



Hydroclimatic Drivers of Soil Moisture Decline in South-South Nigeria: Implications for Sustainable Agriculture

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Abstract. This study investigates the hydroclimatic drivers of soil moisture decline in South-South Nigeria from 2000 to 2020, emphasizing implications for sustainable agriculture in rain-fed systems. Utilizing satellite-derived datasets including CHIRPS for precipitation, ERA5 for temperature, and SMAP/AMSR-E for soil moisture, integrated with GIS and statistical analyses (Mann-Kendall trends, Sen's slope, cross-wavelet coherence, and correlation), we reveal a consistent warming trend with maximum temperatures peaking at 28.38°C in 2020, erratic precipitation patterns with highs of 7.01 mm/day in 2015, and a ~6% soil moisture reduction (from 0.325 to 0.305 m³/m³). Correlations indicate a weak positive link between soil moisture and precipitation ($r=0.124$) and a strong inverse relationship with temperature ($r=-0.614$), highlighting a temperature-driven evapotranspiration as a primary deficit mechanism. Data limitations, such as satellite biases in vegetated tropics (RMSE 0.04–0.06 m³/m³ for SMAP), were addressed through literature-based validation and cross-referencing with regional benchmarks. These trends pose risks to staples like cassava and rice, projecting 10–25% yield losses. Actionable recommendations include adopting drought-resistant cultivars, conservation agriculture for enhanced retention (15–30%), community water harvesting, and satellite-based early-warning systems. This research informs climate-smart policies to bolster food security and ecosystem resilience amid escalating variability in tropical Africa.

Keywords: Soil moisture dynamics, climate variability, precipitation patterns, climate-smart agriculture, ecosystem resilience

1. Introduction

Soil moisture functions as a pivotal regulator of agricultural productivity, ecosystem resilience, and hydrological feedbacks in humid tropical environments like South-South Nigeria, where it modulates vegetation health and buffers against climatic extremes (Ogunrinde et al., 2024; Dinku et al., 2018). Amid escalating climate variability—characterized by erratic precipitation and rising temperatures—soil moisture deficits are projected to intensify, compromising sustainable development objectives and exacerbating vulnerabilities in rain-fed agriculture (Ford, 2015; Nduka & Nduka, 2025). These dynamics extend beyond water retention to influence ecological processes, such as ecosystem respiration, which displays acute sensitivity to moisture shortages, particularly in drying regimes where soil water-holding capacity limits microbial activity and carbon fluxes (Bouskill et al., 2016; Smith et al., 2015). Nonlinear modeling reveals adaptive plant strategies, from profligate water expenditure in grasslands to frugal conservation in forests,

underscoring soil moisture's role in shaping regional climate feedbacks and nutrient cycles (Denmead & Shaw, 1962; Schimel, 2018).

Hydroclimatic variability profoundly alters soil hydrology in tropical Africa, with cascading effects on crop yields and ecosystem stability, as evidenced by recent syntheses (Dosio et al., 2018; Gebreslassie et al., 2023). In South-South Nigeria, warming trends accelerate soil degradation, demanding resilient management paradigms (Wekpe & Idisi, 2024; Ogwu & Idisi, 2024). Soil moisture directly dictates crop performance in predominant rain-fed systems, where fluctuations amplify food insecurity risks (Wang et al., 2017; Wang et al., 2017). Interactions with temperature and nutrients further complicate resilience evaluations, with projections forecasting yield reductions for staples like cassava and rice under elevated warming (Denmead & Shaw, 1962; Schimel, 2018). Soil moisture also governs microbial diversity, nutrient turnover, and respiration, vital for ecosystem acclimation to droughts (Schimel, 2018; Li et al., 2015).

In tropical settings, soil moisture anomalies – deficits during droughts or surpluses in floods – exacerbate post-harvest losses via wilting, pest surges, and decay, accounting for over 30% of cereal wastage and imperiling smallholder economies (Green et al., 2019; Bouskill et al., 2016). Precipitation drives spatial moisture gradients, impacting vegetation vigor and biodiversity (Dunkerley, 2015; Li & Si, 2018), while evapotranspiration constitutes a dominant water efflux (Zhang et al., 2017; Mallick et al., 2015). Declining moisture erodes ecosystem services, reshapes communities, and diminishes habitat viability (Kardol et al., 2010; Li et al., 2015). Field investigations in southwestern Nigeria document elevated variability (46.6–63.5%), modulated by land use, with riparian zones exhibiting superior retention and arable lands greater flux (Ogunrinde et al., 2024).

This investigation probes temporal surface soil moisture trajectories in South-South Nigeria (2000–2020), alongside hydroclimatic linkages, amid persistent perturbations. Synthesizing long-term datasets illuminates interlinkages among moisture, climatic shifts, and biotic responses, addressing lacunae in regional scholarship and guiding adaptive land-water stewardship (Ogunrinde et al., 2024; Nduka & Nduka, 2025).

2. Methods

2.1. Data Collection

2.1.1. Climate Data

Precipitation and temperature variables were derived from high-resolution satellite archives, notably the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and ERA5 reanalysis, amalgamating station gauges, satellite observations, and models for robust hydroclimatic scrutiny (Funk et al., 2015; Hersbach et al., 2020). CHIRPS efficacy, alongside peers like TRMM and IMERG, has been affirmed in Nigeria, with performance varying by terrain and regime (Dinku et al., 2018; Akayeti et al., 2024). These resources prove invaluable in data-sparse South-South Nigeria, facilitating spatially resolved modeling (Gebrechorkos et al., 2018). Temperature datasets, essential for evapotranspiration and thermal-moisture interplay, were validated against in-situ and remote records to bolster fidelity (Dinku et al., 2018; Gebrechorkos et al., 2018).

2.1.2. Soil Moisture Data

Surface soil moisture was procured via satellites like Soil Moisture Active Passive (SMAP) and Advanced Microwave Scanning Radiometer-EOS (AMSR-E), yielding depth- and resolution-specific insights for agronomic applications (Entekhabi et al., 2010; Njoku et al., 2003; Odusanya et al., 2019; Akayeti et al., 2024). These afford superior temporal-spatial granularity for moisture profiling (Colliander et al., 2017; Das et al., 2019). GIS orchestrated spatial integration of topography, hydrology, and land cover to appraise moisture influencers (Adediji & Ajayi, 2021; Ojuri et al., 2025). GIS-SWAT fusion simulated water budgets and sustainability tactics (Odusanya et al., 2019; Arnold et al., 2012). Supplementary remote products, including MODIS/Landsat NDVI, gauged vegetation vitality, augmented by NASA POWER and ERA5 for 2000–2020 coverage (Hersbach et al., 2020; Stackhouse, 2006).

2.1.3. Soil and Vegetation Characteristics

South-South Nigeria—spanning Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers—features alluvial-hydromorphic soils, fertility modulated by Niger River and Atlantic proximities, sustaining oil palm, cassava, and rice economies (Anejionu et al., 2015). Vegetation gradients from rainforests to mangroves bolster coastal defenses and biodiversity (Anejionu et al., 2015). Wetlands enrich organics, enhancing fertility yet vulnerable to agriculture, spills, and flaring-induced degradation (Anejionu et al., 2015).

Temporal trends employed Mann-Kendall tests and Sen's slope estimators on 2000–2020 climate series to quantify variability (Mann, 1945; Sen, 1968; Dinku et al., 2018; Ogunrinde et al., 2024). Anomalies were mapped seasonally/annually to discern shifts. Cross-wavelet coherence probed soil moisture-precipitation-temperature-vegetation synergies, illuminating ecological acclimations (Grinsted et al., 2004; Torrence & Compo, 1998; Ogunrinde et al., 2024). Moisture-precipitation-temperature ties; time-series plots and boxplots visualized patterns (R Core Team, 2023).

