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ARTIGO ORIGINAL

Four decades of soil moisture decline: a remote sensing analysis of southern ñeembucú, Paraguay (1983-2023)

Quatro décadas de declínio da umidade do solo: uma análise de sensoriamento remoto do sul de Ñeembucú, Paraguai (1983-2023)

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Porfírio Domingo Arévalos Vera[1]
https://orcid.org/0009-0000-8726-3193
Universidad Nacional de Pilar, Paraguay
E-mail: darevalos@gmail.com

Walter Esfrain Pereira[2]
https://orcid.org/0000-0003-1085-0191
http://lattes.cnpq.br/2768224289814375
Universidade Federal da Paraíba, Centro de Ciências Agrárias, PB, Brasil
E-mail: wep@cca.ufpb.br

Abstract

The objective of this research is to analyze the evolution of soil moisture in the southern region of Ñeembucú Department from 1983 to 2023, utilizing remote sensing data and geospatial processing techniques, as well as to evaluate soil moisture trends at different depths (0 to 290 cm). The focus is on changes that have occurred over the last four decades in an area characterized by wetlands. The selected area covers a total surface of 6,636.499 km2, encompassing the districts of Pilar, Humaitá, Paso de Patria, General Díaz, Mayor Martínez, Isla Umbú, Desmochados, Guazu Cuá, Tacuaras, Villalbín and Laureles. Remote sensing data and geospatial processing techniques were employed, using image collections from "NASA/FLDAS/NOAH01/C/GL/M/V001" and "ECMWF/ERA5_LAND/MONTHLY_AGGR" from Google Earth Engine, filtered for the study area. Variables of interest included soil water content in layers: 0-10 cm, 10-40 cm, 40-100 cm and 100-200 cm, and 0-7 cm, 7-28 cm, 28-100 cm and 100-289 cm, respectively. It was verified generalized decrease in soil moisture across all layers, most pronounced in surface layers. Deeper layers experienced a more gradual reduction. In conclusion, the southern region of Ñeembucú has experienced a consistent reduction in soil moisture over the past four decades, attributed to both climatic and anthropogenic factors. This study highlights the urgent need to adopt mitigation measures and sustainable management practices to preserve ecosystems and ensure long-term water resource availability.

Keywords: soil moisture dynamics; remote sensing; wetland ecosystems.

[1] Graduado em Agronomia, Doctor em Desarrollo y Defensa Nacional
[2] Graduado em Agronomia, D. Sc. em Fitotecnia.

Resumo

O objetivo desta pesquisa é analisar a evolução da umidade do solo na região sul do Departamento de Ñeembucú de 1983 a 2023, utilizando dados de sensoriamento remoto e técnicas de processamento geoespacial, bem como avaliar as tendências de umidade do solo em diferentes profundidades (0 a 290 cm). O foco está nas mudanças ocorridas nas últimas quatro décadas em uma área caracterizada por zonas úmidas. A área selecionada abrange uma superfície total de 6.636,499 km², englobando os distritos de Pilar, Humaitá, Paso de Patria, General Díaz, Mayor Martínez, Isla Umbú, Desmochados, Guazu Cuá, Tacuaras, Villalbín e Laureles. Foram empregados dados de sensoriamento remoto e técnicas de processamento geoespacial, utilizando coleções de imagens "NASA/FLDAS/NOAH01/C/GL/M/V001" e "ECMWF/ERA5_LAND/MONTHLY_AGGR" do Google Earth Engine, filtradas para a área de estudo. As variáveis de interesse incluiram o conteúdo de água no solo em camadas: 0-10 cm, 10-40 cm, 40-100 cm e 100-200 cm, e 0-7 cm, 7-28 cm, 28-100 cm e 100-289 cm, respectivamente. Verificou-se diminuição generalizada da umidade do solo em todas as camadas, mais pronunciada nas camadas superficiais. As camadas mais profundas experimentaram uma redução mais gradual. Em conclusão, a região sul de Ñeembucú sofreu uma redução consistente da umidade do solo ao longo das últimas quatro décadas, atribuída a fatores tanto climáticos quanto antropogênicos. Este estudo destaca a necessidade urgente de adotar medidas de mitigação e práticas de gestão sustentável para preservar os ecossistemas e garantir a disponibilidade de recursos hídricos a longo prazo.

Palavras-chave: *dinâmica da umidade do solo; sensoriamento remoto; ecossistemas de zonas úmidas.*

1. Introduction

Soil moisture content is fundamental to the dynamics that develop in the soil, the interaction with vegetation, and the exchange of matter and energy with the atmosphere. Soil moisture directly influences essential ecological processes, such as nutrient availability for plants, microbial activity, and ecosystem stability. Its relevance increases in fragile ecosystems such as wetlands, where the hydrological regime and groundwater masses at various depths are determinants for their sustainability. In these environments, both excess and lack of moisture can trigger significant changes in ecosystem structure and functioning.

Wetlands, defined as transitional areas between terrestrial and aquatic ecosystems, are highly productive and provide a wide range of ecosystem services, such as water resource provision, biodiversity maintenance, climate regulation, and protection against extreme events like floods and droughts (Lubal, 2024; Ballut-Daju, 2022). However, these ecosystems are under constant degradation due to human activities and climate change. According to the Ramsar Convention Secretariat (2015) and Zivec et al. (2023), wetland surface area has drastically decreased globally, affecting their functionality and biodiversity. Particularly in the southern region of Ñeembucú Department, a significant decrease in forested areas, marshes, grasslands, and prairies has been observed over the last 35 years (Vera & Pereira, 2024), suggesting that soil moisture levels have also decreased due to environmental deterioration.

Soil moisture plays a crucial role in various disciplines such as climate science, agriculture, soil science, and the hydrological cycle. It affects processes like runoff, land-atmosphere interactions, and net gas exchange in ecosystems (Li et al., 2022).

Caicedo-Rosero et al. (2021) highlight that soil moisture depends on the forces acting on water molecules, determined by soil structure and composition. Adsorption and capillary forces retain water in soil pores, ensuring adequate moisture levels. Soil texture, defined by the proportion of clay, silt, and sand, influences the soil's capacity to store water and carbon, with clay soils retaining more water due to their higher quantity of micropores and specific properties (Varón-Ramírez et al., 2022).

Additionally, soil organic matter plays an essential role in water retention. Soils with higher organic matter content have a better capacity to retain moisture, which improves soil structure and infiltration capacity (Molina et al., 2022). Soil moisture variability is high both in time and space, due to the heterogeneity of soil properties, topography, vegetation cover, evapotranspiration, and precipitation uniformity (Quintana Molina et al., 2023). This variability affects water availability for plants and soil microorganisms, influencing biogeochemical processes and ecosystem stability (Srivastava et al., 2022).

Measuring soil moisture is essential for understanding the biological, hydrological, agronomic, and ecological characteristics of soil (Rasheed et al., 2022). Traditionally, these measurements over large areas require significant time and resource efforts. However, remote sensing technologies have revolutionized this field, allowing the acquisition of accurate and real-time data through satellite image analysis (León Fernández & Garavito Rincón, 2021). Satellite images provide broad and periodic coverage, facilitating continuous monitoring and precise estimation of changes in soil moisture (Santi Ruiz, 2018). This monitoring capability is especially useful in extensive and difficult-to-access areas, such as wetlands, where traditional data collection can be costly and laborious.

In the southern region of Ñeembucú Department, the decrease in soil moisture has been attributed to a combination of climatic and anthropogenic factors. The IPCC report (2021) indicates that climate change has increased temperatures and altered precipitation patterns, which in this area translates to lower annual precipitation or more concentrated rainfall in short periods. Smurov et al. (2023) and Smith & Chang (2020) corroborate that the increase in evapotranspiration, due to increased temperatures and altered precipitation, has significantly contributed to the reduction of soil moisture. Moreover, human activities, such as intensive agricultural practices and deforestation, have exacerbated this situation. Czigány et al. (2023) and Pysarenko & Krakovska (2022) point out that deforestation and intensive agricultural operations increase evapotranspiration and alter soil moisture dynamics, while Botta et al. (2022) observe that soil compaction from livestock activities decreases the soil's capacity to retain water.

The implications of this decrease in soil moisture are significant for sectors such as agriculture, water resource management, and biodiversity conservation. Bogati et al. (2023) highlight that lower moisture reduces microbial activity and nutrient cycling, affecting agricultural productivity. Zhou et al. (2023) add that dry soil layers harm vegetation and ecosystem services, while DeVilleneuve (2023) warns about increased erosion, which puts habitats and water quality at risk. These consequences not only affect agricultural productivity but also compromise the health of ecosystems and the resilience of human communities that depend on them.

To mitigate these effects, it is essential to implement sustainable water and soil management strategies. Kazemzadeh et al. (2021) propose watershed management practices and increasing vegetation cover to improve water retention. Reforestation and conservation of native forests, as suggested by Chai et al. (2024) and Chen et al. (2024), are crucial for stabilizing soil moisture levels, as trees increase rainwater infiltration and reduce evapotranspiration rates. Additionally, Azizi et al. (2024) and Shahzad et al. (2024) emphasize the need for integrated management that connects surface and groundwater, thus ensuring water sustainability. These strategies not only help conserve soil moisture but also promote ecosystem resilience in the face of climatic variations and anthropogenic pressures.

