases)) * 100.

4. Methodology

The development and validation of the map adhered to the methodology outlined in FAO, 2020 (See Figure 2). Following the cartographic approach proposed by FAO, the digital model employed for mapping soil salinity-related properties was the "quantile random forest" (FAO, 2020; Omuto et al., 2020), a function within the “soilassessment” package. Specifically the “regmodelsuit” function is used for guiding the selection of the best prediction model which in our case was "quantrandforest."

For validation and accuracy assessment, the "cross-validation" technique was applied. This involved utilizing all soil sampling sites with a selection parameter set to "Random," ensuring result consistency. The validation process was repeated five times to calculate the average results.

Additionally, uncertainty was estimated using the "predUncertain-quantile random forest" function in R (See Figure 3). The uncertain quantity was determined through a bootstrap approach, extracting uncertainty at a 95% confidence interval using the "preduncertain" function within the soil assessment package (Efron, 1992).

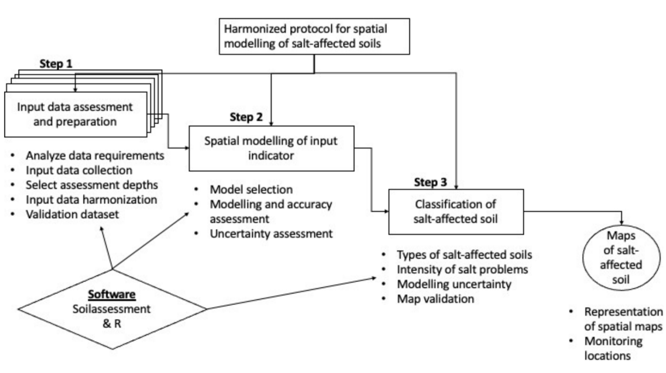

Figure 2. Methodological approach (Taken from FAO, 2020). / Figura 2. Enfoque metodológico (Tomado de FAO, 2020).

Technical specifications of the generated maps are as follows:

a) The properties (EC, pH, and ESP) were mapped through 0 to 30 cm depths.

b) The coordinate reference system utilized was the "Geographic Coordinate System," with datum WGS84, in decimal degrees.

c) The spatial resolution was 1 km² (approximately 30 arc seconds).

To model the spatial variation of each mapped property (EC, pH, and ESP), various covariates were incorporated, including:

- Precipitation
- Minimum monthly temperature
- Annual average cloud cover
- Digital elevation model
- Topographic humidity index
- Vegetation index
- Vegetation cover and current land use
- USDA and WRB soil class map
- Soil pH
- MODIS satellite imagery
- Geological ages based on surface geology

5. Results and Discussion

5.1. Proportions of Salt-Affected Areas

Overall, Paraguay’s soils at a depth of 0 to 30 cm generally exhibit low levels of salts (see Figure 4), with the Western Region or Paraguayan Chaco (Dryland) soils showing comparatively higher levels (see Plate 1). Salinity, as highlighted by Taleisnik, 2021, can vary based on climate, with higher levels observed in soils of dry climates. It is important to note that the surface area of salt-affected soils in both the western and the eastern regions of Paraguay may potentially be higher than the reported values. This is attributed to the scarcity of available data and the spatial resolution limitations of the maps, which might not accurately represent areas with localized concentrations and a tendency toward sodicity. Table 2 provides the calculated area of soils affected by salts. The accuracy of the created maps for EC, ESP and pH is presented in Table 3.

