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RESEARCH ARTICLE

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Revealing the Feedback Loop: Comparing Satellite and Sensor-derived Meteorological Parameters in Groundnut Cultivation

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ABSTRACT

Background: Studying soil moisture's impact on groundnut, particularly under rainfed conditions, is crucial for improving quality and yield. This research explores soil moisture dynamics using satellite and in-situ sensor data to enhance water management and crop predictions, focusing on the feedback mechanisms between soil moisture and weather variables.

Methods: The study was conducted at the Oil Seed Research Station (TNAU) in Tindivanam, Tamil Nadu, using the groundnut variety TMV 14. Soil moisture and weather parameters were monitored at critical crop growth stages, using an in-situ soil moisture sensor (Cr 300) and compared with satellite data from SMAP, ERA5 and Sentinel 1A with environmental factors. Statistical analysis was carried out using SAS JMP Pro and network analysis via Cytoscape 3.8.2 software.

Result: Pre-monsoon soil moisture SMAP, SMAP-RZSM and sensor (VWC at 10cm) were found to increase in post-monsoon. Strong positive correlations were attained between SMAP-SM and SMAP-RZSM (r=0.94), indicating a reinforcing loop. Whereas, the negative feedback was observed between SMAP-SM and deeper soil temperatures (-0.91). It underscores the dynamic interplay between soil moisture and atmospheric conditions, essential for developing efficient water management strategies and enhancing crop resilience to climate variability.

Key words: Feedback, Groundnut, Satellite, Sensor, Soil moisture.

INTRODUCTION

Groundnut (*Arachis hypogaea* L.) is an important pulse and oilseed crop in the world. It is cultivated mainly for its edible oil, protein and fatty acids. Its kernel contains high protein content (22-30%), edible oil (44-56%) and fatty acids among which oleic acid, linoleic acid and palmitic acid constitute 90% of the total fatty acid composition in groundnut (Mirdoraghi *et al*., 2024). High-oleic groundnut has a longer shelf-life and better flavour quality. In India, 70% of groundnuts are grown as rainfed crops and they are subjected to intermittent soil moisture stress, where the yield and quality of groundnuts are reduced (Priya *et al*., 2024). To improve the nutritional quality of groundnut under rainfed conditions, it is essential to study the effect of soil moisture stress on the performance of crops. The crop performance in rainfed regions is dramatic, due to water dwindling and shortages. Assessments of crop yield prediction pave the way to find the influence of soil moisture and related weather parameters to ensure sustainable practices with proper planning and monitoring, even in low water or no water conditions under environmental fluctuations (Roja *et al*., 2020). Climate plays a significant role in agricultural production as it determines a large portion of output. In addition to moisture, temperature, relative humidity, solar radiation, wind speed, pest and disease incidence and soil microbiology can all have an impact on production (Crow *et al*., 2018). Climate change research is essential for adapting agricultural crop management, particularly for plants whose growth, development, grain quality and production are more sensitive to climatic variations. Among the climate parameters, soil moisture, maximum and minimum temperatures, average temperature and solar radiation had the highest R^2 values and the lowest RMSE. Whereas, wind speed and relative humidity had lower correlation values and higher errors than the other variables. The NASA

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platform's grid size contributed to low model adjustments because its extension is kilometric and can overlap areas. It should be especially beneficial to growers who do not have surface weather stations near their farms (Barboza *et al*., 2024).

Objectives of the study

The key objective of this research is to,

- Conduct a detailed comparative analysis of soil moisture data from satellite and sensor sources.
- Provide insights that could enhance the accuracy of soil moisture monitoring and prediction in agricultural practices, particularly for groundnut crops.

MATERIALS AND METHODS

The study was carried out in the Oil Seed Research Station (TNAU) in Tindivanam at 12°213886′ latitude and 79°672351′ longitude, Groundnut (*Arachis hypogaea* L.) is a soil moisture-sensitive crop, sown in both predominant seasons of Tamil Nadu-*Kharif* and *Rabi* (Akuraju *et al*., 2017) in the year of 2023-24. The crop variety used for the study was TMV 14. The soil moisture and weather parameters were monitored and observations were taken at critical crop growth stages such as seedling (15 days after sowing), vegetative (30 DAS), flowering (45 DAS), pegging (60 DAS), pod filling (75 DAS) and harvest stages (105 DAS). The soil moisture sensor tower installed at the site is shown in Fig 1.