Furthermore, it is fundamental to strengthen research and continuous monitoring of soil moisture. Mane et al. (2024) highlight the importance of developing and refining advanced sensor technologies to obtain reliable data, although they recognize challenges in costs and technological adoption. The implementation of monitoring systems based on remote sensing allows for a more detailed and timely assessment of soil conditions, facilitating informed decision-making for water resource management and ecosystem conservation.

Understanding the processes that affect soil moisture in Ñeembucú's wetlands not only provides an accurate assessment of their current state but also opens the door to estimating other ecosystem components and anthropogenic interventions. This knowledge is essential for designing and implementing management strategies that ensure environmental sustainability and the productivity of agricultural systems in the region.

Based on the above, the objective of this research is to analyze the evolution of soil moisture in the southern region of Ñeembucú Department during the period from 1983 to 2023, using remote sensing data and geospatial processing techniques, as well as to evaluate soil moisture trends at different layers (0 to 290 cm).

2. Methodology

This work focuses on the analysis of soil moisture in the southern region of Ñeembucú Department, using remote sensing data and geospatial processing techniques. For this purpose, image collections "NASA/FLDAS/NOAH01/C/GL/M/V001" and "ECMWF/ERA5_LAND/MONTHLY_AGGR" from Google Earth Engine were used, filtered for the studied area. Five specific periods were selected for analysis, in 10-year intervals: 1983, 1993, 2003, 2013, and 2023, covering a span of 40 years. The variables of interest included water volume (fraction) in soil layers: 0-10 cm, 10-40 cm, 40-100 cm, and 100-200 cm, as well as 0-7 cm, 7-28 cm, 28-100 cm, and 100-289 cm, respectively.

The southern region of Ñeembucú Department was delimited as the study area, covering a surface of 6,636.499 km², located at coordinates: minimum longitude: -58.66491223954913, minimum latitude: -27.306219282698216, maximum longitude: -57.18209360492629, maximum latitude: -26.595706376858836.

To process and analyze the data, a Python script was developed using specialized libraries such as GeoPandas, NumPy, Xarray, and HoloViews. The workflow began with loading the geometry of the chosen region from a GeoJSON file using GeoPandas. This geometry was subsequently used to mask the data and limit the analysis to the area of interest.

Soil moisture data were processed for each selected year and depth, calculating annual means for each variable. These values were classified into four classes using percentiles. The calculate_percentiles function determined the limits of these classes, and the classify_data function assigned each soil moisture value to a specific class based on these percentiles. For each combination of year and variable, a heat map was generated using HoloViews, with a color scale ranging from red to blue to represent soil moisture content.

To improve visual interpretation, the contour of the study area was superimposed on each map; additionally, percentages corresponding to each soil moisture class were calculated and presented in table form alongside each map.

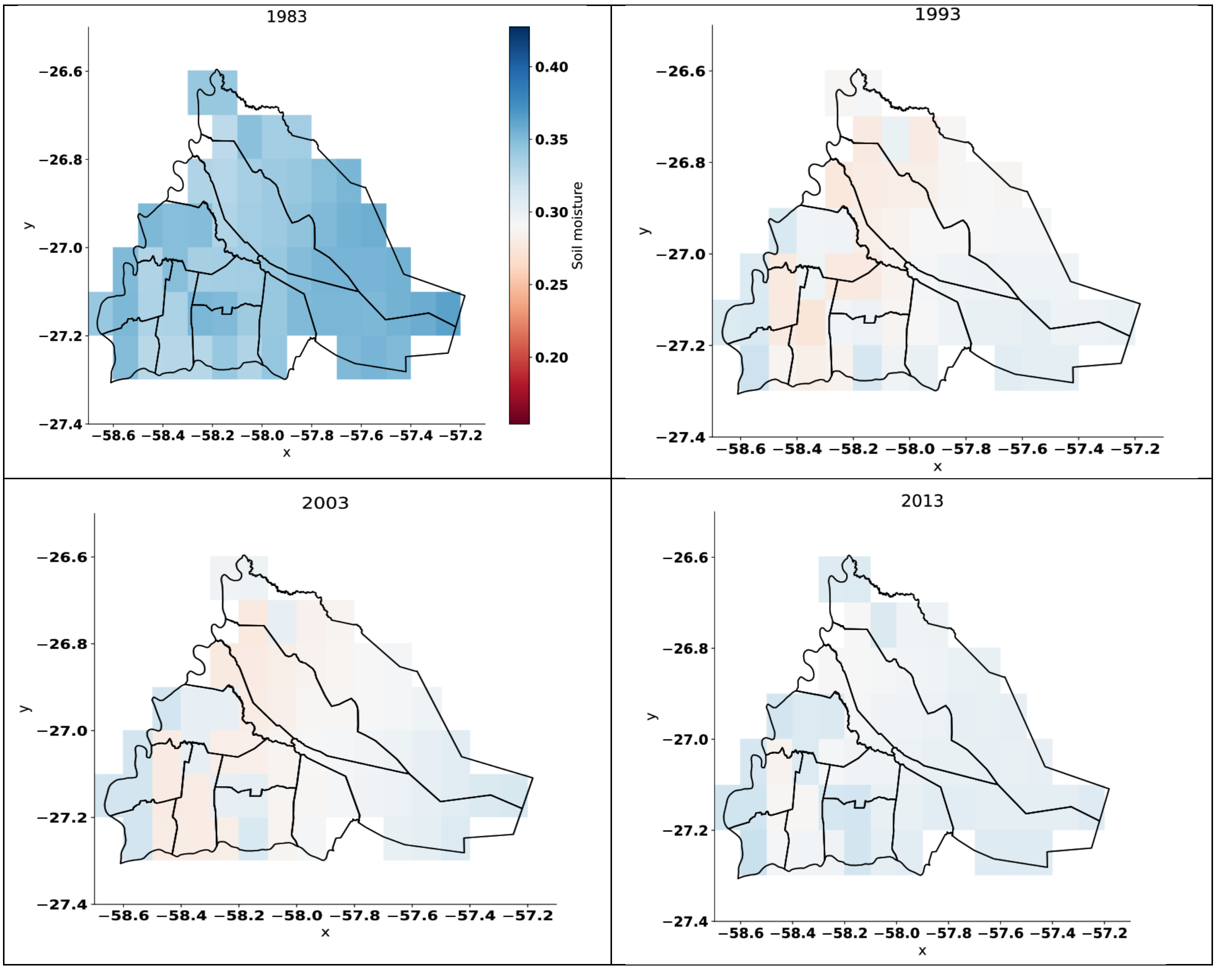
Pearson correlation was also calculated between soil moisture contents in similar layers from the two satellites.

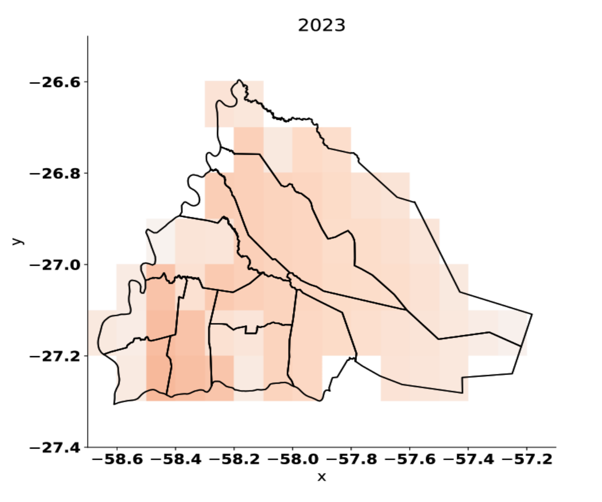
3. Results and Discussion

Results from NASA/FLDAS Satellite

Moisture in the 0 to 10 cm Layer

In 1983, the surface layer (0-10 cm) presented intermediate to high moisture (0.31-0.38 m^3 m^{-3}) uniformly. From 1993, a notable reduction in moisture is observed, increasing areas with low values (0.16-0.18 m^3 m^{-3}) mainly in the center and southwest. For 2003 and 2013, this trend intensifies, decreasing areas of intermediate moisture and concentrating on drier areas. In 2023, low moisture predominates (0.16-0.28 m^3 m^{-3}), with an almost disappearance of intermediate levels and greater spatial variability (Figure 1).