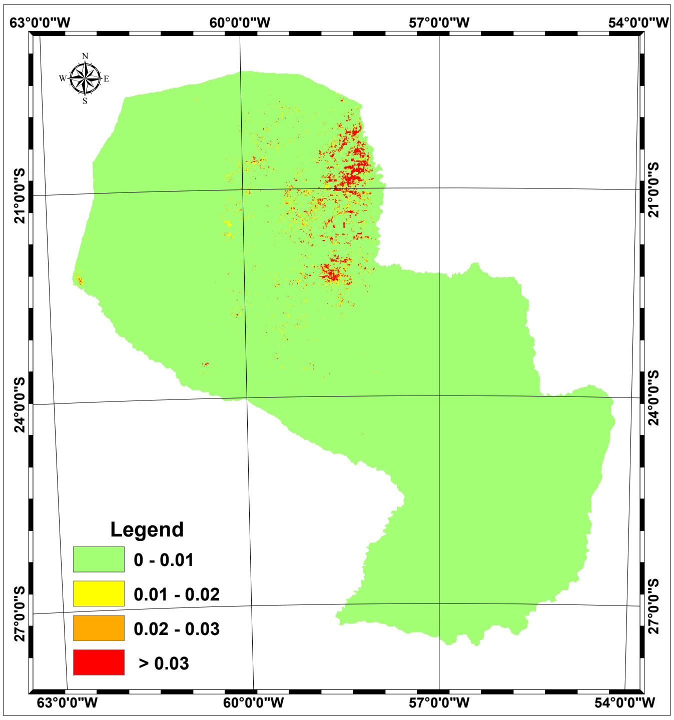

Figure 3. Uncertainty of the final map of Salt-Affected Soils of Paraguay, 0 – 30 cm depth. / Figura 3. Incertidumbre del mapa final de Suelos Afectados por Sal del Paraguay, 0 – 30 cm de profundidad.

Table 2. Summary of salt-affected areas of Paraguay, 0 to 30 cm depth / Table 2. Resumen de áreas afectadas por la sal del Paraguay, 0 a 30 cm de profundidad

Class Code	Map Values	Proportion (%)	Area (Ha)
None	None	97.49	39.654.252,48
Slight Salinity	Slight Salinity	0.91	370.144,32
Slight Sodicity	Slight Sodicity	1.60	650.803,20
Total			**40.675.200**

5.2. Drivers of Salt-Affected Soils

In Paraguay's soils, the factors influencing the presence of salinity can be categorized into two main groups:

- Primary Factors / Natural Factors: These include a dry climate, high temperatures, high evapotranspiration, parental soil material with alluvial deposits, and groundwater with significant salt content. In dry climates, like the Paraguayan Chaco, insufficient rainfall impedes salt leaching, and elevated temperatures on the soil surface may contribute to salt crystal accumulation. Natural causes involve the presence of aquifers or saline surface groundwater, concentrated mainly in the transition zone between the humid and dry Chaco. This belt, spanning 50 to 75 km in width and 500 km in length, features lagoons, marshes, and low fields naturally high in salts. Soil salinization, as indicated by Zhu et al., 2022, can exhibit spatial and temporal variability, influenced by factors such as salt concentration in water, groundwater fluctuation, and artificial irrigation.
- Secondary Factors / Human-Induced Factors: These arise primarily from human activities, such as land-use changes, extensive deforestation, loss of soil protection, exposure to high temperatures, and erosion. The existence of saline or sodium soils in the Paraguayan Chaco is influenced by a combination of natural and anthropic factors. The anthropic factor has significantly exacerbated the salinization problem in the Paraguayan Chaco over recent decades. According to Gebremedhin et al., 2018; and Jobbágy et al., 2021, salinization can intensify due to human actions, particularly land use and vegetation changes. Deforestation, especially in the central Chaco, facilitates salt enrichment in surface layers through rapid groundwater rise since the 1960s. The significant increase in land use change, particularly the conversion of forests to pasture at a rate approaching 100,000 hectares per year, has resulted in approximately 1,000,000 hectares of pasture by present estimates (Glatzle et al., 2020). Furthermore, the construction of dams and roads contributes to salinization by inducing river drying, favoring saline outcrops. This process is believed to lead to the emergence of highly saline groundwater to the surface due to hydrostatic pressure, potentially eliminating fresh water at the surface.

Table 3. Accuracy assessment of produced DSM for pH, EC and ESP maps / Tabla 3. Evaluación de la precisión del DSM producido para mapas de pH, CE y ESP

0 - 30 cm	Biasc	RMSEc (%)	Rsquaredc (Ha)
EC (ds/m)	1.04	1.23	0.3
pH	0.27	0.66	0.42
ESP (%)	1.28	1.66	0.36

5.3. Practices for Managing Salt-Affected Soils

In the Chaco region of Paraguay, soil management practices aimed at mitigating the adverse effects of salinization primarily revolve around several key strategies:

- Selection of Soils: Choosing and utilizing soils with low salt levels is crucial. Minimizing disturbance to the soil surface during clearing activities is emphasized.