The in-situ soil moisture sensor (Cr 300) data was used to validate seasonal observations of satellite data (Ghasempour *et al*., 2022). At regular intervals, the logger data has been collected from the flux sensor. Satellites such as SMAP (Soil Moisture Active Passive), ERA5 and Sentinel 1A data were used for the comparative study. Satellite data were processed and downloaded from Google Earth Engine (GEE). The parameters utilized are detailed below in Table 1.

The statistical analysis of correlation and network analysis (path analysis) has been performed to study the relationship between each parameter and the sources used. The parameters were weighed concerning the Stages of crop phenology (Latha *et al*., 2024). The sense of reinforcement and balancing leads to establishing a favorable environment at the regional level/ field itself. The feedback loop nature (sensitivity rating) was enumerated critically through >0.5, 0.5 to -0.5 and <-0.5 as a positive, neutral and negative feedback mechanism, respectively (Wei *et al*., 2024; Balota *et al*., 2024). Correlation analysis was done using SAS JMP Pro 17 software (licensed; Parker *et al*., 2023) and network analysis by Cytoscape 3.8.2 software (Wiatrowska *et al*., 2021).

RESULTS AND DISCUSSION

Positive, negative and neutral feedback loop mechanisms in *kharif*

The SMAP-SM and SMAP-RZSM (0.9397) show a strong positive correlation suggesting a reinforcing loop between surface and root zone soil moisture. SMAP-SM and ST 10 cm (0.8921) had higher soil moisture correlates with higher soil temperature at 10 cm, potentially due to water's heat capacity. Short wavelengths (Sentinel 1A; C band) are applicable for SM retrieval for bare soils or sparse vegetation cover, longer wavelengths (SMAP; L band) are partially attenuated by vegetation canopies of groundnut and are amenable for near surface and RZSM determination, contribute to the measured microwave signals (*e.g.*, brightness temperature) increases with

(Photo captured by: Muthumanickam D).

Fig 1: Experimental site with *in situ* sensor.

wavelength (Sadeghi *et al*., 2019). The very strong positive correlation (0.9849) between root zone soil moisture and soil temperature at 10 cm. VWC (all depths) and SMAP-SM/SMAP-RZSM rely upon Strong positive correlations indicating a reinforcing relationship between soil moisture and volumetric water content. PET (Potential Evapotranspiration) shows strong positive correlations with SMAP-SM (0.9695) and SMAP-RZSM (0.8767), suggesting a complex relationship where higher soil moisture may lead to increased potential for evaporation. The contribution of soil moisture contents to soil temperature (r=0.690) and canopy temperature (r=0.545) is tightly coupled due to the pulse cropping pattern (Ding *et al*., 2021; Guna *et al*., 2024). The correlation weightage and positive feedback network have been illustrated in Fig 2.

Fig 3 depicts the negative feedback mechanism of SMAP-SM and ST 45 cm (-0.9127) employed strong negative correlation suggests deeper soil temperatures decrease as surface soil moisture increases, possibly due to evaporative cooling. These relationships highlight the tight coupling between soil moisture and soil thermal properties, as well as the influence of atmospheric conditions. Soil temperatures at different depths displayed significant correlations in both seasons. The arid environment has a smaller fluctuation range of -1.03 to 0.71, indicating more stable soil moisture conditions. In contrast, the semi-arid environment exhibits a larger fluctuation range of -2.16 to 2.23, suggesting more variability in soil moisture levels. Geographic characteristics of the arid condition are in a more stable climatic region, while the semi-arid environment experiences more extreme weather patterns,

Table 1: Details of sources and meteorological parameters.