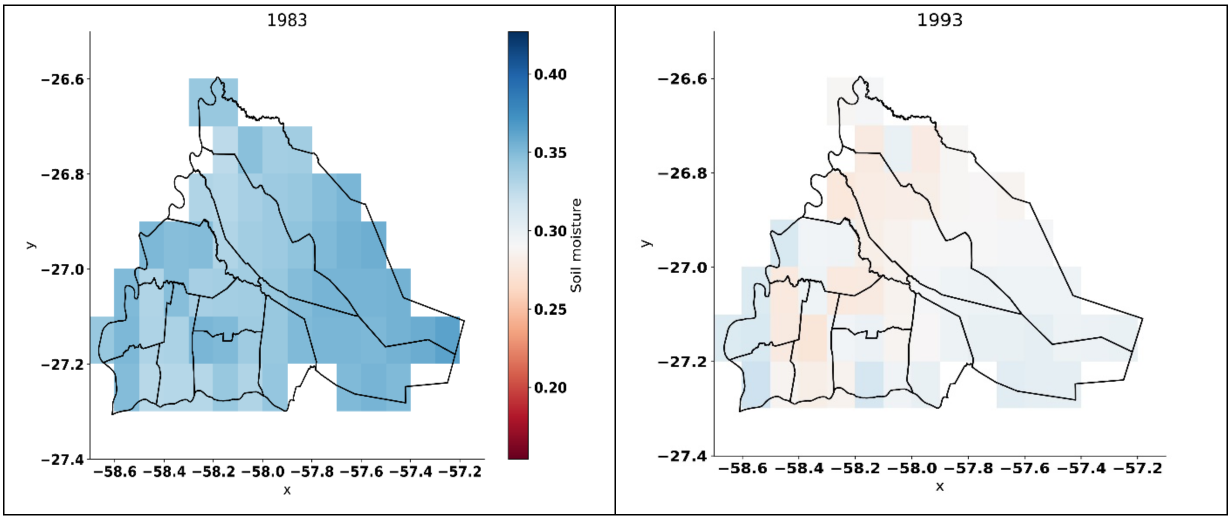


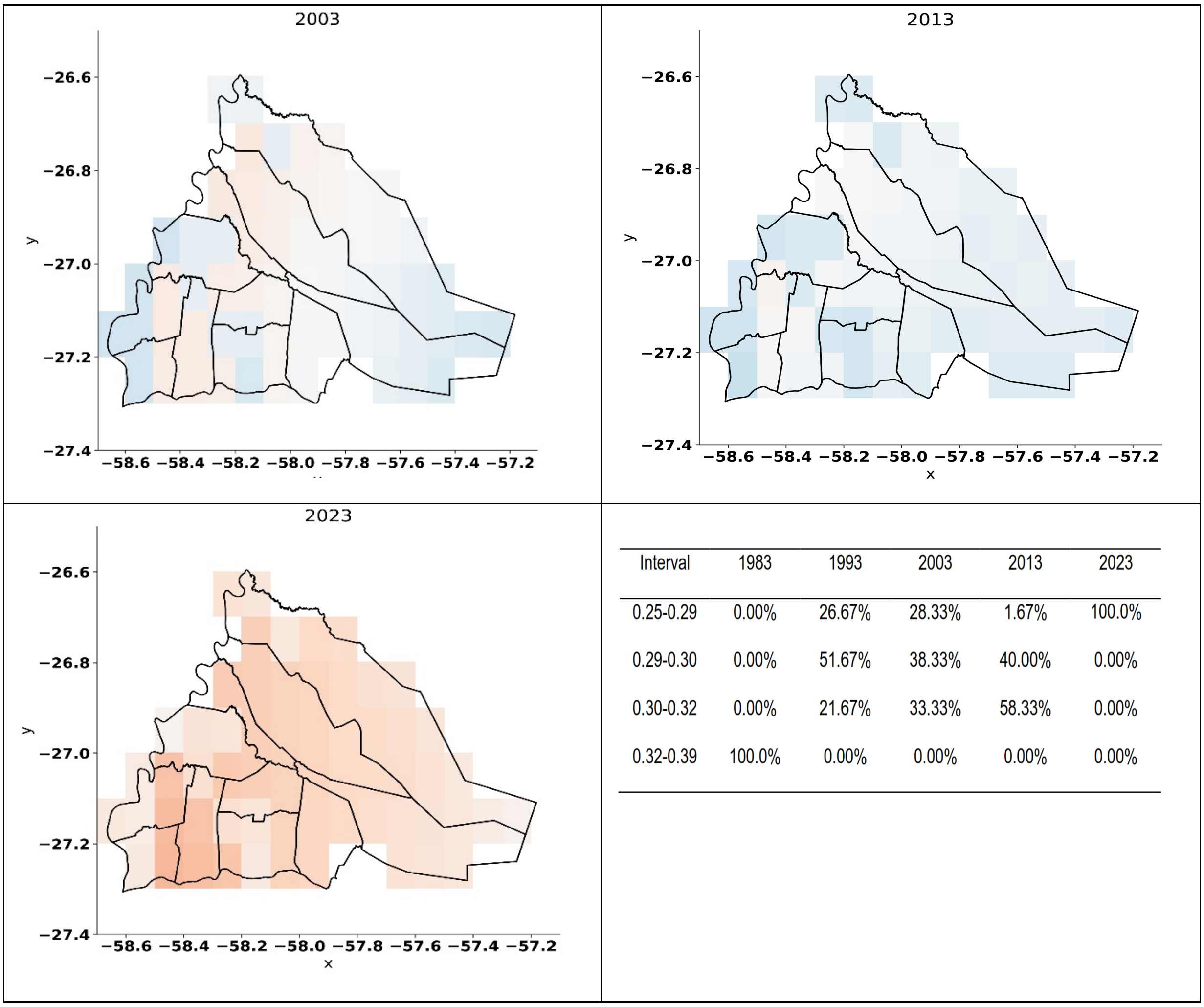
Interval	1983	1993	2003	2013	2023
0.26-0.28	0.00%	18.33%	43.33%	10.00%	91.67%
0.28-0.29	0.00%	45.00%	36.67%	46.667%	6.67%
0.29-0.31	0.00%	36.67%	20.00%	43.33%	1.67%
0.31-0.38	100.0%	0.00%	0.00%	0.00%	0.00%

Figure 1 – Soil moisture in the layer 0 - 10 cm from 1983 to 2023, estimated by satellite NASA/FLDAS and its respective percentual classification

Moisture in the 10 to 40 cm Layer

In 1983, moisture at 40 cm was uniform and medium-high (0.32-0.39 m^3 m^{-3}), with slight decreases in the southwest. From 1993, the distribution becomes more heterogeneous with a general reduction. This decrease persists and worsens in 2003 and 2013, concentrating mainly in the center and southwest. By 2023, low moisture predominates (0.25-0.29 m^3 m^{-3}) in these areas, evidencing a significant reduction compared to previous decades (Figure 2).



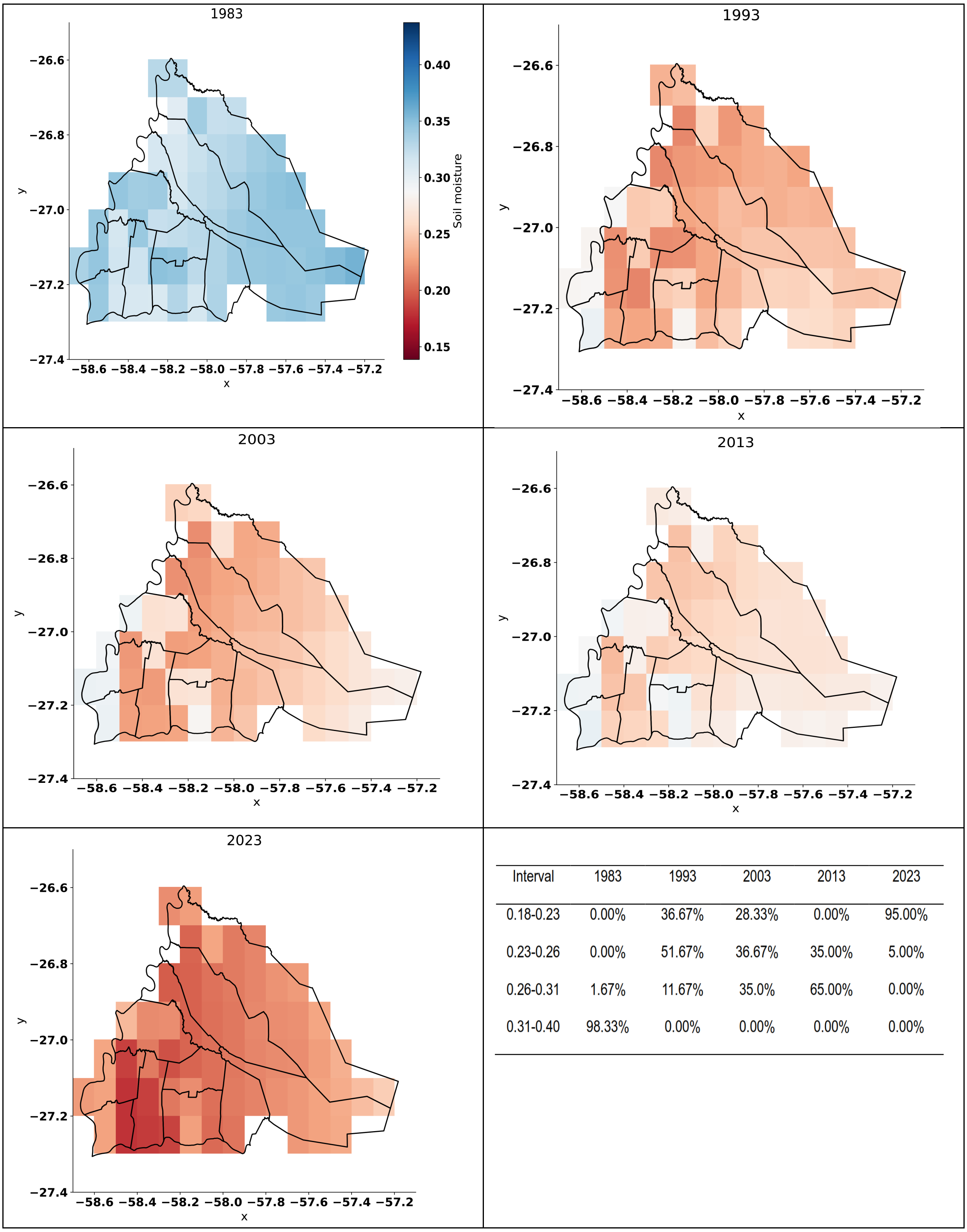


Interval	1983	1993	2003	2013	2023
0.25-0.29	0.00%	26.67%	28.33%	1.67%	100.0%
0.29-0.30	0.00%	51.67%	38.33%	40.00%	0.00%
0.30-0.32	0.00%	21.67%	33.33%	58.33%	0.00%
0.32-0.39	100.0%	0.00%	0.00%	0.00%	0.00%