MAP OF SALT - AFFECTED SOILS OF PARAGUAY, 0 – 30 CM. DEEP

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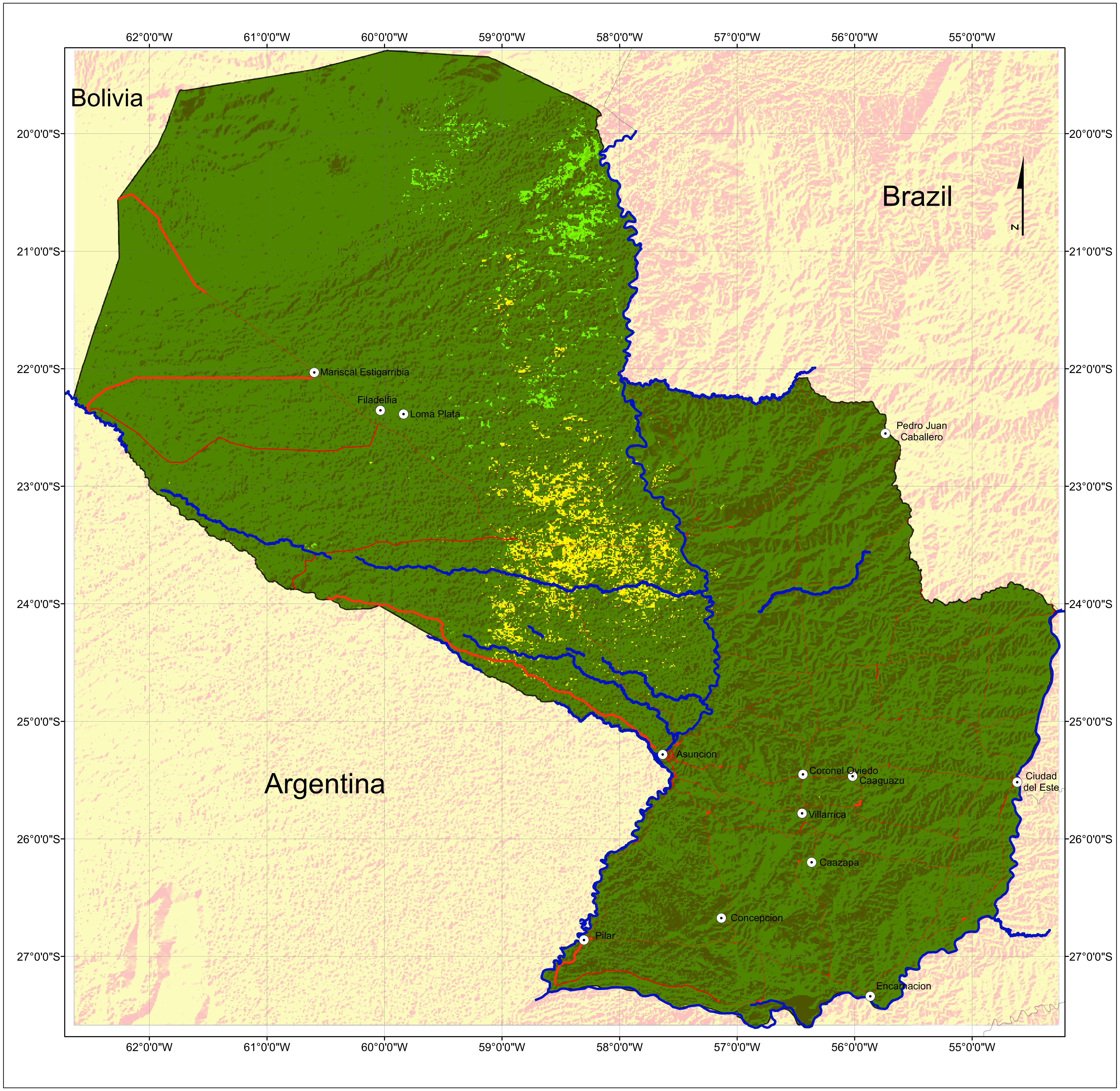