Source	Parameter
Soil moisture tower (Cr 300)	Volumetric water content at 10 cm, 30 cm and 45 cm (VWC;%)
	Soil temperature at 10 cm, 30 cm and 45 cm (ST; °C)
	Horizontal wind speed (WS; m/s)
	Horizontal wind direction degree (WDV; °)
	Rain (mm)
	Relative humidity (RH; %)
	Net radiation (NR; Watts/m^2)
SMAP (Soil moisture active passive; Reichle *et al*., 2022)	Soil Moisture (SM; %)
	Root Zone Soil Moisture (RZSM; %)
Sentinel 1A (European Space Agency, 2024)	Backscatter Vertical-Vertical (VV; σ°)
	Backscatter Vertical-Horizontal (VH; σ°)
ERA5 (Muñoz Sabater, 2019)	Soil Moisture (SM; %)
	Forecast Albedo (Albedo; No unit)
	Surface Net Solar Radiation (SNSR; J/m^2)
	Potential Evapotranspiration (PET; m)

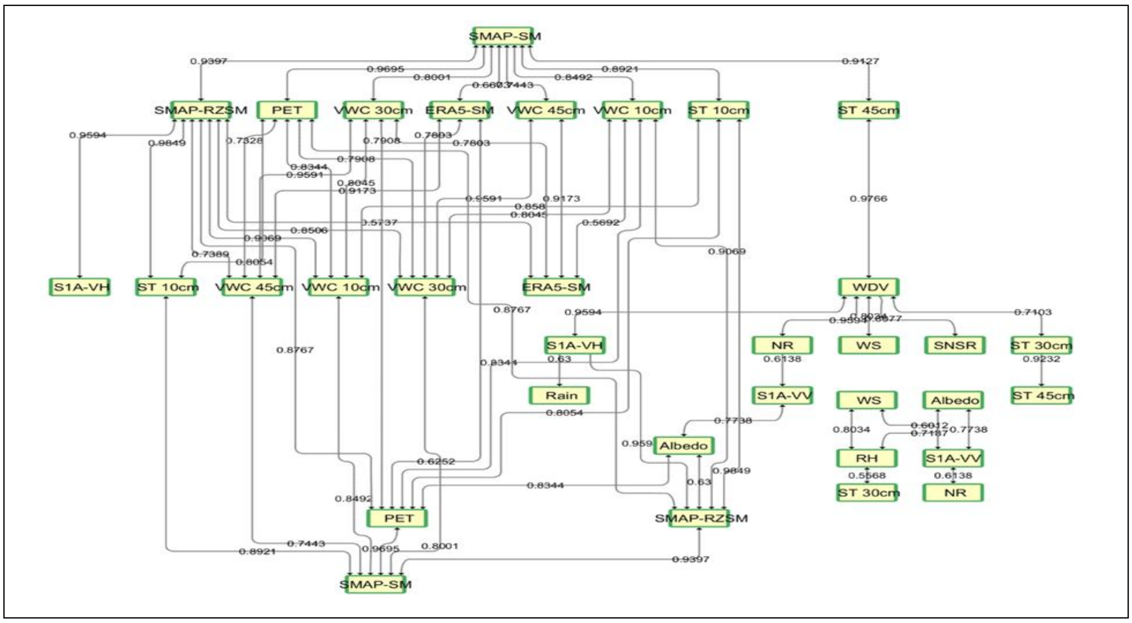

Fig 2: The positive feedback loop of *Kharif* season (>0.5).

contributing to its greater fluctuations in soil moisture. Semi-arid environment is less likely affected by drought events, leading to significant changes in the soil moisture compared to the arid, which experiences less severe drought conditions (Guo *et al*., 2023). An increasing trend in VWC (Volumetric Water Content) can be noticed during the starting phase of the study period, during June-July and reaching its maximum value during August-September could be related to the sowing, growing and maturing phases of the Kharif crop and groundnut. A decreasing trend was observed during October-November may be due to the harvesting of the crops (Suman *et al*., 2021). The negative-positive feedback transition thresholds in August are generally lower than in June and July (Wei *et al*., 2024). SMAP-RZSM and WS (-0.9610) have a strong negative correlation between root zone soil moisture and wind speed, indicating the potential for increased evaporation with higher wind speeds. ST 10 cm and WS (-0.9766) rated a potentially very strong negative correlation between soil temperature at 10 cm and wind speed, suggesting the cooling effects of wind. Albedo shows moderate negative correlations with soil moisture variables, indicating potential feedback where higher soil moisture leads to lower albedo, which could affect surface energy balance. It was evident by the vegetative water content and greenness of groundnut (Hasan *et al*., 2014; Zhu *et al*., 2024). Compared with the land-meteorological coupling strength (the correlation between precipitation and soil moisture) dominates the negative-positive feedback transition threshold. This study sheds new insights into drought feedback (Wei *et al*., 2024).