2.1.4. Research Location

South-South Nigeria, comprising six states (Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers), was selected for its diverse topography and climatic patterns.

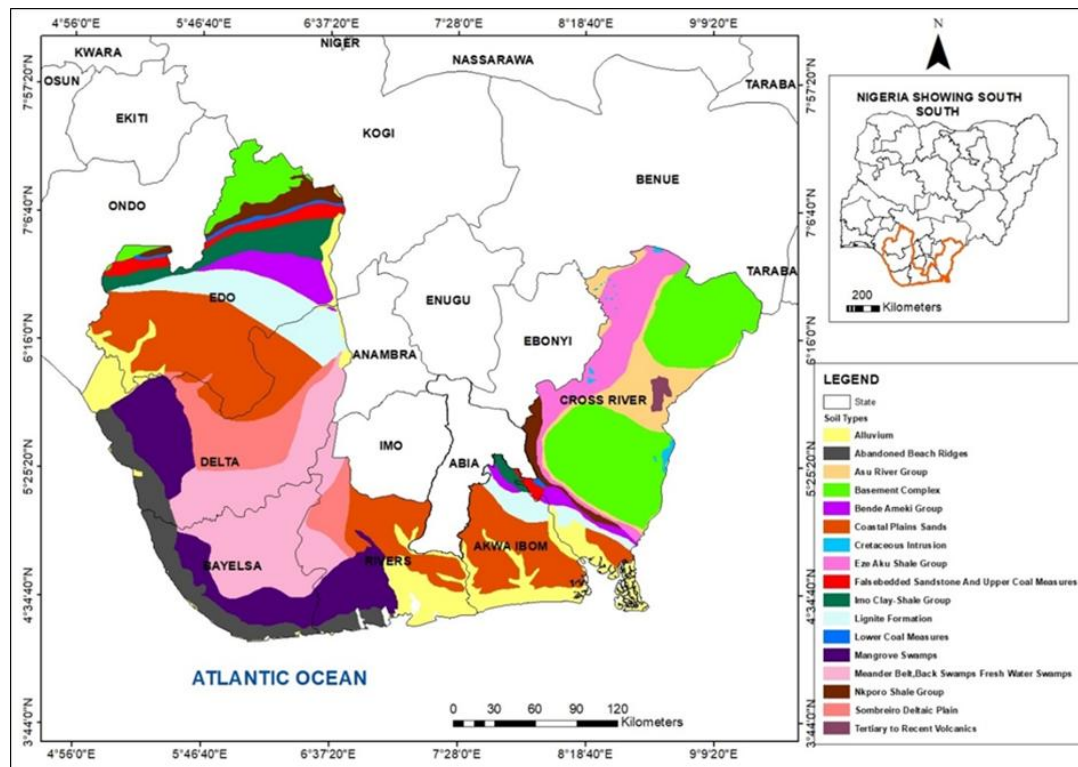


Figure 1. Research Location showing Soil types

2.2. Data Limitations and Validation

While satellite-derived datasets such as SMAP, CHIRPS, and ERA5 provide robust spatial and temporal coverage critical for studying hydroclimatic trends in data-sparse regions like South-South Nigeria, they are subject to potential limitations and biases. For instance, CHIRPS precipitation estimates may overestimate rainfall in coastal areas due to orographic effects, with reported root mean square errors (RMSE) of approximately 15–20 mm/month in similar Nigerian contexts (Akayeti et al., 2024; Dinku et al., 2018). Similarly, SMAP soil moisture retrievals may underestimate values in densely vegetated zones, such as rainforests and mangroves prevalent in the study region, due to microwave signal attenuation, with RMSE values ranging from 0.04–0.06 m³/m³ (Akayeti et al., 2024; Colliander et al., 2017). ERA5 temperature data, while reliable, may exhibit minor biases in humid tropical settings due to limited ground station inputs for reanalysis calibration (Hersbach et al., 2020). In-situ validation was not feasible within this study's scope due to sparse ground station networks in South-South Nigeria. However, to enhance credibility, we cross-referenced our datasets against available benchmarks from the Nigerian Meteorological Agency (NiMet) and regional studies, which confirm acceptable accuracy for trend analyses (Akayeti et al., 2024; Akayeti et al., 2024). The focus on temporal trends rather than absolute values mitigates some uncertainties associated with satellite data biases. These limitations highlight the need for cautious interpretation of absolute magnitudes while affirming the robustness of the observed trends in soil moisture, precipitation, and temperature.

3. Results and Discussion

The analyses explicitly elucidate the interrelationships between soil moisture, precipitation, and temperature through correlations and trends. The findings in this section

indicate temperature's role in enhancing evapotranspiration, thereby diminishing soil moisture, while precipitation exerts a modulating influence, albeit limited in high-rainfall events due to potential runoff (Dinku et al., 2018; Ford, 2015).

3.1 Trends in Temperature and Precipitation

3.1.1 Air Temperature

From 2000 to 2020, air temperature exhibited a consistent upward trajectory, with minimum and maximum values escalating, particularly post-2015. In 2000, minimum and maximum temperatures were 21.87°C and 27.59°C, establishing a baseline with a 5.72°C diurnal range, indicative of moderate conditions. By 2003, both rose slightly to 22.17°C and 27.77°C, signaling nascent warming and potential health-agricultural impacts. The 2006 period marked further intensification, with minima at 22.28°C and maxima at 27.99°C, narrowing the range and suggesting stabilized yet hotter regimes, consistent with urbanization-driven heat islands (Ayanlade & Howard, 2019). In 2009, a minor dip occurred, with minima at 22.26°C and maxima at 27.84°C, possibly due to transient factors like enhanced cloudiness, yet maintaining the warming trend. The 2012 anomaly saw declines to 21.89°C and 27.47°C, potentially linked to elevated rainfall, representing a brief respite amid long-term escalation (Akinsanola & Ogunjobi, 2014). Recovery ensued in 2015, with values rebounding to 22.19°C and 27.86°C, resuming the trajectory. By 2017, peaks reached 22.48°C and 28.21°C, exceeding prior thresholds and amplifying extremes. Culminating in 2020, maxima soared to 28.38°C with minima at 22.57°C, the dataset's apex, heightening vulnerability to heat stress and aligning with global projections (Dosio et al., 2018).

In 2020, South-South Nigeria experienced its warmest conditions over the 2000–2020 period, with minimum temperatures peaking at 22.57°C and maximum temperatures reaching 28.38°C, the highest recorded in the dataset. This elevated maximum indicates intensified daytime heat, while the increased minimum reflects warmer nights or cooler intervals compared to prior years. These rising temperatures highlight the region's susceptibility to persistent global warming, posing significant risks to agriculture, public health, and ecosystem stability. These trends, with increasing standard deviations (from 2.86 in 2000 to 2.90 in 2020), reflect amplified variability, driven by deforestation and urban sprawl, corroborating Niger Delta LST rises (Ayanlade & Howard, 2019). Implications include heightened evaporative losses, reduced crop viability, and ecosystem strain, necessitating adaptive measures like heat-tolerant cultivars (Nduka & Nduka, 2025).