Figure 2 – Soil moisture in the layer 10 - 40 cm from 1983 to 2023, estimated by satellite NASA/FLDAS

Moisture in the 40 to 100 cm Layer

In 1983, moisture at 100 cm was homogeneous (0.31-0.40 m^3 m^{-3}). From 1993, it reduces towards lower ranges (0.23-0.26 m^3 m^{-3}), especially in the southwest and center. This trend continues in 2003 and intensifies in 2013, with greater dryness and variability. In 2023, low moisture predominates (0.16-0.23 m^3 m^{-3}) in the center and southwest, showing a significant decrease compared to previous years (Figure 3).

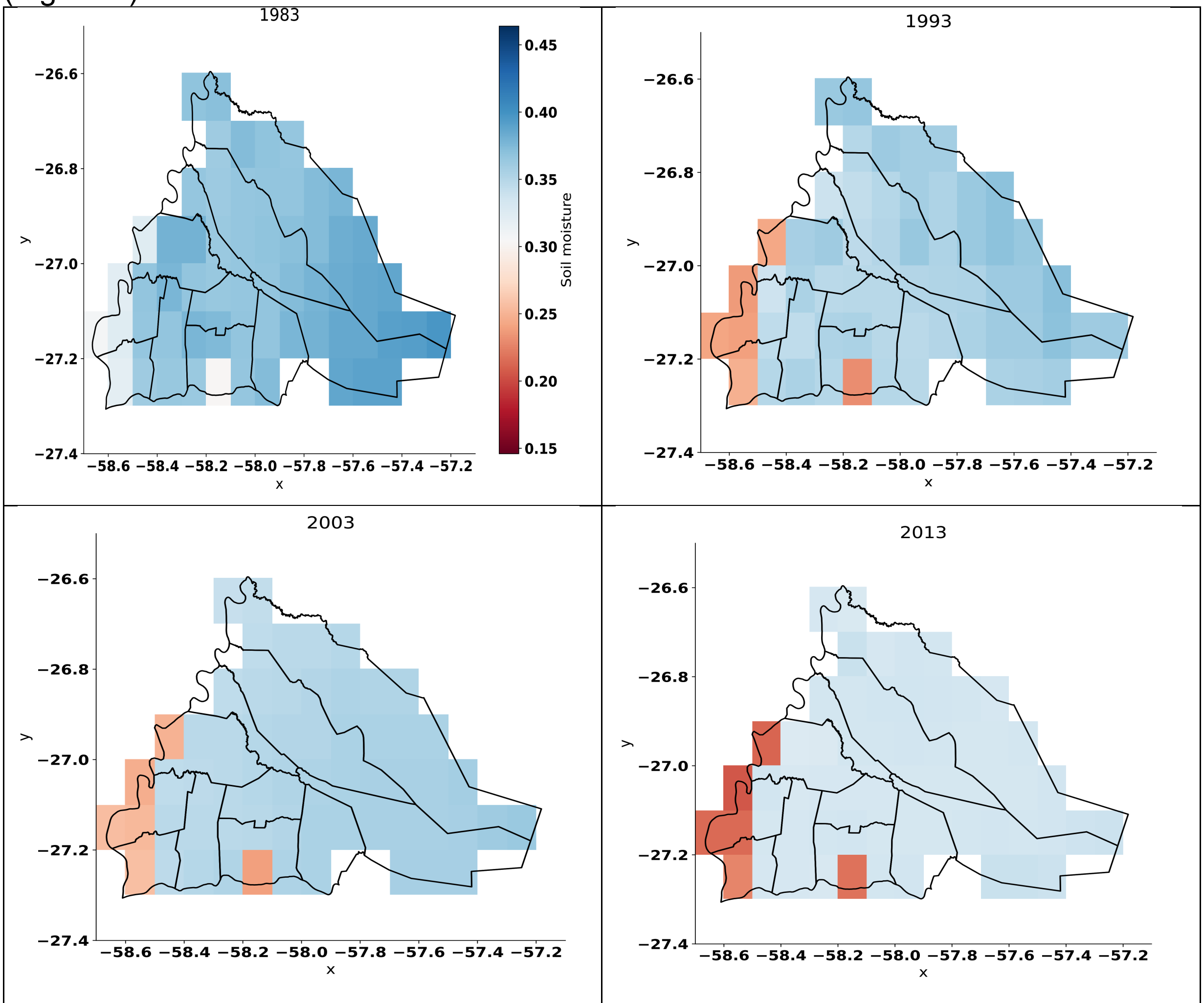


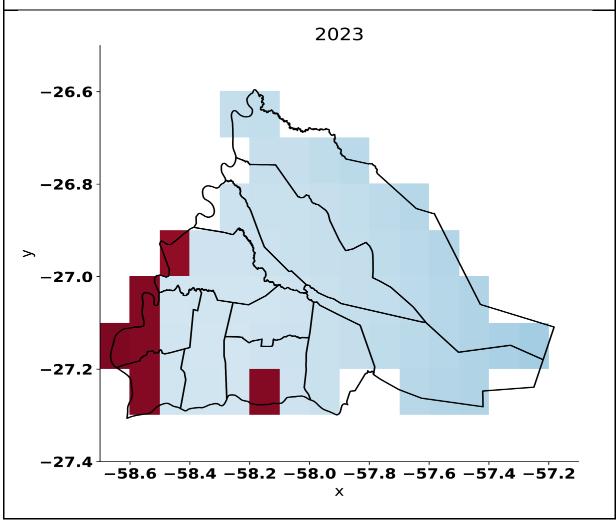
Interval	1983	1993	2003	2013	2023
0.18-0.23	0.00%	36.67%	28.33%	0.00%	95.00%
0.23-0.26	0.00%	51.67%	36.67%	35.00%	5.00%
0.26-0.31	1.67%	11.67%	35.0%	65.00%	0.00%
0.31-0.40	98.33%	0.00%	0.00%	0.00%	0.00%

Figure 3 – Soil moisture in the layer 40 - 100 cm from 1983 to 2023, estimated by satellite NASA/FLDA

Moisture in the 100 to 200 cm Layer

In 1983, moisture at 200 cm was heterogeneous and high (0.36-0.42 m^3 m^{-3}) in the east and other areas. From 1993, it decreases to 0.35-0.36 m^3 m^{-3}, especially in the southwest, a trend that continues and intensifies in 2003 and 2013. By 2023, low values predominate (0.34-0.35 m^3 m^{-3}) in much of the area, while in the southwest predominate values of 0.16-0.34 m^3 m^{-3}, reflecting a considerable reduction of moisture (Figure 4).





Interval	1983	1993	2003	2013	2023
0.16-0.34	10.0%	10.00%	10.00%	90.00%	28.33%
0.34-0.35	0.00%	28.33%	35.00%	10.00%	60.00%
0.35-0.36	5.00%	45.00%	53.33%	0.00%	11.67%
0.36-0.42	85.00%	16.67%	1.67%	0.00%	0.00%

Figure 4 – Soil moisture in the layer 100 - 200 cm from 1983 to 2023, estimated by satellite NASA/FLDAS