S1A-VV and S1A-VH with most of the variables generally exhibit weak correlations, suggesting limited feedback relationships with other parameters. The probability of the occurrence of backscatter anomalies (P_{ano}) is a statistical method that looks for the" fingerprints" of subsurface scattering, *i.e.*, an anti-correlation between backscatter and soil moisture. Even with a higher risk that it overestimates the extent of subsurface scattering. Furthermore, it can be computed monthly, making it possible to use it for masking only measurements acquired during the dry season (Wagner *et al*., 2024). Mostly weak correlations were obtained in NR with other variables, indicating limited direct feedback loops with other measured parameters also portrayed in the Network path analysis graph (Fig 4).

Positive, negative and neutral feedback loop mechanisms in *rabi*

A strong positive correlation was found between SMAP-SM and ERA5-SM (0.8575) and between surface and also root zone soil moisture of SMAP (0.7610). Soil moisture from ERA5 and VWC 30 cm of soil moisture tower, has a very strong positive correlation (0.9564). This positive correlation (0.7194) suggests that as root zone soil moisture increases, the volumetric water content at 30 cm also increases (Manohara *et al*., 2020). A strong positive correlation (0.9317) indicates that volumetric water content at different depths such as VWC 30 and 45 cm found closely related in the sensor installed in the Groundnut field. The soil moisture tower measures (~3 cm) with the principle of dielectric constant (dielectric permittivity) and more accurately (± 3%; Colliander *et al*., 2017; Montzka *et al*., 2021) over the frequency of 1-18 GHz (Suman *et al*., 2021). PET and ERA5-SM (0.9571) suggest that higher soil moisture measured by ERA5 corresponds with higher Potential Evapotranspiration. Kumar *et al*., 2024

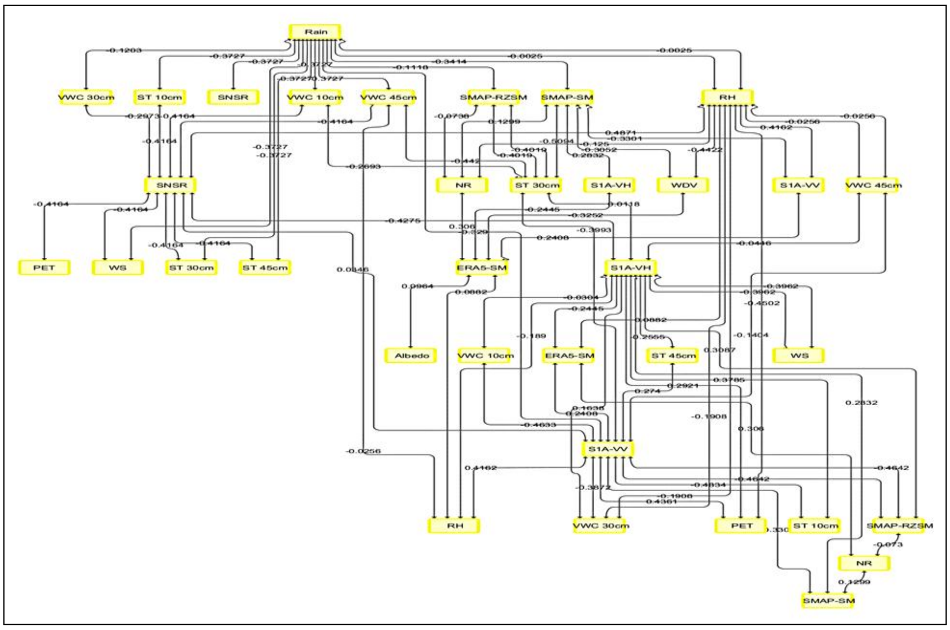

Fig 3: Neutral feedback loop of *kharif* season (-0.5 to 0.5).

corroborated that the soil moisture content at every 0.1 m depth (up to 1.6 m) in the crop root zone was recorded daily using the soil moisture probe throughout the crop period. The variation in the field soil moisture was observed during each repetition. The variation of soil moisture at 0.10 m (0.20 cm^3 cm^{-3}) and 0.40 m (0.16 cm^3 cm^{-3}) depth was found. The rise in moisture indicates wetting events (rainfall/irrigation). The irrigation was provided as soon as the moisture in the crop root zone depleted to 30%. The path network analysis is illustrated in Fig 5.