Legend

- None
- SlightSalinity
- SlightSodicity

Conventional signs

- Primary road
- Secondary road
- Trunk road
- Rivers

Scale

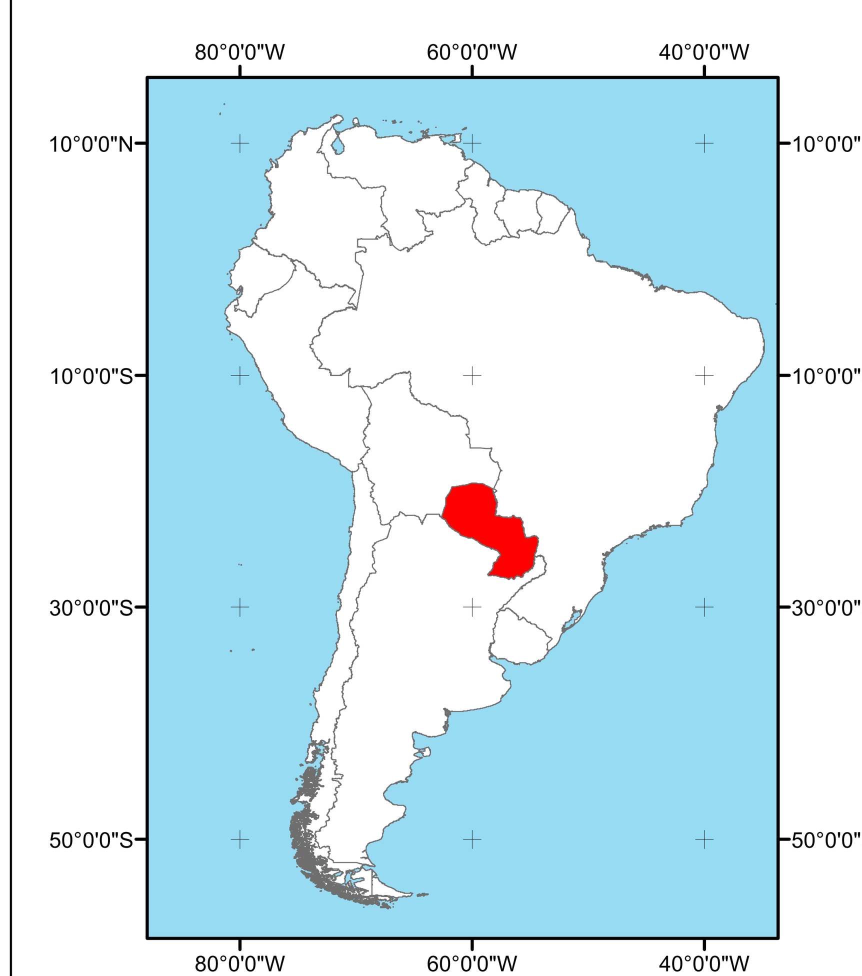
1:1,900,000

Graphic scale

0 60 120

Kilometers

Relative location



- Vegetative Cover: Maintaining continuous soil coverage with dense vegetation for as long as possible is a key practice. This approach includes the establishment of living barriers to mitigate the impacts of both wind and water erosion.
- Organic Matter Retention: Maximizing the retention of organic matter on the soil is considered good management practice.
- Irrigation Management: When introducing irrigation water, precautions are taken to avoid reaching saline horizons. This is particularly relevant in areas where salinity is present to prevent the capillarity effect from salinizing the arable or adjacent layers.

Figure 4: Salt-affected soils of Paraguay, Central Chaco, 0 to 30 cm depths. / Figura 4: Suelos, de 0 a 30 cm de profundidad, afectados por la salinidad de Paraguay, Chaco Central.

Additionally, Glatzle et al., 2020, and Da Silva Dias et al., 2021, underscore the importance of promoting the adoption of salt- and drought-tolerant crops as a part of effective management. Social technologies that enhance food production are also highlighted.

Moreover, Da Silva Dias et al., 2021, suggest that utilizing reject brine for agricultural purposes can be economically viable in rural communities, contributing to the environmental conservation of soil and water resources. It is crucial, however, to consider both the salinity of the water input for desalinizers and the local soil conditions where reject brine is applied for growing crops.

Lamontagne et al., 2005, stress the significance of understanding spatial and vertical variability in hydraulic recharge for designing effective salinity remediation strategies.

Finally, Yao et al., 2022, recommend extracting an appropriate amount of groundwater based on availability and salinity levels. Artificial recharge of aquifers with severe salt accumulation is identified as a potential strategy to reduce both agricultural production losses and groundwater salinity.

6. Conclusions

The initial salinity maps derived for Paraguay's soils in this study provide a clear, albeit general, depiction of the highest concentrations of salts and sodium in the Paraguayan Chaco (Western Region). This region is characterized by high temperatures and minimal annual rainfall. Conversely, in the Eastern Region with its humid climate, the presence of salts at depths of 0 to 30 cm is either very low or nonexistent.

While acknowledging potential differences between the occurrence of salt-affected soils in the country and the presented maps due to the scale of the study, specific soil conditions, and the limited dataset, we believe it is important to consider the recommendations made herein. Given the scale and limitations of this initial work—such as the scarcity and outdated nature of available data and the shallow depth of the study—it is highly advisable to advocate for monitoring programs. These programs should aim to provide more detailed, updated, and in-depth studies to enhance the accuracy and comprehensiveness of soil salinity assessments in Paraguay.

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