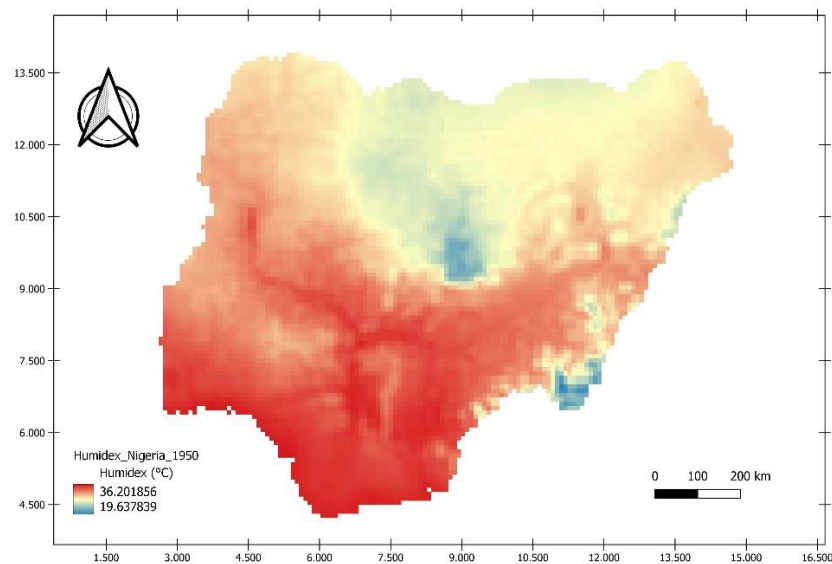


Figure 3.0 (a): Air Temperature-Humidity Index Across Nigeria (1950), Illustrating Warming Patterns Relevant to South-South Trends (2000-2020)

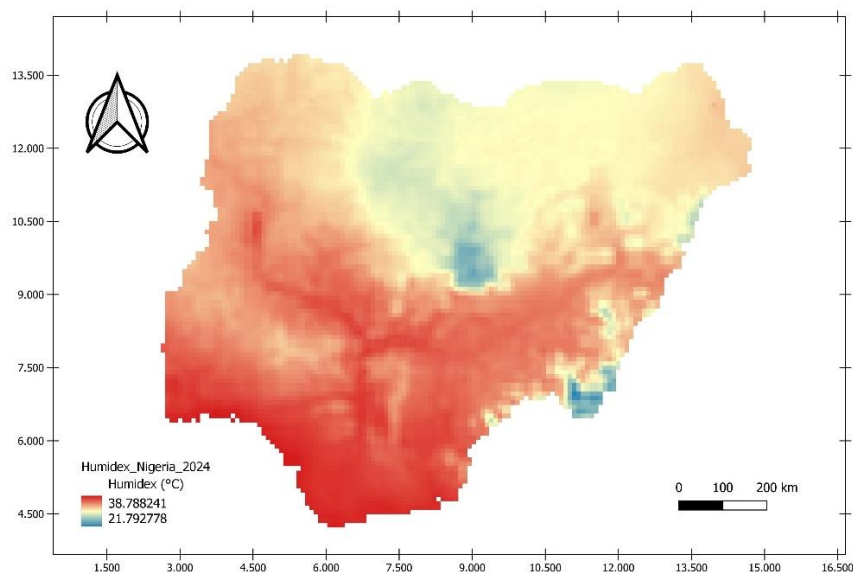
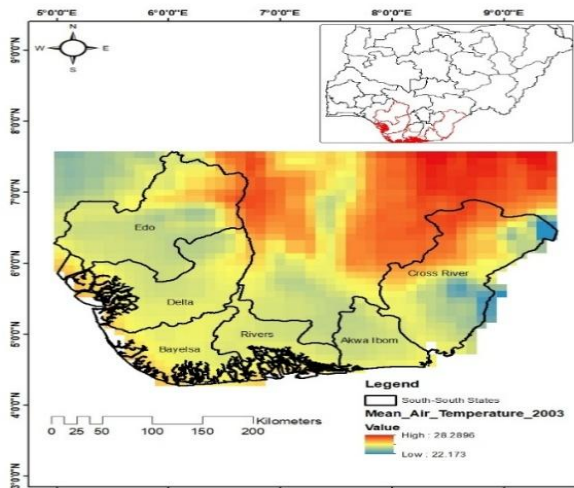
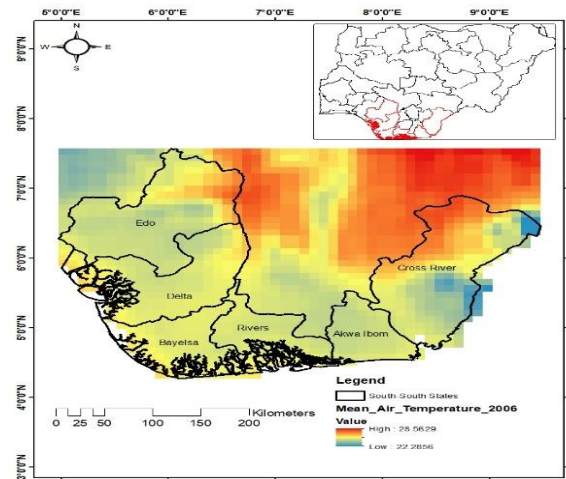


Figure 3.0.1(b): Air Temperature-Humidity Index Across Nigeria (2024), Illustrating Warming Patterns Relevant to South-South Trends (2000-2020). This historical baseline overlaps with the study period (2000-2020) and highlights accelerating warming post-2000, consistent with our findings.



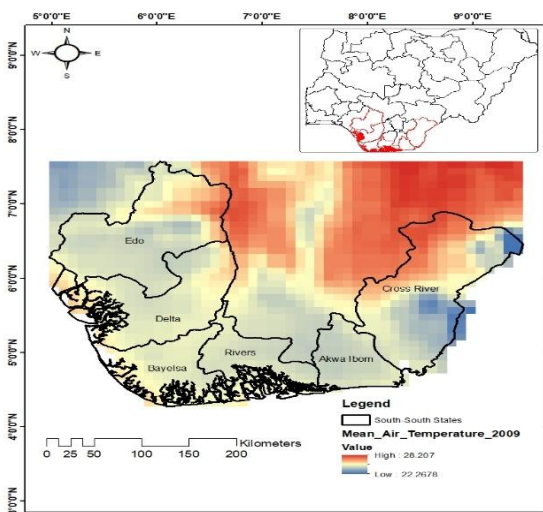
(a)

Figure 3.1. Mean Air Temperature Across States in the South-South region in 2003



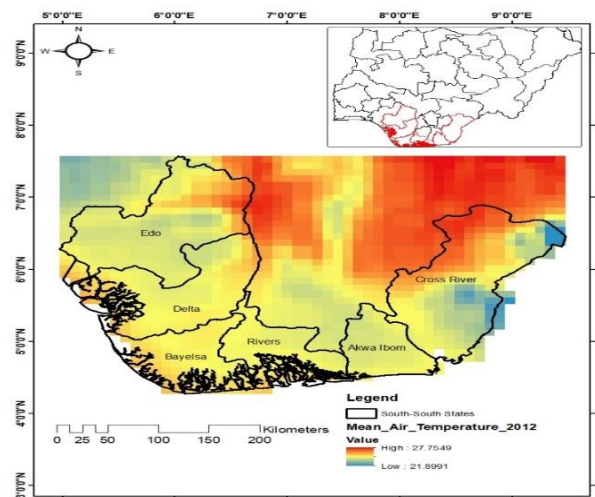
(b)