A moderate negative correlation (-0.4480) suggests that as soil moisture (SMAP-SM) increases, relative humidity (RH) decreases. A strong negative correlation (-0.6406) indicates that higher soil moisture from ERA5 measurements correlates with lower relative humidity. The backscatter S1A-VV and RH (-0.7525) show a strong negative correlation, indicating that higher SAR backscatter values correspond to lower relative humidity. The red-colored orthogonal tree network depicts that well in Fig 6. Strong negative (-0.7472) feedback was obtained between SMAP-RZSM and RH showing that higher root zone soil moisture is associated with lower relative humidity. RH and VWC 10 cm have achieved a moderate negative correlation (-0.4234). A strong negative correlation (-0.7261), shows that as volumetric water content at 30cm increases, relative humidity decreases. A very strong negative correlation (-0.8662), indicates that higher relative humidity corresponds with lower wind speed. A weak negative correlation (-0.1999) suggests limited feedback between relative humidity and surface net solar radiation. The

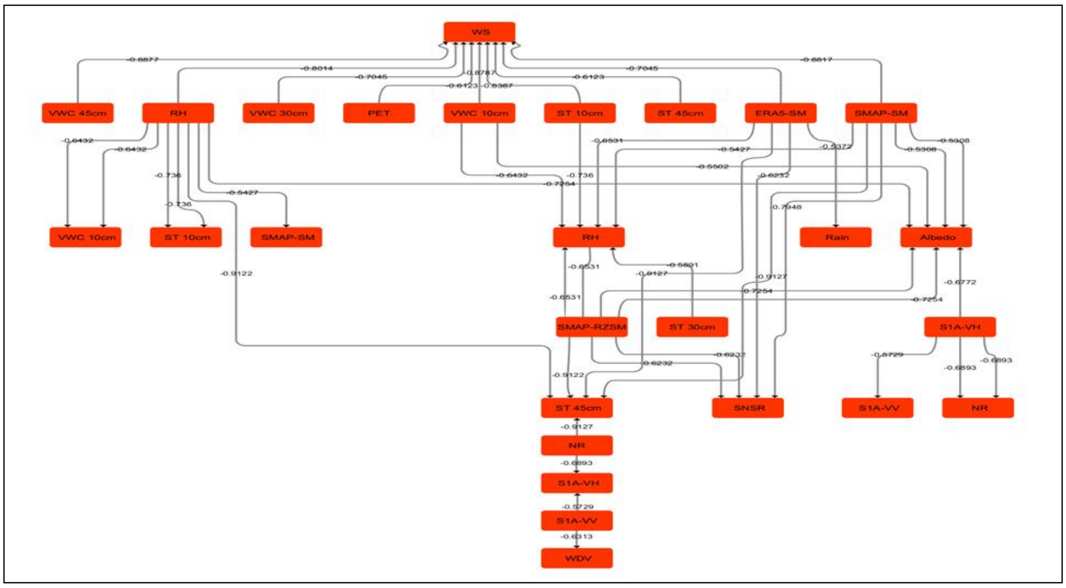

Fig 4: The negative feedback loop of *Kharif* season (< -0.5).

