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IMPROVING LANDSCAPE-BASED LAND MANAGEMENT FOR RAINFED IRRIGATION USING NATURAL PRECIPITATION: A CASE STUDY OF NAVOI REGION, UZBEKISTAN

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Abstract. In arid and semi-arid regions, efficient utilization of natural precipitation is a key factor for sustainable agricultural development. This study aims to improve a landscape-based land management framework for rainfed irrigation using remote sensing data in the Navoi region of Uzbekistan, focusing on the Tomdi, Uchquduq, Nurota, and Konimex districts. Monthly precipitation data from the CHIRPS dataset and vegetation dynamics derived from Landsat-based SAVI were analyzed for the vegetation period. The relationship between precipitation and SAVI was examined using correlation and linear regression analysis to assess the sensitivity of vegetation response to rainfall variability. The results demonstrate a spatially and temporally heterogeneous relationship between precipitation and vegetation activity across the studied districts. In Nurota and Konimex, a stronger positive correlation indicates higher dependence of vegetation growth on natural rainfall, while in Tomdi and Uchquduq the relationship is weaker due to extremely arid conditions and limited soil moisture retention capacity. These findings suggest that landscape characteristics such as soil texture, topography, and natural water accumulation zones play a crucial role in regulating the effectiveness of rainfed agriculture. Based on the results obtained, recommendations are proposed for integrating precipitation-based irrigation planning into landscape-oriented land management schemes. The proposed approach supports adaptive land-use planning, improves water use efficiency, and contributes to the sustainable development of rainfed agricultural systems in arid environments.

Keywords: Rainfed agriculture; SAVI; precipitation; landscape-based land management; remote sensing; Navoi region; Uzbekistan

СОВЕРШЕНСТВОВАНИЕ ЛАНДШАФТНО-ОРИЕНТИРОВАННОГО ЗЕМЛЕПОЛЬЗОВАНИЯ ДЛЯ БОГАРНОГО ОРОШЕНИЯ С ИСПОЛЬЗОВАНИЕМ ЕСТЕСТВЕННЫХ ОСАДКОВ (НА ПРИМЕРЕ НАВОИЙСКОЙ ОБЛАСТИ)

Аннотация. В аридных и семиаридных регионах эффективное использование естественных осадков является ключевым фактором устойчивого развития сельского хозяйства. Целью данного исследования является совершенствование ландшафтно-ориентированного землепользования для богарного орошения на основе данных дистанционного зондирования на территории Навоийской области Узбекистана (Томдинский, Учкудукский, Нуратаинский и Канимехский районы). В работе использованы данные о месячных осадках CHIRPS и значения SAVI, рассчитанные по данным Landsat. Проведен корреляционный и регрессионный анализ взаимосвязи между осадками и динамикой растительного покрова. Полученные результаты показали пространственную неоднородность реакции растительности на осадки: в районах Нурата и Канимех отмечается более выраженная зависимость SAVI от осадков, тогда как в Томди и Учкудуке эта связь слабее из-за экстремальной засушливости и низкой влагоудерживающей способности почв. Результаты исследования могут быть использованы для разработки адаптивных стратегий землепользования, направленных на повышение эффективности богарного земледелия и устойчивости агроландшафтов к климатическим изменениям.

Ключевые слова: Богарное земледелие; SAVI; атмосферные осадки; ландшафтное землепользование; дистанционное зондирование; Навоийская область

Introduction

Rainfed agriculture plays a crucial role in food production in arid and semi-arid regions, where access to surface and groundwater resources for irrigation is limited. In such environments, crop growth and productivity largely depend on the amount, timing, and spatial distribution of natural precipitation [1], [2]. However, increasing climate variability and the rising frequency of droughts have intensified the vulnerability of rainfed agricultural systems, particularly in Central Asia. This necessitates the development of adaptive land management approaches that can integrate climatic, ecological, and landscape factors into agricultural planning [3], [4].

In Uzbekistan, especially in the Navoi region, large areas of agricultural land are classified as rainfed (lalmi) and are characterized by low and highly variable precipitation, high evapotranspiration, and limited soil moisture storage capacity. The districts of Tomdi, Uchquduq, Nurota, and Konimex represent typical dryland agroecosystems, where agricultural productivity is strongly constrained by water availability. Traditional land-use planning practices in these regions are often insufficiently adapted to the spatial heterogeneity of natural resources and the increasing impacts of climate change. Consequently, there is a growing need for landscape-based land management strategies that explicitly account for rainfall patterns, vegetation response, and local environmental conditions [5], [6].