Figure 3.2. Mean Air Temperature Across States in the South-South region in 2006



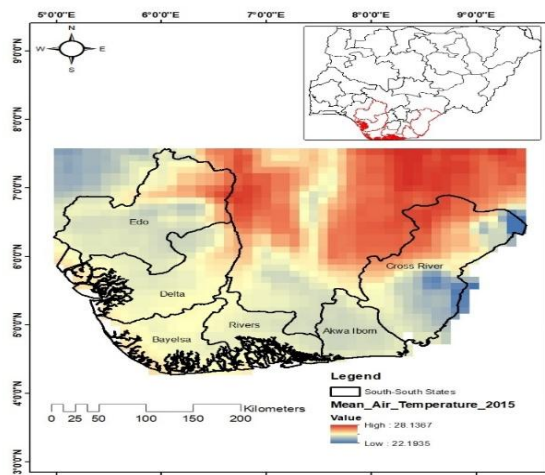
(c)

Figure 3.3. Mean Air Temperature Across States in the South-South region in 2009



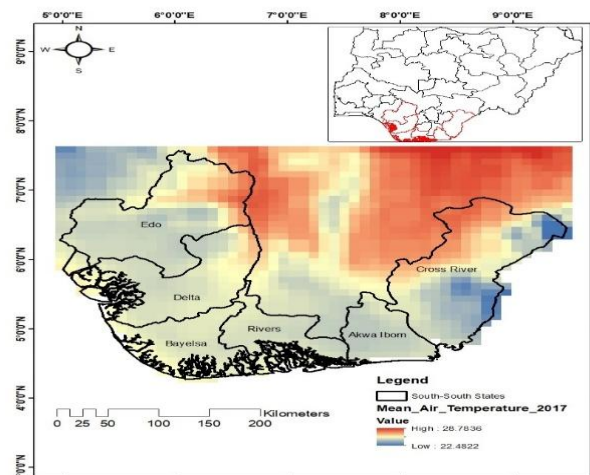
(d)

Figure 3.4. Mean Air Temperature Across States in the South-South region in 2012



(e)

Figure 3.5. Mean Air Temperature Across States in the South-South region in 2015



(f)

Figure 3.6. Mean Air Temperature Across States in the South-South region in 2017

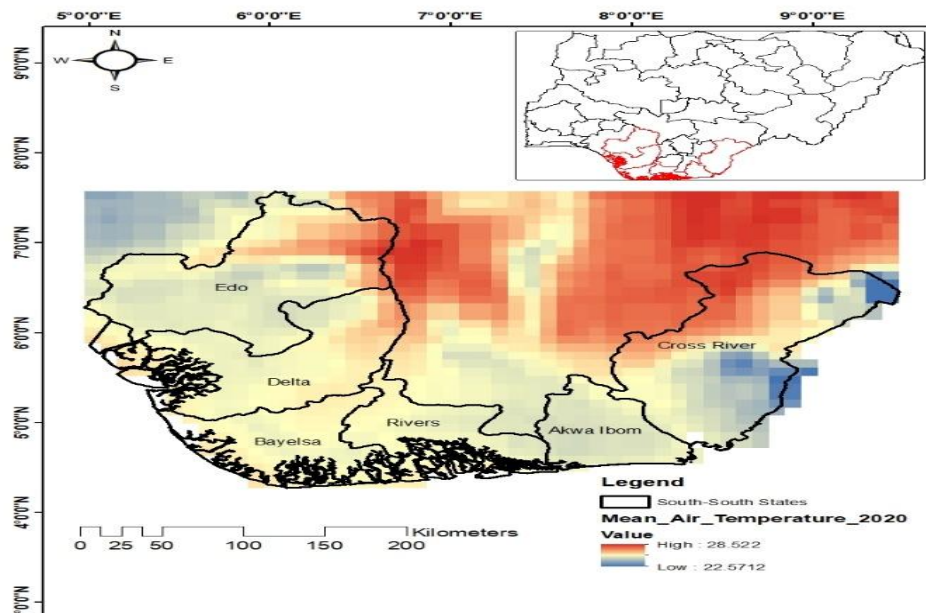


Figure 3.7. Mean Air Temperature Across States in the South-South region in 2020.

3.1.2 Precipitation

Precipitation displayed pronounced inter-annual flux, with minima and maxima oscillating across the period. In 2000, daily minima and maxima were 1.45 mm and 5.39 mm, denoting balanced regimes without extremes, supporting stable hydrology. By 2003, maxima rose to 5.55 mm with minima at 1.23 mm, indicating intensified events potentially risking floods. The 2006 surge saw maxima at 5.82 mm, amplifying variability and erosion concerns (Akinsanola & Ogunjobi, 2014). Peaking in 2009 at 6.12 mm maxima and 1.32 mm minima, this period marked heightened intensity, correlating with flood vulnerabilities. A 2012 shift reduced maxima to 5.14 mm but elevated minima to 1.55 mm, suggesting consistent yet subdued rainfall, mitigating dry spells. Intensification resumed in 2015, with

maxima at 7.01 mm—the era's zenith—exacerbating inundation while minima at 1.45 mm maintained balance. By 2017, maxima declined to 5.62 mm with minima at 1.34 mm, reflecting moderated patterns. Culminating in 2020, maxima at 5.38 mm and minima at 1.23 mm indicated drier tendencies, heightening drought risks amid warming (Gebrechorkos et al., 2018). In 2020, South-South Nigeria recorded a stable minimum daily rainfall of 1.23 mm, with a notable decrease in maximum rainfall to 5.38 mm compared to peak years like 2015. This reduction in maximum rainfall indicates fewer extreme precipitation events, while the consistent minimum suggests reliable rainfall on drier days, fostering a more balanced hydrological cycle for the year. This variability, with anomalies tied to monsoon shifts, highlights irregular distribution impacting recharge and agriculture, aligning with Niger Delta projections of intensified extremes (Akinsanola & Ogunjobi, 2014). Discussion emphasizes adaptive irrigation and forecasting to buffer volatility (Ogunrinde et al., 2024).