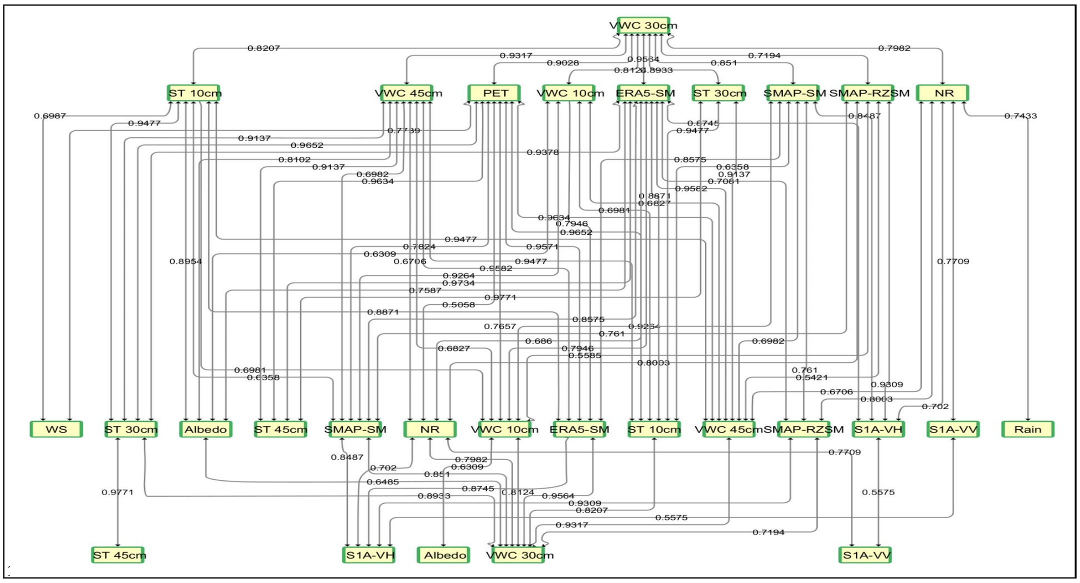

Fig 5: The positive feedback loop of *Rabi* season (>0.5).

feedback process between meteorological and agricultural droughts in land-atmosphere-coupled systems is very complex. Several studies have shown that a certain degree of meteorological drought can be transmitted to agricultural drought due to a lack of atmospheric water vapor. (Zhang *et al*., 2021; Du *et al*., 2021).

A very weak correlation (-0.0200), indicates limited feedback between SAR backscatter values of VV and volumetric water content at 10 cm. A moderate positive correlation (0.4323), suggests a linear relationship between SAR backscatter VH values and Forecast albedo. NR and SMAP-SM (0.5579) with moderate positive correlation. A weak negative correlation between WDV and SMAP-SM (-0.3052) indicates limited feedback between water deficit value and surface soil moisture. A very weak positive correlation (0.0441), suggests limited reinforcing feedback between rainfall and surface soil moisture. A moderate negative correlation (-0.4858), was found between surface net solar radiation (SNSR) and surface soil moisture of SMAP. A strong positive correlation (0.7824), suggests that higher soil moisture corresponds with higher Potential Evapotranspiration. Regarding the dynamic evolution of drought characteristics, the percentages of raster points for drought duration and severity with evaporation as the dominant factor are 30.7% and 32.7% and the percentages with precipitation are 35.3% and 35.0%, respectively (Machikowa *et al*., 2020). Precipitation in semi-arid regions has a positive effect on decreasing drought characteristics, while in arid regions, evaporation dominates the dynamics in drought characteristics due to increasing vegetation transpiration (Guo *et al*., 2023). The optimum yellow labeled network shows the neutrality within