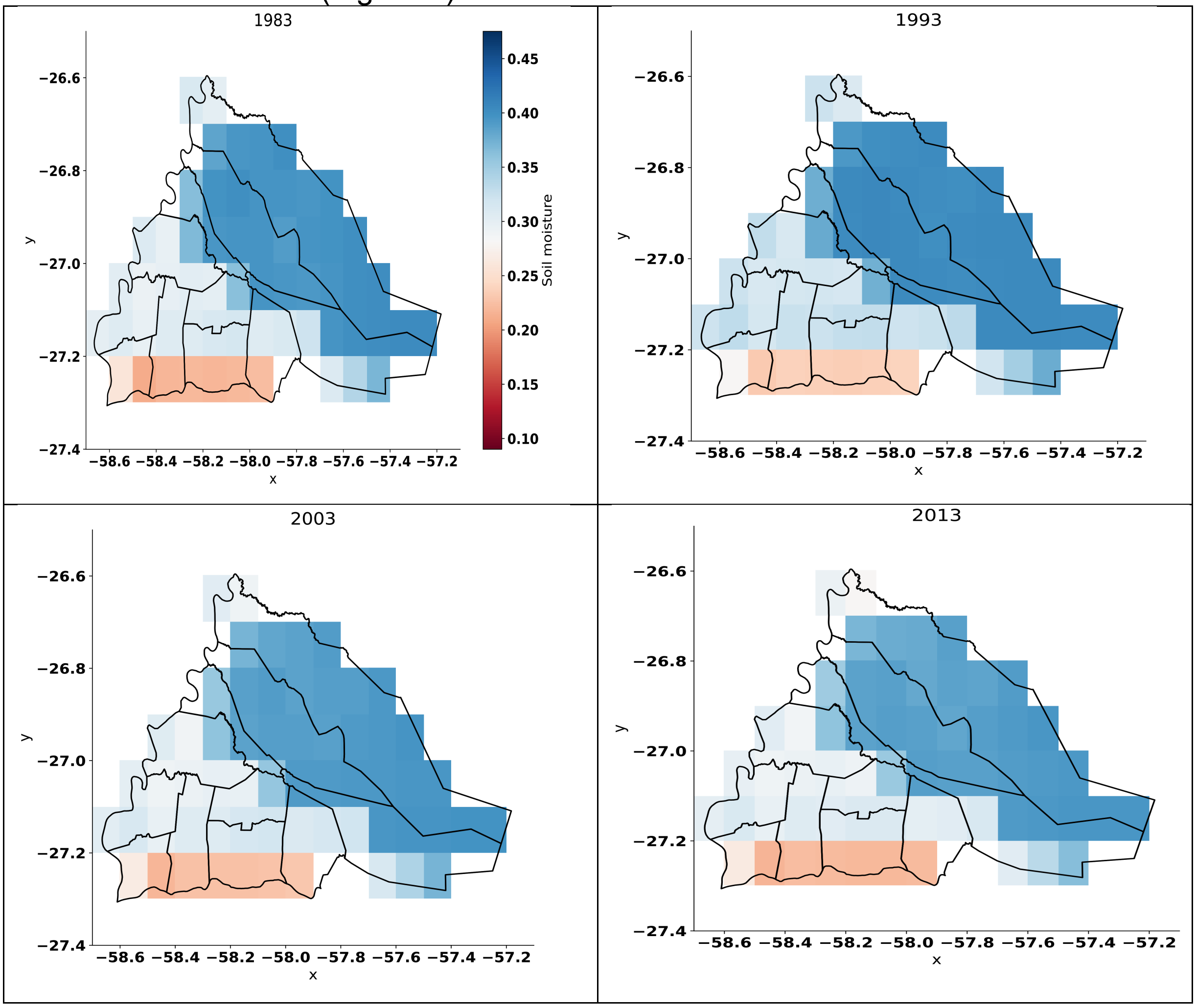
Comparison Between Layers

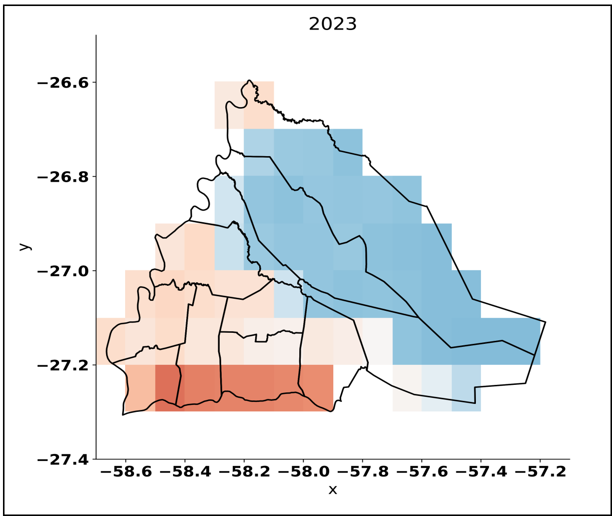
Throughout 1983-2023, all analyzed depths show a general decrease in moisture, with surface layers (10 and 40 cm) reacting first and more pronouncedly. Deep layers (100 and 200 cm) show a later but equally significant reduction. This decrease suggests a possible degradation of hydrological conditions, affecting long-term water availability.

Results from ERA5_LAND Satellite

Moisture in Layer 1 (0-7 cm)

In 1983, moisture was heterogeneous with drier areas in the center and southwest. Until 1993, it remained stable, slightly increasing high values. From 2003, moisture decreases, especially in the center and southwest, intensifying in 2013 and 2023 with a predominance of low values (0.18-0.32 $m^3\ m^{-3}$) and 0.32-0.37 $m^3\ m^{-3}$, and reduction of wet areas (Figure 5).



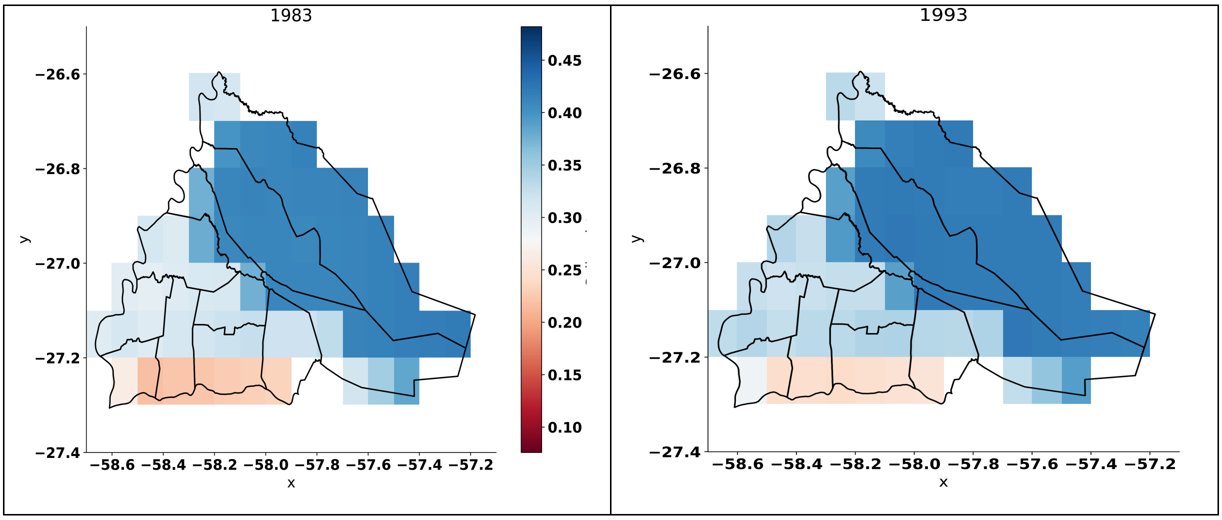


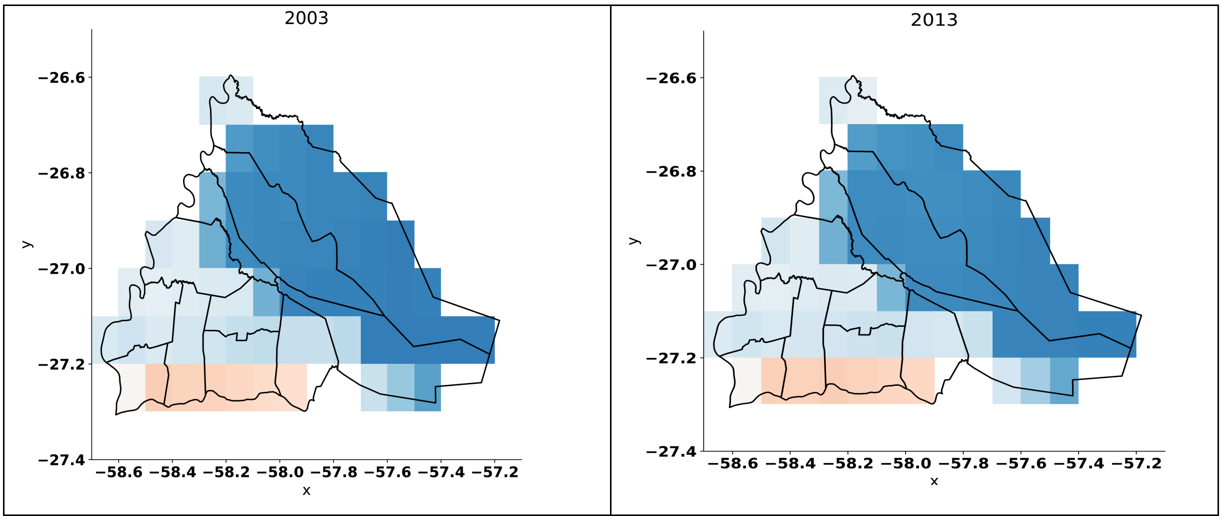
Interval	1983	1993	2003	2013	2023
0.18-0.32	43.33%	21.67%	43.33%	45.00%	46.67%
0.32-0.37	6.67%	25.00%	8.33%	8.33%	53.33%
0.37-0.40	15.00%	8.33%	40.00%	45.00%	0.00%
0.40-0.42	35.00%	45.00%	8.33%	1.67%	0.00%

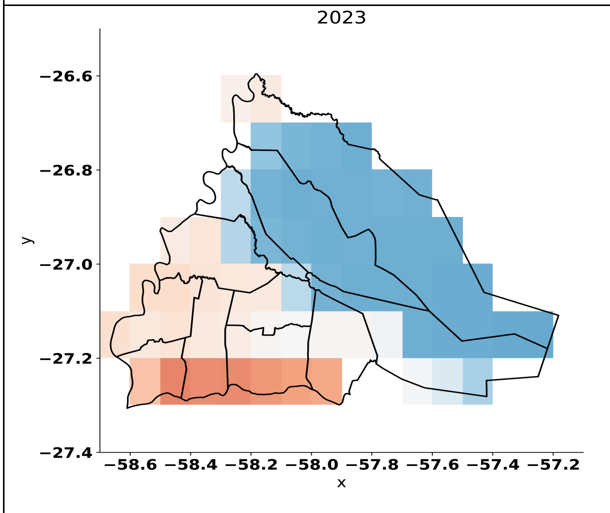
Figure 5 – Soil moisture in the layer 0 - 7 cm from 1983 to 2023, estimated by satellite ERA5_LAND

Moisture in Layer 2 (7-28 cm)

Similar to layer 1, in 1983 moisture was heterogeneous. From 1993, a slight reduction is observed, intensifying in 2003 and 2013 with more dry areas (0.18-0.33 m^3 m^{-3}. In 2023, low values predominate, especially in the southwest (Figure 6).