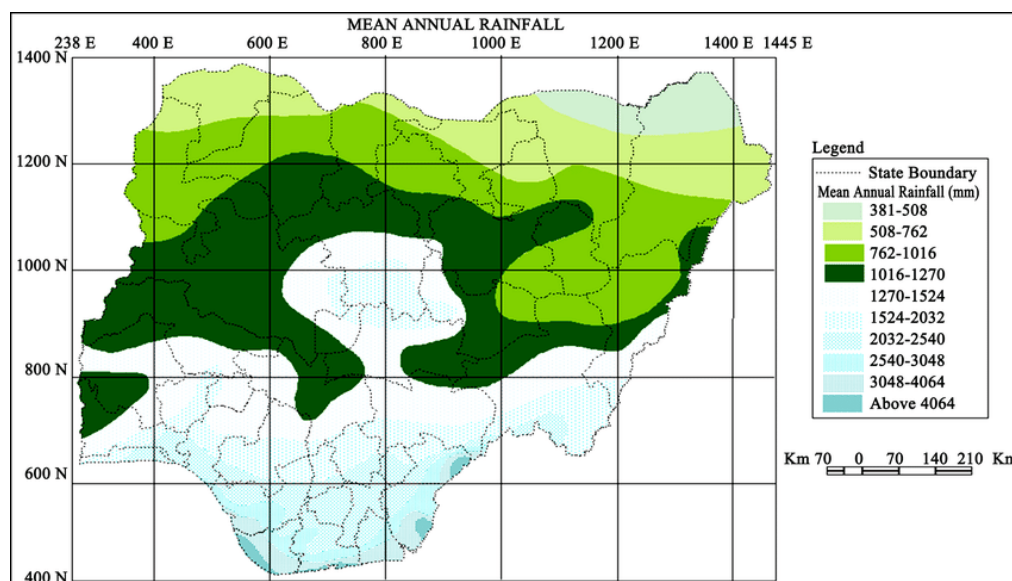
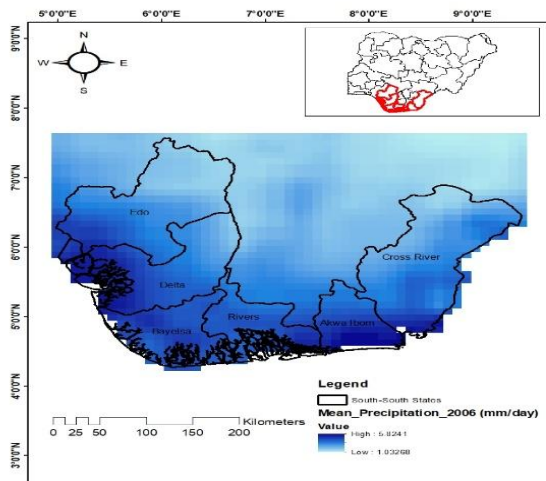
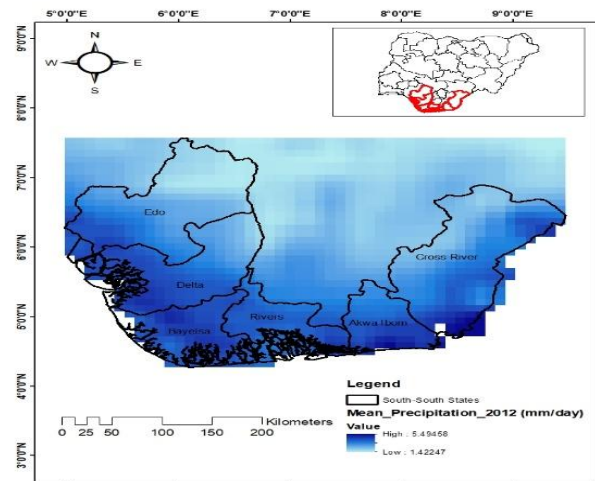


Figure 3.8. Mean Annual Rainfall Patterns in Nigeria, Highlighting South-South Variability (Relevant to 2000-2020 Trends). The 1951-2009 data provide context for the study's 2000-2020 focus, showing persistent monsoon influences amid recent intensification (Akinsanola & Ogunjobi, 2014).



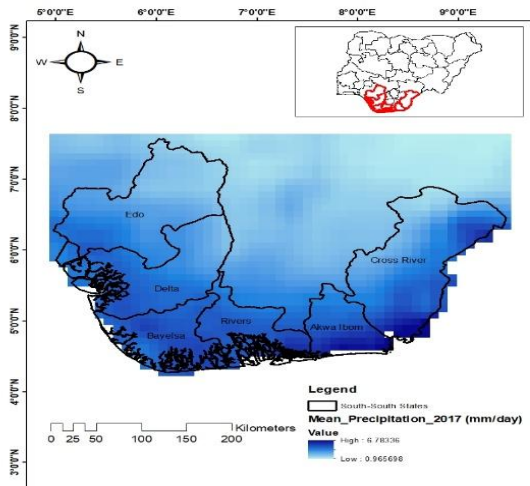
(a)

Figure 3.9. Mean Precipitation Across States in the South-South region in 2006



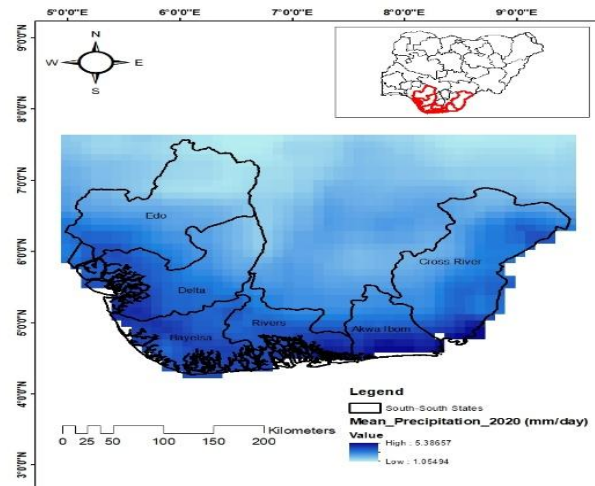
(b)

Figure 3.10. Mean Precipitation Across States in the South-South region in 2012



(a)

Figure 3.11. Mean Precipitation Across States in the South-South region in 2017



(b)

Figure 3.12. Mean Precipitation Across States in the South-South region in 2020

3.2 Soil Moisture Variability

Soil moisture evinced a declining trajectory, with mean values receding from 0.325 m^3/m^3 in 2009 to 0.305 m^3/m^3 in 2020, signaling eroded retention amid climatic pressures (Odusanya et al., 2019). Seasonal peaks aligned with wet phases, yet amplitude waned, reflecting diminished recharge efficacy (Odusanya et al., 2019). In 2000, minima and maxima were 0.17 m^3/m^3 and 0.46 m^3/m^3 , indicating balanced retention. By 2003, maxima dipped to 0.45 m^3/m^3 with minima at 0.18 m^3/m^3 , suggesting initial deficits. The 2006 period stabilized maxima at 0.46 m^3/m^3 , yet variability persisted. Peaks in 2009 reached 0.47 m^3/m^3 maxima with 0.19 m^3/m^3 minima, correlating with wetter years. Declines ensued in 2012 to 0.44 m^3/m^3 maxima and 0.17 m^3/m^3 minima, amplifying drought susceptibility. Rebounds in 2015 saw maxima at 0.45 m^3/m^3 , but sustained minima at 0.18 m^3/m^3 . By 2017, minima fell

to $0.17 \text{ m}^3/\text{m}^3$ with maxima at $0.46 \text{ m}^3/\text{m}^3$, indicating flux. In 2020, minima hit $0.16 \text{ m}^3/\text{m}^3$ and maxima $0.45 \text{ m}^3/\text{m}^3$, the nadir, underscoring aridification (Akayeti et al., 2024). These patterns, influenced by evaporative hikes and erratic rains, imperil agronomy and ecology, necessitating mulching and agroforestry (Wang et al., 2017; Schimel, 2018).

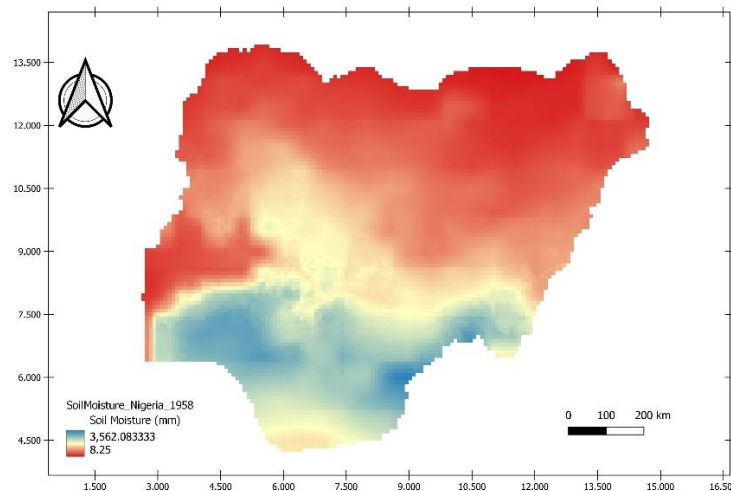


Figure 3.13: Drought Indices (Including Soil Moisture Proxies) Across Nigeria (1958), Illustrating South-South Trends of the study years (2000-2020)