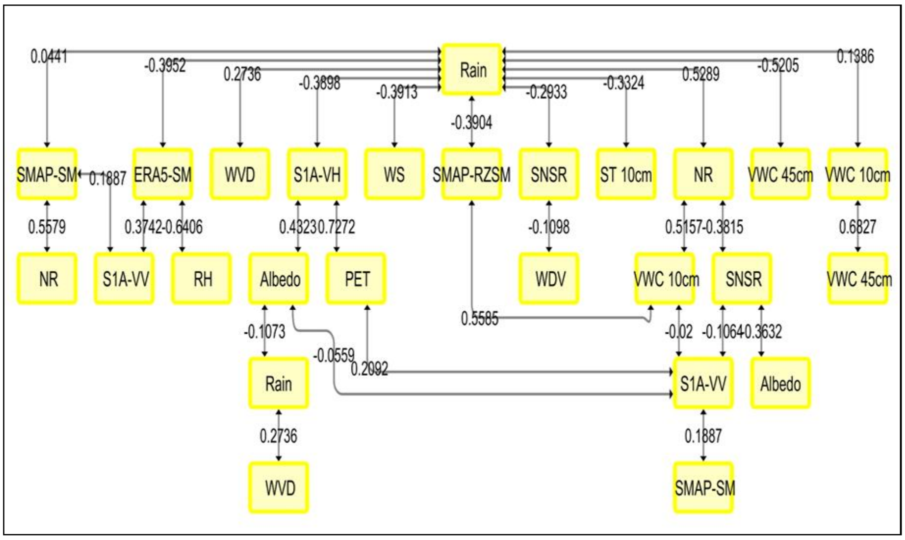

Fig 6: Neutral feedback loop of *Rabi* season (-0.5 to 0.5).

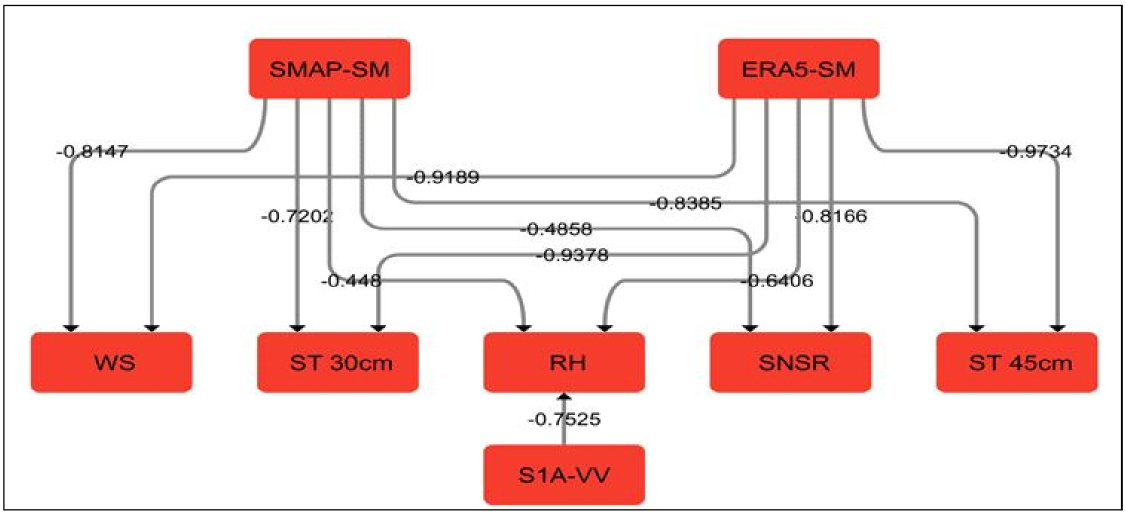

Fig 7: The negative feedback loop of *Rabi* season (< -0.5).

variables in Fig 7. The analysis reveals strong correlations between SMAP-SM, ERA5-SM and various parameters, highlighting soil moisture's critical role in subsurface water dynamics and its complex feedback loops with atmospheric conditions.

CONCLUSION

The study reveals significant variations in soil moisture, temperature and atmospheric conditions at a groundnut crop site during the pre-monsoon and post-monsoon seasons, highlighting dynamic soil-atmosphere interactions throughout the crop's growth cycle. Strong positive relationships, like the ones seen between surface and root zone soil moisture (SMAP-SM and SMAP-RZSM) and 10 cm of soil temperature, show how thermal properties and Potential Evapotranspiration are affected by feedback loops that reinforce each other. Significant negative correlations, such as those between root zone soil moisture and wind speed, highlight the complex interaction of soil moisture dynamics and atmospheric conditions. These relationships are especially pronounced in the Kharif and Rabi seasons, when soil moisture and temperature variables consistently show strong correlations, emphasizing their importance in the soil-atmosphere system. The findings also attest to possible discrepancies between satellite and sensor based soil moisture estimates, with SMAP satellite data showing stronger correlations. Overall, this comprehensive analysis emphasizes the complex feedback mechanisms within the soil-atmosphere system, which are critical for understanding and managing agricultural practices in the face of climate variability.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

On behalf of all authors, we declare that there are no conflicts of interest regarding the publication of this article.

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