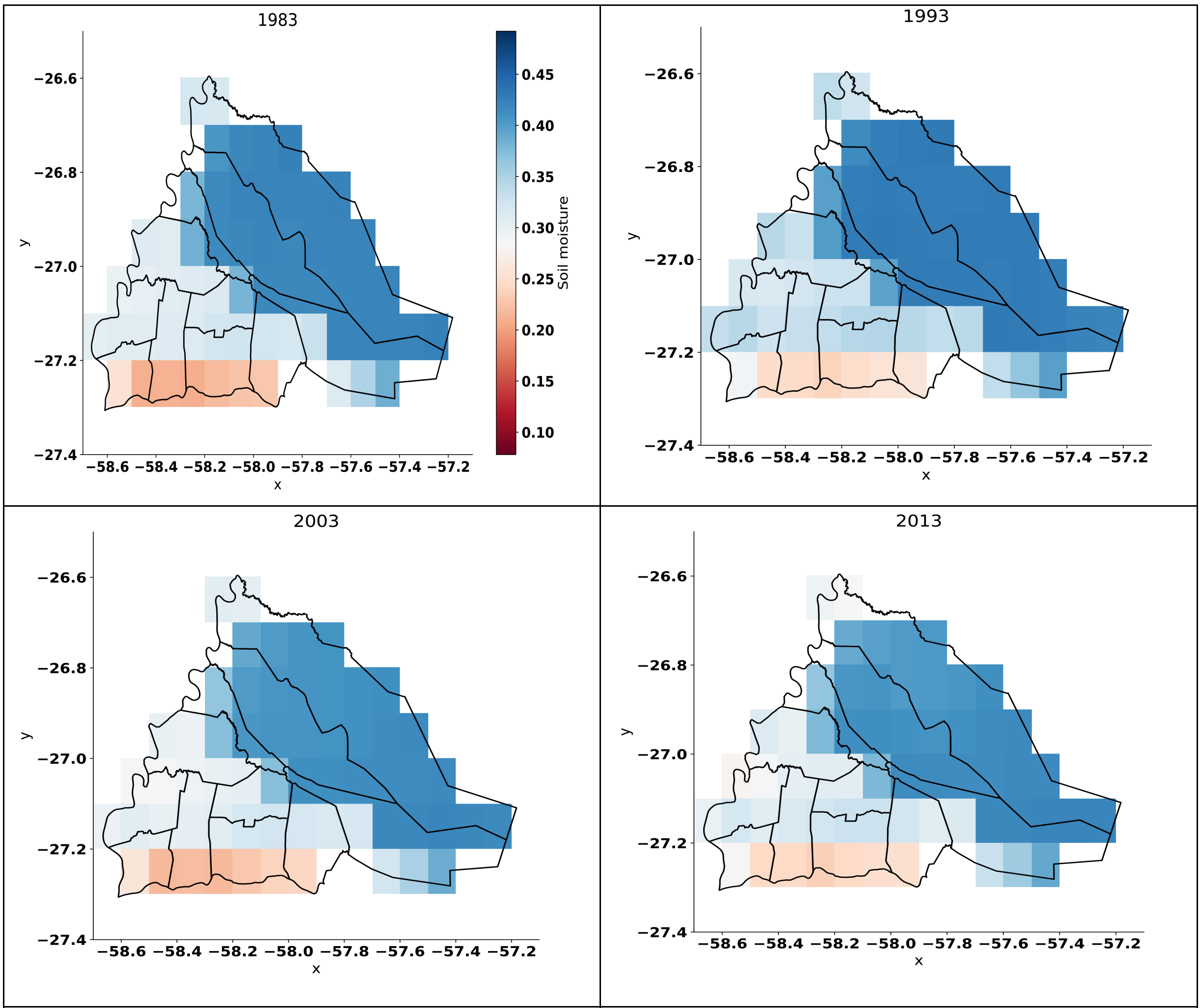


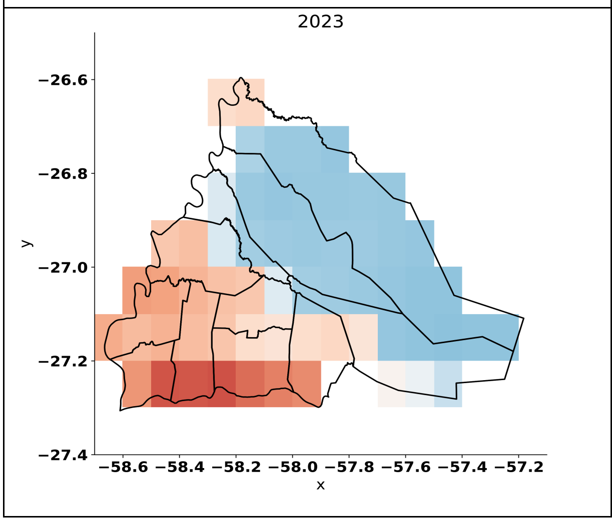
Interval	1983	1993	2003	2013	2023
0.18-0.33	43.33%	20.00%	40.0%	45.0%	46.67%
0.33-0.38	8.33%	26.67%	11.67%	6.67%	53.33%
0.38-0.41	35.00%	8.33%	26.67%	43.33%	0.00%
0.41-0.43	13.33%	45.00%	21.67%	5.00%	0.00%

Figure 6 – Soil moisture in the layer 7 - 28 cm from 1983 to 2023, estimated by satellite ERA5_LAND

Moisture in Layer 3 (28-100 cm)

In 1983, moisture was varied, with higher percentages (0.42-0.44 m^3 m^{-3}) predominating. From 1993, it gradually decreases, with greater dryness from 2013 and a notable reduction in 2023, concentrating on low values (0.15-0.32 m^3 m^{-3}) and decreasing wet areas (Figure 7).