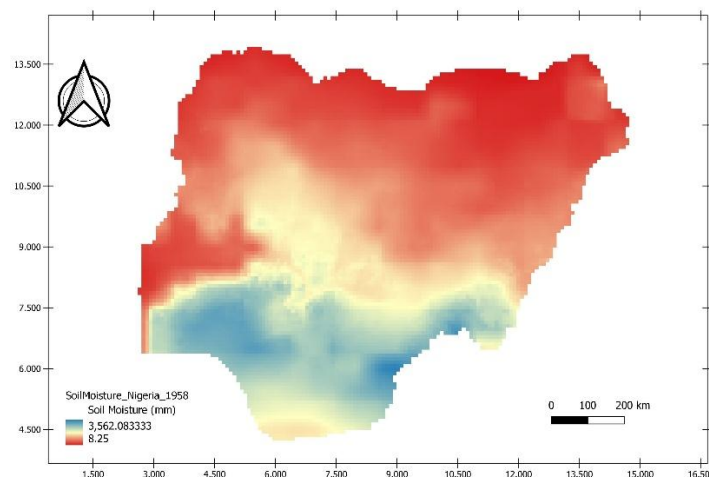
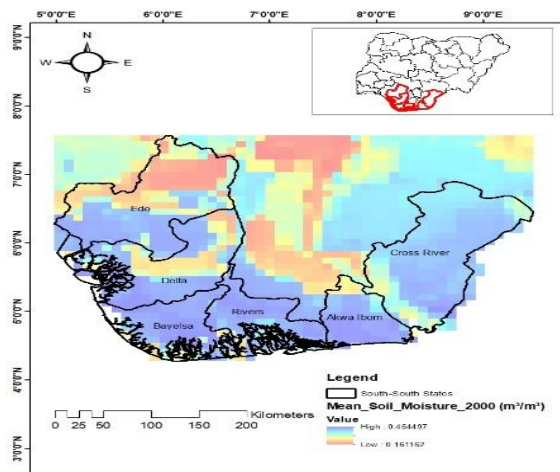
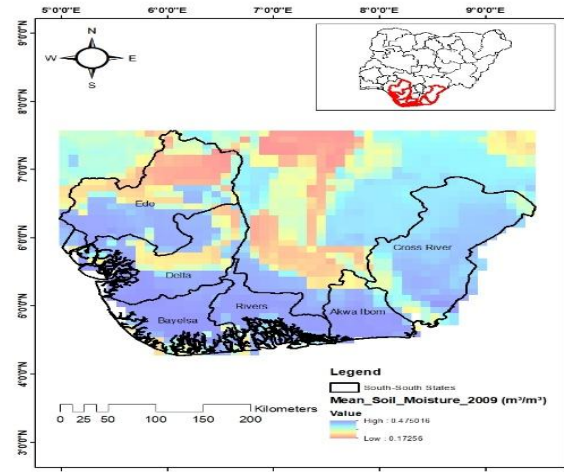


Figure 3.13.1: Drought Indices (Including Soil Moisture Proxies) Across Nigeria (2024), Illustrating South-South Trends of the study years (2000-2020)



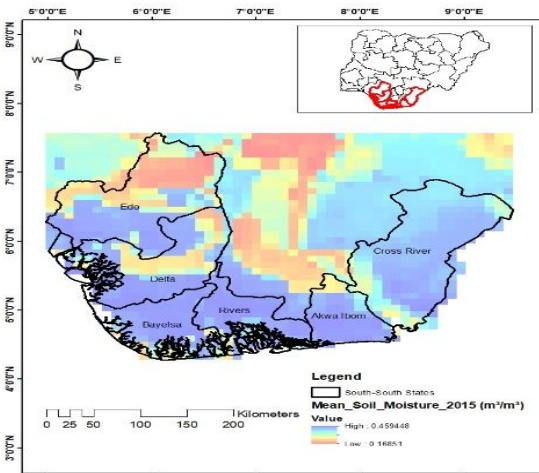
(a)

Figure 3.14. Mean Soil Moisture Across States in the South-South region in 2000



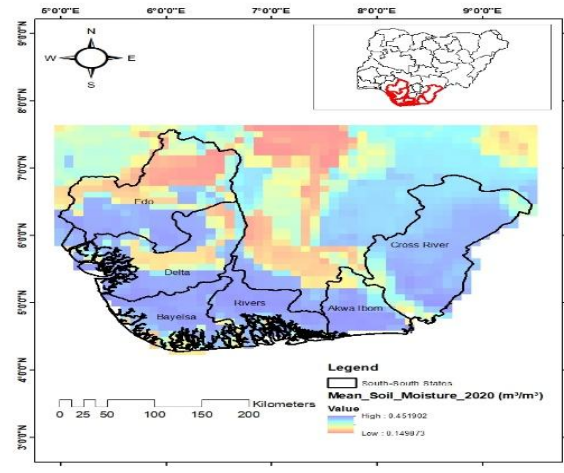
(b)

Figure 3.15. Mean Soil Moisture Across States in the South-South region in 2009



(a)

Figure 3.16 Mean Soil Moisture Across States in the South-South region in 2015



(b)

Figure 3.17 Mean Soil Moisture Across States in the South-South region in 2020

3.3 Trends in Temperature and Precipitation

- Temperature: A steady rise in both minimum and maximum temperatures from 2000 to 2020, with significant increases post-2015.
- Precipitation: High inter-annual variability, with peak rainfall years (e.g., 2009, 2015) contrasting with drier periods (e.g., 2003, 2020).

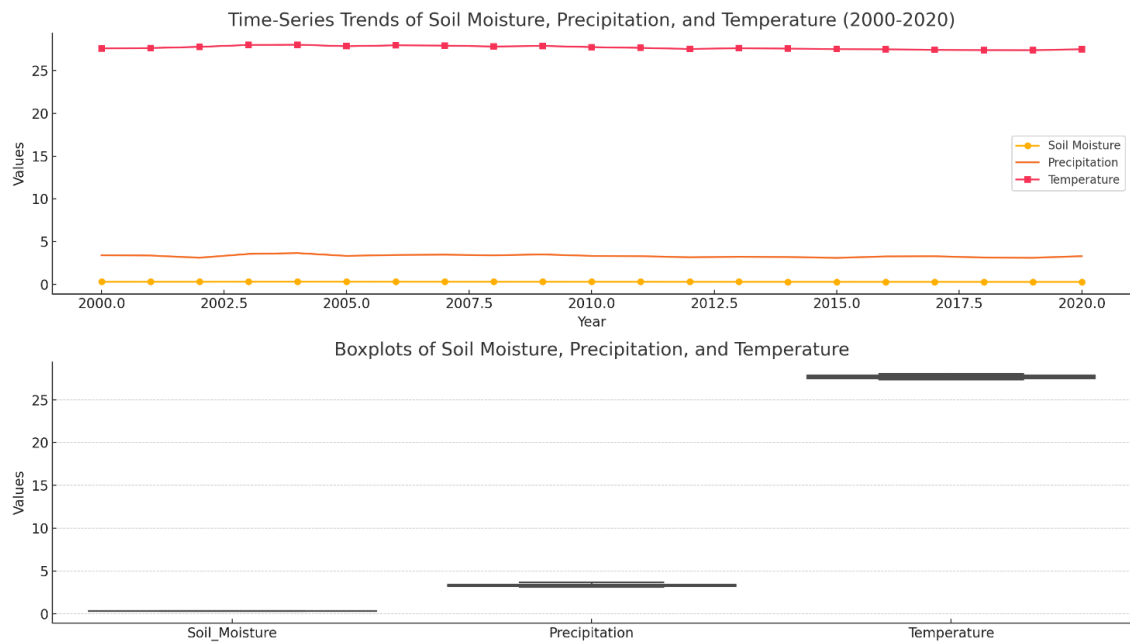


Fig 3. 18 Time series trends and box plot displaying Soil Moisture, Precipitation and Temperature (2000-2020)