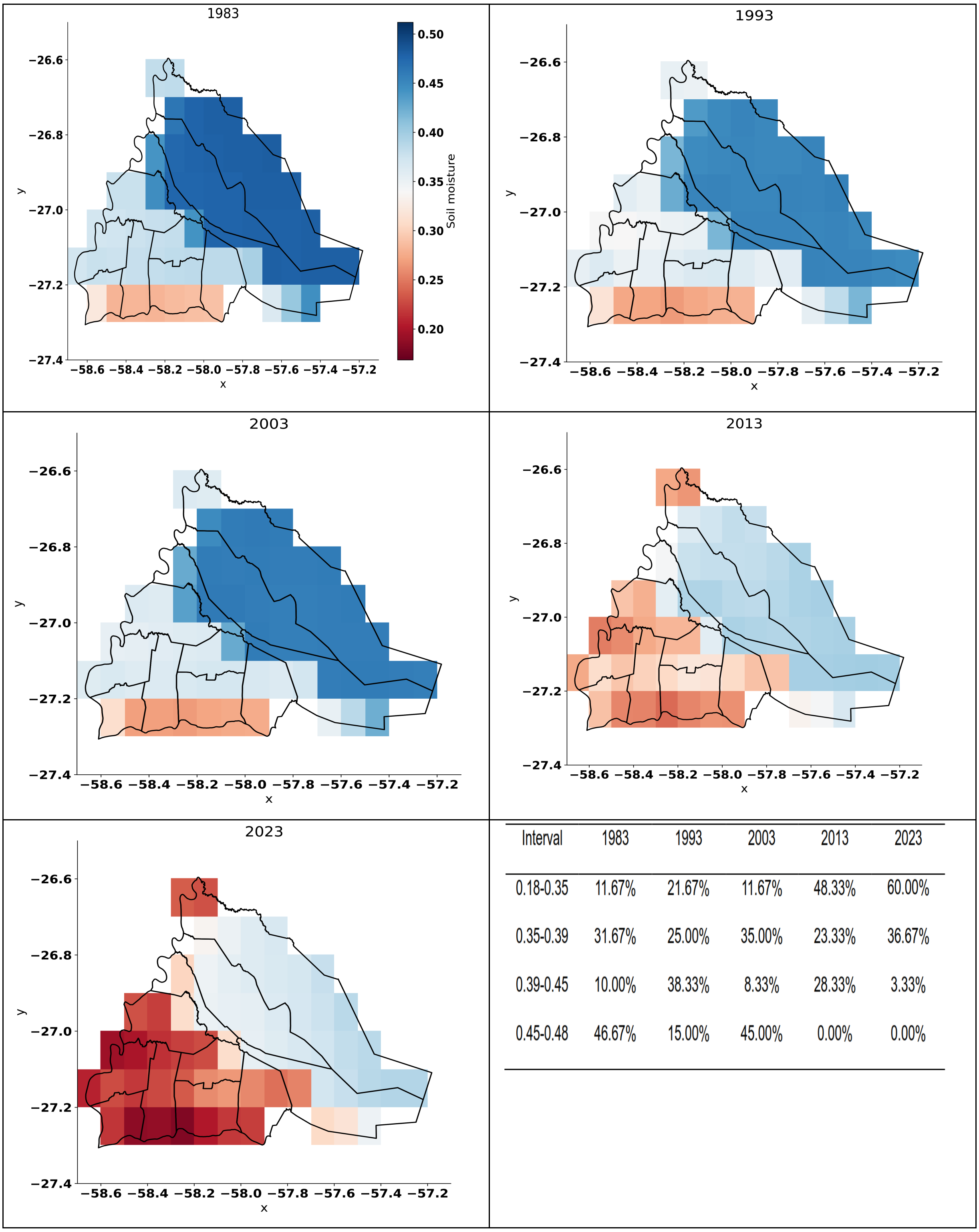


Interval	1983	1993	2003	2013	2023
0.15-0.32	36.67%	15.00%	41.67%	36.67%	51.67%
0.32-0.37	10.00%	31.67%	10.00%	11.67%	48.33%
0.37-0.42	8.33%	8.33%	41.67%	41.67%	0.00%
0.42-0.44	45.00%	45.00%	6.67%	10.00%	0.00%

Figure 7 – Soil moisture in the layer 28 - 100 cm from 1983 to 2023, estimated by satellite ERA5_LAND

Moisture in Layer 4 (100-289 cm)

Initially heterogeneous and high (0.45-0.48 m^3 m^{-3}) in 1983, moisture decreases from 1993. The trend accentuates in 2003 and 2013, and in 2023, low values prevail (0.18-0.35 m^3 m^{-3}), significantly reducing wet areas (Figure 8).



Interval	1983	1993	2003	2013	2023
0.18-0.35	11.67%	21.67%	11.67%	48.33%	60.00%
0.35-0.39	31.67%	25.00%	35.00%	23.33%	36.67%
0.39-0.45	10.00%	38.33%	8.33%	28.33%	3.33%
0.45-0.48	46.67%	15.00%	45.00%	0.00%	0.00%

Figure 8 – Soil moisture in the layer 100 - 289 cm from 1983 to 2023, estimated by satellite ERA5_LAND

Comparison Between Layers

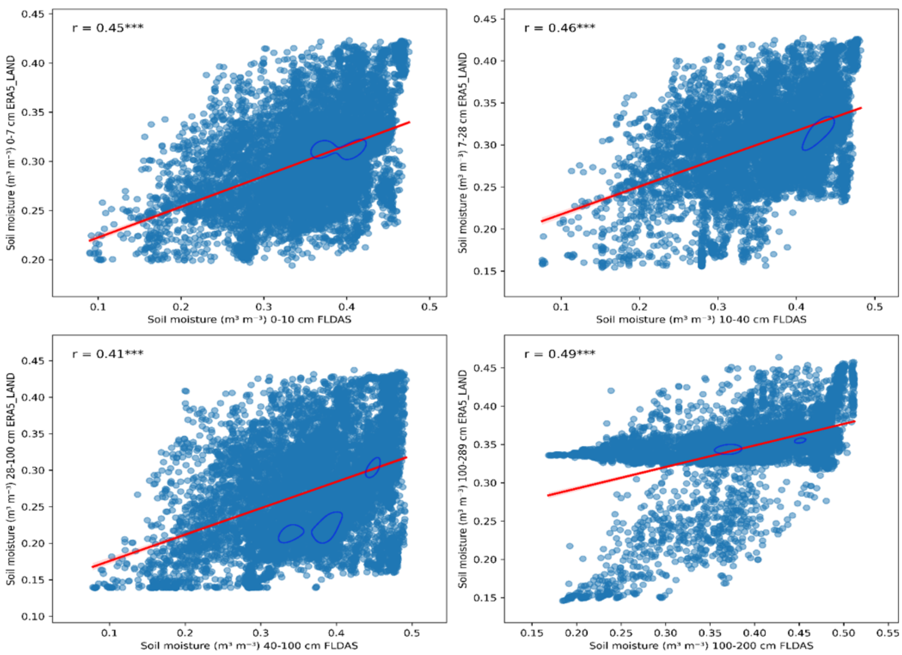
All layers show a decrease in moisture, with surface layers (0-7 and 7-28 cm) experiencing earlier and more pronounced changes. Deep layers (28-100 and 100-289 cm) respond later but equally show a significant reduction in 2023. This pattern suggests alterations in water recharge and potential depletion of underground reserves.

Comparison Between Satellites

When comparing the results obtained with the two satellite datasets (NASA/FLDAS and ERA5_LAND) for different soil layers, some similarities and differences are observed in the evolution of soil moisture over the period 1983-2023. Both datasets show a general trend of decreasing moisture in most areas and depths analyzed, especially in surface layers (0-10 cm and 10-40 cm) from 1993 onwards. However, the magnitude of moisture decrease and spatial variability of moisture patterns differ between the two datasets. In general, ERA5_LAND data show a more pronounced decrease in moisture in surface layers, especially in 2023, with a greater extent of areas with low moisture values. On the other hand, NASA/FLDAS data show greater spatial variability in soil moisture, with areas experiencing more intense decreases than others.

In deeper layers (40-100 cm and 100-200 cm), the decrease in moisture is less pronounced in both datasets but intensifies from 2013 onwards. In these layers, ERA5_LAND data also show a more intense decrease in moisture compared to NASA/FLDAS data, especially in 2023. These differences in results can be attributed to various factors, such as the algorithms used to estimate soil moisture, the source of meteorological data used to force the models, and the specific characteristics of the study area. It is important to note that both datasets are products of numerical models and, therefore, are subject to uncertainties.

The correlation in the different layers is positive and significant at p 0.1% by the t-test, varying from 0.41 to 0.49 (Figure 9), which confirms the similarity of the results obtained.



***: Significant at $p \leq 0.001$ by the t-test.

Figure 9 – Correlation of soil moisture contents estimated by the two satellites in their respective layers.

Discussion

Advances in remote sensing have allowed for a more precise understanding of soil moisture at various spatial and temporal scales, ensuring the reliability of the data obtained. Abdulraheem et al. (2023) highlight that remote sensing provides broad and non-destructive coverage, facilitating continuous monitoring of soil moisture. Moreover, Liu et al. (2023) point out that machine learning algorithms have significantly improved data accuracy, especially in complex environments with vegetative interference.

In this study, the results show a generalized decrease in soil moisture between 1983 and 2023, aligning with global trends observed by Liu et al. (2019), who found similar reductions in areas affected by climate change and intensive land use. This decrease can be attributed to both climatic and anthropogenic factors. The IPCC report (2021) indicates that climate change has increased temperatures and altered precipitation patterns, which in our study area translates to lower annual precipitation or more concentrated rainfall in short periods, corroborated by Smurov et al. (2023) and Smith and Chang (2020), who link increased evapotranspiration with these climatic variations.

On the other hand, human activities have also influenced the reduction of soil moisture. Czigány et al. (2023) and Pysarenko and Krakovska (2022) identify that intensive agricultural practices and deforestation increase evapotranspiration and alter soil moisture dynamics. Additionally, Botta et al. (2022) observe that soil compaction from livestock activities decreases the soil's capacity to retain water. In the same study area, Vera and Pereira (2024) verified an increase in bare soil surfaces and a decrease in the extent of swamps, forests, and grasslands and prairies, contributing for the decreased soil content verified in this research.

The implications of this decrease in moisture are significant for sectors such as agriculture, water resource management, and biodiversity conservation. Bogati et al. (2023) note that lower moisture reduces microbial activity and nutrient cycling, affecting agricultural productivity. Zhou et al. (2023) add that dry soil layers harm vegetation and ecosystem services, while DeVilleneuve (2023) warns about increased erosion, which puts habitats and water quality at risk.

To mitigate these effects, it is essential to implement sustainable water and soil management strategies. Kazemzadeh et al. (2021) propose watershed management practices and increasing vegetation cover to improve water retention. Reforestation and conservation of native forests, as suggested by Chai et al. (2024) and Chen et al. (2024), are also crucial for stabilizing soil moisture levels. Additionally, Azizi et al. (2024) and Shahzad et al. (2024) emphasize the need for integrated management that connects surface and groundwater, thus ensuring water sustainability.

Finally, it is fundamental to strengthen research and continuous monitoring of soil moisture. Mane et al. (2024) highlight the importance of developing and refining sensor technologies to obtain reliable data, although they recognize challenges in costs and technological adoption.