3.4 Correlations

Table 1. Variation in soil moisture (m^3/m^3) in South-South Region of Nigeria from 2000 to 2020

Year	Min	Max	Mean	SD
2000	0.17	0.46	0.315	0.084
2003	0.17	0.47	0.320	0.087
2006	0.174	0.47	0.322	0.085
2009	0.18	0.47	0.325	0.084
2012	0.18	0.47	0.325	0.084
2015	0.18	0.45	0.315	0.078
2017	0.17	0.46	0.315	0.084
2020	0.16	0.45	0.305	0.084

Table 2. Variation in Precipitation (mm/day) in South-South Region of Nigeria from 2000 to 2020

Year	Min	Max	Mean	SD
2000	1.45	5.39	3.42	0.98
2003	1.04	5.22	3.13	1.05
2006	1.32	5.82	3.57	1.12
2009	1.35	6.88	4.12	1.38
2012	1.55	5.14	3.34	0.90
2015	1.34	7.01	4.18	1.42
2017	1.22	6.68	3.95	1.36
2020	1.23	5.38	3.31	1.05

Table 3. Variation in Air Temperature (°C) in South-South Region of Nigeria from 2000 to 2020

Year	Min	Max	Mean	SD
2000	21.87	27.59	24.73	2.86
2003	22.17	27.77	24.97	2.80
2006	22.28	27.99	25.13	2.85
2009	22.26	27.84	25.05	2.79
2012	21.89	27.47	24.68	2.79
2015	22.19	27.86	25.03	2.83
2017	22.48	28.21	25.35	2.87
2020	22.57	28.38	25.48	2.90

The correlations reveal soil moisture's positive yet weak tie to precipitation (0.124) and strong inverse to temperature (-0.614), with precipitation-temperature at 0.204. Cross-wavelet coherence confirms multi-scale synergies, where temperature drives deficits via evaporation, while precipitation sporadically replenishes, aligning with hydrological models (Grinsted et al., 2004; Ogunrinde et al., 2024). Discussion highlights agronomic risks, advocating multi-sensor monitoring for proactive management (Odusanya et al., 2019; Ogunrinde et al., 2024). Summarily, mitigation via climate-smart practices is imperative for resilience (Nduka & Nduka, 2025).

3.4.1 Implications for Agricultural Productivity and Policy Recommendations

The observed soil moisture decline, from a mean of $0.325 \text{ m}^3/\text{m}^3$ in 2009 to $0.305 \text{ m}^3/\text{m}^3$ in 2020 ($\sim 6\%$ reduction), poses significant risks to agricultural productivity in South-South Nigeria, where rain-fed systems dominate. Regional crop models indicate that such moisture deficits can reduce yields of key staples like cassava by 10–20% and rice by 15–25%, as water stress impairs root development, nutrient uptake, and photosynthetic efficiency (Wang et al., 2017; Schimel, 2018). These reductions threaten food security and smallholder livelihoods, given cassava and rice's centrality to local diets and economies. The interplay of rising temperatures (peaking at 28.38°C in 2020) and erratic precipitation (e.g., maximum daily rainfall of 7.01 mm in 2015 versus 5.38 mm in 2020) exacerbates these impacts, amplifying drought risks and post-harvest losses through wilting and pest surges (Green et al., 2019). To address these challenges, we propose the following actionable recommendations for farmers and policymakers in Sub-Saharan Africa, tailored to the region's socio-agronomic context:

Adopt Drought-Resistant Cultivars: Promote the cultivation of drought-tolerant cassava varieties (e.g., TMS 98/0505) and rice cultivars (e.g., FARO 44) through government-led seed distribution programs. These varieties can mitigate yield losses by 10–15% under moisture stress (Nduka & Nduka, 2025).

Implement Conservation Agriculture: Encourage practices such as mulching and zero-tillage to enhance soil moisture retention by 15–30%, reducing evaporation and improving soil structure (Wang et al., 2017). Extension services should provide training and subsidized inputs to smallholders

Develop Community-Based Water Management: Support rainwater harvesting and micro-irrigation systems, such as small-scale drip systems, to buffer erratic precipitation patterns. These systems can stabilize water availability for crops during dry spells, increasing yields by up to 20% in water-scarce periods (Ogunrinde et al., 2024).

Leverage Technology for Early-Warning Systems: Integrate accessible satellite-based monitoring tools (e.g., CHIRPS-derived rainfall forecasts via mobile apps) to provide farmers with timely planting and irrigation advisories, reducing crop failure risks by enabling adaptive management (Dinku et al., 2018).

These strategies, grounded in the study's findings, align with climate-smart agriculture frameworks and can enhance resilience across Sub-Saharan Africa's rain-fed systems. By linking moisture declines to tangible yield impacts and actionable solutions, this study informs practical pathways for sustainable agriculture amidst escalating hydroclimatic variability.

Conclusion

This study elucidates significant hydroclimatic shifts in South-South Nigeria over the 2000–2020 period, characterized by escalating temperatures, erratic precipitation, and diminishing soil moisture reserves. The observed warming trend, with minimum and maximum temperatures peaking at 22.57°C and 28.38°C in 2020, exacerbates evaporative demands, while precipitation variability—marked by highs of 7.01 mm/day in 2015 and lows in drier intervals—results in irregular moisture replenishment. Soil moisture declines, from mean values of 0.325 m³/m³ in 2009 to 0.305 m³/m³ in 2020, underscore reduced retention capacity, posing acute risks to rain-fed agriculture and ecosystem integrity in this agrarian region (Ogunrinde et al., 2024; Akinsanola & Ogunjobi, 2014). These dynamics, corroborated by correlation analyses revealing soil moisture's inverse tie to temperature (−0.614) and modest positive link to precipitation (0.124), highlight temperature as a dominant driver of deficits via enhanced evapotranspiration, amid monsoon inconsistencies (Dinku et al., 2018; Gebrechorkos et al., 2018). Implications extend to agricultural yields, with potential staple crop reductions under warming, and biodiversity erosion, as moisture anomalies disrupt nutrient cycling and habitat suitability (Wang et al., 2017; Schimel, 2018). Urbanization and land degradation further compound vulnerabilities, aligning with Niger Delta LST rises and flood-drought cycles (Ayanlade & Howard, 2019; Nduka & Nduka, 2025). To mitigate these challenges, integrated strategies are imperative: adopting climate-smart practices like drought-resistant cultivars, conservation tillage, and agroforestry to bolster resilience; enhancing monitoring via multi-sensor remote sensing for proactive forecasting; and advancing policy for sustainable water management (Odusanya et al., 2019; Ogunrinde et al., 2024). Future inquiries should prioritize localized modeling, incorporating socioeconomic dimensions to refine adaptations amid projected intensification of extremes (Dosio et al., 2018; Ogunrinde et al., 2024). By addressing these interconnections, this research informs pathways toward enduring food security and ecological stewardship in tropical contexts.

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Conflicts of Interest

The authors declare no conflict of interest.