The findings of this research, which evidence a constant decrease in soil moisture from 1983 to 2023, are consistent with previous studies that relate climate change and human activities to soil moisture degradation. The trend observed in our study area reflects a similar response to that reported by Liu et al. (2019) and Smurov et al. (2023), confirming the combined influence of climatic and anthropogenic factors in the reduction of soil moisture. Furthermore, the practical implications identified in this study reinforce the need to adopt mitigation strategies proposed by authors such as Kazemzadeh et al. (2021) and Chai et al. (2024) to counteract the negative effects on agriculture and biodiversity.

4. Conclusions

1. The analysis conducted using remote sensing and geospatial processing techniques revealed a sustained decrease in soil moisture in the southern region of Ñeembucú Department during the period from 1983 to 2023.

2. The evaluation of soil moisture trends at various depths (0 to 290 cm) showed a generalized decrease across all analyzed layers, with the most pronounced effects in the surface layers. The deeper layers experienced a more gradual reduction.

3. Given the decrease in soil moisture and its negative implications for agriculture, water resource management, and biodiversity, it is crucial to implement sustainable management strategies.

4. The comparative analysis of data from two different satellite sources (NASA/FLDAS and ERA5_LAND) strengthens the reliability of the findings, being verified positive correlation between these datasets, despite some variations.

References

ABDULRAHEEM, M.I., ZHANG, W., LI, S., MOSHAYEDI, A.J., FAROOQUE, A.A. & HU, J. Advancement of Remote Sensing for Soil Measurements and Applications: A Comprehensive Review. **Sustainability**. 2023, 15, 15444. https://doi.org/10.3390/su152115444

AZIZI, K., AZARI, A. & BANSOULEH, B.F. Integrated operation of water resources in climate change conditions, considering uncertainty based on coupled dynamic models of surface water and groundwater. **Research Square**, 2024. https://doi.org/10.21203/rs.3.rs-4087508/v1

BALLUT-DAJU, G.A., SANDOVAL HERAZO, L.C., FERNÁNDEZ-LAMBERT, G., MARÍN-MUÑIZ, J.L., LÓPEZ MÉNDEZ, M.C., & BETANZO-TORRES, E.A. Factors Affecting Wetland Loss: A Review. **Land** 2022, 11, 434. https://doi.org/10.3390/land11030434

BOGATI, K., SEWERNIAK, P. & WALCZAK, M. Efecto de los cambios en la humedad del suelo en suelos agrícolas: respuesta de la comunidad microbiana, diversidad enzimática y fisiológica. **Preguntas ecológicas**, v. 34, n. 4, p. 1-33, 2023. Available in: https://apcz.umk.pl/EQ/article/view/44164

BOTTA, G.F., NARDON, G.F. & GUIRADO CLAVIJO, R. Soil Sustainability: Analysis of the Soil Compaction under Heavy Agricultural Machinery Traffic in Extensive Crops. **Agronomy**, v. 12, n. 282, 2022. https://doi.org/10.3390/agronomy12020282

CAICEDO-ROSERO, L. C., MÉNDEZ-ÁVILA, F. DE J., GUTIÉRREZ-ZEFERINO, E. & FLORES-CUAUTLE, J. DE J. A. Medición de humedad en suelos, revisión de métodos y características. **Pädi Boletín Científico de Ciencias Básicas e Ingenierías del ICBI**, v.9, n.17, p.1-8, 2021. https://doi.org/10.29057/icbi.v9i17.7035

CHAI Y., SHI, X., ZHANG, R. & HAN, C. Effects of conventional soil and water conservation measures on soil moisture of sloping land in the loess region. **Water Supply**, 2024. 24 (4): 1298–1314. https://doi.org/10.2166/ws.2024.074

CHEN, J., ZHANG, L., LUO, W., LYU, Y., CHENG, A. & WANG, L. The impact of natural vegetation restoration on surface soil moisture of secondary forests and shrubs in the karst region of southwest China. **Hydrological Processes**, v. 38, n. 5, 2024. https://doi/10.1002/hyp.15161

CZIGÁNY, S., SARKADI, N., LÓCZY, D., CSÉPL, O.A., BALOGH, R., FÁBIÁN, S.Á., CIGLIˇC, R., FERK, M., PIRISI, G. & IMRE, M. Impact of Agricultural Land Use Types on Soil Moisture Retention of Loamy Soils. **Sustainability**, v. 15, n. 4925, 2023. https://doi.org/10.3390/su15064925

DEVILLENEUVE, S., KELLY, A., MIYANAKA, N., SHANMUHASUNDARAM, T., MURPHREE, P. & WYATT, B.M. Impacts of vegetation and topsoil removal on soil erosion, soil moisture, and infiltration. **Agrosystems, Geosciences & Environment**, v. 6, n. 3, 2023. https://doi.org/ 10.1002/agg2.20402

IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: **Cambridge University Press**, 2021.

KAZEMZADEH, M., SALAJEGHEH, A., MALEKIAN, A., LIAGHAT, A., & HASHEMI, H. Análisis del cambio de humedad del suelo en el marco de prácticas de gestión de cuencas hidrográficas utilizando datos in situ y de teledetección en una cuenca hidrográfica pareada. **Environ Monit Assess**, v. 193, n. 299, 2021. https://doi.org/10.1007/s10661-021-09078-y

MANE, S., DAS, M., SINGH, G., COSH, M. & DONG, Y. Advancements in dielectric soil moisture sensor Calibration: A comprehensive review of methods and techniques. **Computers and Electronics in Agriculture**, Volume 218. 2024. https://doi.org/10.1016/j.compag.2024.108686

LI, T., MU, T., LIU, G., YANG, X., ZHU, G., & SHANG, C. A. A Method of Soil Moisture Content Estimation at Various Soil Organic Matter Conditions Based on Soil Reflectance. **Remote Sens.**, v. 14, n. 2411, 2022. https://doi.org/10.3390/rs14102411

LIU, Y., LÜ, Y., FU, B., HARRIS, P. & WU, L. Quantifying the spatio-temporal drivers of planned vegetation restoration on ecosystem services at a regional scale, Science of The Total. **Environment**, V. 650, n. 1. 2019. https://doi.org/10.1016/j.scitotenv.2018.09.082.

LIU, Y., ZHAO, W., ZHANG, Z., HUA, T. & SANTOS FERREIRA, C.S. The role of nature reserves in conservation effectiveness of ecosystem services in China. **Journal of Environmental Management**, v. 342, 118228, 2023. https://doi.org/10.1016/j.jenvman.2023.118228.

LUBAL, M.J. Evaluation of Importance of Birds from Non-Tidal Wetlands: A Review. Uttar Pradesh. **Journal of zoology**, v. 45, n. 15, p. 18-24, 2024. https://doi:10.56557/upjoz/2024/v45i154217

PYSARENKO, L.A. & KRAKOVSKA, S. Impact of deforestation on soil and canopy moisture evaporation on the territory of Ukraine based on data from the LUMIP numerical experiment. **Geofizicheskiy Zhurnal**, v. 43, n. 6, p. 221–247, 2022. https://doi.org/10.24028/gzh.v43i6.251564

SHAHZAD, L., SHARIF, F., TAHIR, A., RIAZ, U., BATOOL, M., BATOOL, M. & MAHMOOD, A. Making the Water-Soil-Waste Nexus Work. **CRS**, 2024. https://doi:10.1201/9781003358169-6

SMITH, R.K. & CHANG, D.C. The utilization of a recursive algorithm to determine trends of soil moisture deficits in the Mid-Atlantic United States. **Climatic Change**, v. 163, p. 217–235, 2020. https://doi.org/10.1007/s10584-020-02898-w

SMUROV S. I., GRIGOROV O. V. & ERMOLAEV S. N. The influence of climate change on crop yields and soil moisture reserves. **Agrarian Bulletin of the Urals**, n. 05 (234), p. 35–52, 2023. https://doi:10.32417/1997-4868-2023-235-06-35-52

VARÓN-RAMÍREZ, V.M., ARAUJO-CARRILLO, G.A. & GUEVARA SANTAMARÍA, M.A. Colombian soil texture: building a spatial ensemble model. **Earth System Science**, v. 14, p. 4719–4741, 2022. https://doi.org/10.5194/essd-14-4719-2022

VERA, P.D.A. & PEREIRA, W.E. Evolution of land cover from 1989 to 2023 in the southern region of the Ñeembucú department, Paraguay. **Revista JRG de Estudos Acadêmicos**, v. 7, n. 14, p. e14931, 2024. https://doi:10.55892/jrg.v7i14.931.

ZHOU, Z., YUNQIANG, R., RUIJIE, L., QI, L., ZHAO, Y., XU, Y., YONGPING, P. & HUANG, J.B. The deterioration and restoration of dried soil layers: New evidence from a precipitation manipulation experiment in an artificial forest. **Journal of Hydrology**, v. 625, Part B, 2023. https://doi.org/10.1016/j.jhidrol.2023.130087

ZIVEC, P.; SHELDON, F.; CAPON, S.J. Natural regeneration of wetlands under climate change. **Front. Environ. Sci.**, v. 11, n. 989214, 2023. http://doi:10.3389/fenvs.2023.989214