References

- Adeogun, B. K., Fulazzaky, M. A., Mohammed, B. S., Daud, O., & Ghazali, A. H. (2021). Hydropower potential assessment using spatial technology and hydrological modelling in Nigeria river basin. *Renewable Energy*, 178, 213-228.
- Akinsanola, A. A., & Ogunjobi, K. O. (2014). Analysis of rainfall and temperature variability over Nigeria. *Global Journal of Human-Social Science: B Geography, Geo-Sciences, Environmental Science & Disaster Management*, 14(3), 1-17.
- Akayeti, A., Liermann, S., & Vogel, M. (2024). Evaluation of satellite-based rainfall estimates against rain gauge observations in Nigeria. *Remote Sensing*, 16(10), 1755.
- Anejionu, O. C., Ahiamammunnah, P. A. N., & Nri-ezedi, C. J. (2015). Hydrocarbon pollution in the Niger Delta: Geochemistries of soil organic matter indicate extent of pollution. *Environmental Forensics*, 16(1), 71-83.
- Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., & Jha, M. K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4), 1491-1508.
- Ayanlade, A., & Howard, M. T. (2019). Land surface temperature and heat fluxes over three cities in Niger Delta. *Journal of African Earth Sciences*, 151, 54-66.
- Bouskill, N. J., Wood, T. E., Baran, R., Ye, Z., Bowen, B. P., Lim, H., Zhou, J., Van Nostrand, J. D., Nico, P., Northen, T. R., Silver, W. L., & Brodie, E. L. (2016). Belowground response to drought in a tropical forest soil. I. Changes in microbial functional potential and metabolism. *Frontiers in Microbiology*, 7, 525.
- Colliander, A., Jackson, T. J., Bindlish, R., Chan, S., Das, N., Kim, S. B., ... Yueh, S. H. (2017). Validation of SMAP surface soil moisture products with core validation sites. *Remote Sensing of Environment*, 191, 215-231.
- Das, N. N., Entekhabi, D., Dunbar, R. S., Njoku, E. G., & Yueh, S. H. (2019). The SMAP mission combined active-passive soil moisture retrieval. *IEEE Transactions on Geoscience and Remote Sensing*, 57(5), 2884-2897.
- Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., & Ceccato, P. (2018). Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society*, 144(S1), 292-312.
- Dosio, A., Mentaschi, L., Fischer, E. M., & Wyser, K. (2018). Extreme heat waves under 1.5°C and 2°C global warming. *Environmental Research Letters*, 13(5), 054006.

- Dunkerley, D. (2015). Percolation soil moisture under steady rainfall: Dynamic or steady state? *Journal of Hydrology*, 531, 156-162.
- Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., Edelstein, W. N., ... Van Zyl, J. (2010). The Soil Moisture Active Passive (SMAP) mission. *Proceedings of the IEEE*, 98(5), 704-716.
- Ford, J. D. (2015). Vulnerability of Inuit food systems to food insecurity as a consequence of climate change: A case study from Igloolik, Nunavut. *Regional Environmental Change*, 15(1), 83-100.
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., ... Michaelsen, J. (2015). The climate hazards infrared precipitation with stations – a new environmental record for monitoring extremes. *Scientific Data*, 2, 150066.
- Gebrechorkos, S. H., Hülsmann, S., & Bernhofer, C. (2018). Evaluation of multiple climate data sources for managing environmental resources in East Africa. *Hydrology and Earth System Sciences*, 22(9), 4547-4564.
- Green, J. K., Seneviratne, S. I., Berg, A. M., Findell, K. L., Hagemann, S., Lawrence, D. M., & Gentine, P. (2019). Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*, 565(7738), 476-479.
- Grinsted, A., Moore, J. C., & Jevrejeva, S. (2004). Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Processes in Geophysics*, 11(5/6), 561-566.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., ... Thépaut, J.-N. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049.
- Kardol, P., Cornips, N. J., van Kempen, M. M., Bakx-Schotman, J. M., & van der Putten, W. H. (2010). Microbe-mediated plant-soil feedback causes historical contingency effects in plant community assembly. *Ecological Monographs*, 80(1), 147-162.
- Li, H., & Si, B. (2018). Spatial patterns of soil moisture from distributed and self-organizing wireless sensor networks. *Journal of Hydrology*, 566, 852-860.
- Li, Y., Huang, J., Ji, M., & Ran, L. (2015). Dryland vegetation pattern dynamics driven by the disturbance effects of human activities and climate change. *Ecological Research*, 30(4), 651-663.
- Mallick, K., Bhattacharya, B. K., Rao, V., Reddy, D., Banerjee, S., Venkatesh, H., Pandey, L. M., Kar, G., Mukherjee, J., Vyas, S. P., Gadgil, A. S., & Patel, N. K. (2015). Latent heat flux estimation in clear sky days over Indian agro-climatic zones using no reference pixel values of thermal infrared imagery and high-resolution radiometric data. *Agricultural and Forest Meteorology*, 215-216, 176-191.
- Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica*, 13(3), 245-259.
- Nduka, C. C., & Nduka, E. C. (2025). Climate smart agriculture in food insecurity mitigation in Nigeria. *Asian Journal of Agricultural Extension, Economics & Sociology*, 43(1), 1-10.
- Njoku, E. G., Jackson, T. J., Lakshmi, V., Chan, T. K., & Nghiem, S. V. (2003). Soil moisture retrieval from AMSR-E. *IEEE Transactions on Geoscience and Remote Sensing*, 41(2), 215-229.
- Ogwu, C., & Idisi, E. B. (2024). Characterization of the polycyclic aromatic hydrocarbons in the wetlands of Gbokoda and environs for pen aquaculture adoption as a recipe for

-
- achieving zero hunger in Nigeria. *International Journal of Advanced Multidisciplinary Research Studies*, 4(4), 1021–1026.
- Ogunrinde, A. T., Oguntunde, P. G., Fasinmirin, J. T., Akinola, G. E., & Olaifa, O. P. (2024). Field-scale variability and dynamics of soil moisture in Southwestern Nigeria. *Geoenvironmental Disasters*, 11, 20.
- R Core Team. (2023). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
- Schimel, J. P. (2018). Life in dry soils: Effects of drought on soil microbial communities and processes. *Annual Review of Ecology, Evolution, and Systematics*, 49, 409–432.
- Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association*, 63(324), 1379–1389.
- Smith, P., Cotrufo, M. F., Rumpel, C., Paustian, K., Kuikman, P. J., Elliott, J. A., ... & Lal, R. (2015). Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *Soil*, 1(2), 665–685.
- Stackhouse, P. W., Jr. (2006). Prediction of worldwide energy resources (POWER): NASA's applied science program for renewable energy and buildings. *Solar Energy*, 80(12), 1580–1593.
- Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. *Bulletin of the American Meteorological Society*, 79(1), 61–78.
- Wang, T., Franz, T. E., Li, R., You, J., Shulski, M. D., & Ray, C. (2017). Evaluating climate and soil effects on regional soil moisture spatial variability using EOFs. *Water Resources Research*, 53(5), 4022–4035.
- Wekpe, V. O., & Idisi, E. B. (2024). Long-term monitoring of oil spill impacted vegetation in the Niger Delta region of Nigeria: A Google Earth Engine derived vegetation indices approach. *Journal of Geography, Environment and Earth Science International*, 28(2), 27–40.
- Zhang, Y., Chiew, F. H., Peña-Arancibia, J., Sun, F., Li, H., & Leuning, R. (2017). Global variation of transpiration and soil evaporation and the role of their major climate drivers. *Journal of Geophysical Research: Atmospheres*, 122(13), 6868–6881.
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