Remote sensing provides a powerful tool for monitoring vegetation dynamics and water–vegetation interactions over large areas with high temporal resolution. Vegetation indices derived from satellite imagery are widely used as proxies for plant health, biomass, and photosynthetic activity. Among them, the Soil-Adjusted Vegetation Index (SAVI) is particularly suitable for arid and semi-arid regions, as it minimizes the influence of exposed soil background, which is a dominant feature in sparsely vegetated dryland landscapes. Compared to NDVI, SAVI offers improved sensitivity in areas with low vegetation cover and high soil reflectance, making it more appropriate for assessing vegetation response to precipitation in rainfed systems.

Several studies have demonstrated the usefulness of vegetation indices for analyzing the relationship between precipitation and vegetation dynamics. However, many existing approaches rely on generalized thresholds or coarse-scale analyses that do not adequately capture local landscape variability. In heterogeneous dryland environments, vegetation response to rainfall is strongly modulated by terrain, soil texture, land cover, and microclimatic conditions. Therefore, a spatially explicit and landscape-oriented assessment is essential for understanding how natural precipitation can be effectively utilized for agricultural production [7], [8], [9].

The objective of this study is to analyze the relationship between monthly precipitation and vegetation dynamics using SAVI in the Tomdi, Uchquduq, Nurota, and Konimex districts of the Navoi region, and to use this information to support the improvement of landscape-based land management for rainfed irrigation. Specifically, the study aims to (i) quantify the temporal and spatial variability of SAVI in response to precipitation, (ii) assess the strength of the precipitation–vegetation relationship using correlation and regression analysis, and (iii) identify

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landscape conditions that enhance or limit the effectiveness of rainfed agriculture. The results are intended to provide a scientific basis for integrating remote sensing indicators into land-use planning and for improving the sustainability and resilience of rainfed agricultural systems under changing climatic conditions [10], [11].

Materials and Methods

Study Area

The study was conducted in the Navoi region of Uzbekistan, focusing on four districts characterized by predominantly rainfed agricultural systems: Tomdi, Uchquduq, Nurota, and Konimex. These districts are located in arid to semi-arid climatic zones with low annual precipitation, high interannual variability of rainfall, and limited water availability for irrigation. The landscape is dominated by steppe, semi-desert, and mountain foothill environments, with agricultural activities primarily dependent on natural precipitation.

The selected districts represent typical dryland agroecosystems where agricultural productivity is constrained by climatic and landscape factors. These areas provide an appropriate spatial context for analyzing precipitation–vegetation relationships and for developing landscape-based land management strategies for rainfed agriculture.

Data Sources

The study integrated satellite-based and climatic datasets within the Google Earth Engine (GEE) cloud computing environment.

1. Precipitation Data: Monthly precipitation was derived from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) daily dataset, which provides gridded rainfall estimates at approximately 5 km spatial resolution. Daily precipitation values were aggregated to monthly sums (mm/month) for the analysis period.

2. Satellite Imagery: Landsat 8 Collection 2 Level-2 surface reflectance products were used to derive vegetation indices. These images provide atmospherically corrected reflectance data at 30 m spatial resolution and are suitable for time-series vegetation analysis.

3. **Administrative Boundaries:** District boundaries were obtained from a vector shapefile and used to define regions of interest (ROIs) for zonal statistics and spatial analysis.

All datasets were reprojected and spatially aligned within GEE to ensure consistency.

Preprocessing of Satellite Data

Landsat 8 images were filtered by date and spatial extent and subjected to cloud, cloud-shadow, and snow masking using the QA_PIXEL band. Surface reflectance values were scaled according to official calibration coefficients. Only cloud-free pixels within the growing season (April–September) were retained for further analysis. Monthly composites were generated by averaging all available Landsat observations within each month to reduce noise and data gaps caused by cloud cover.

Computation of the Soil-Adjusted Vegetation Index (SAVI)

Vegetation condition was assessed using the Soil-Adjusted Vegetation Index (SAVI), which is particularly suitable for arid and semi-arid regions where exposed soil strongly influences spectral reflectance. SAVI was computed using the following formula:

$$SAVI = \frac{(NIR - Red)}{(NIR + Red + L)} \times (1 + L)$$

where:

- NIR is the near-infrared reflectance (Landsat 8 Band 5),
- Red is the red reflectance (Landsat 8 Band 4),
- L is the soil brightness correction factor, set to 0.5.

Monthly mean SAVI values were calculated for each district.

Precipitation–Vegetation Relationship Analysis

Monthly precipitation totals and mean SAVI values were extracted for each district and organized into a time series dataset. Linear regression analysis was performed to quantify the relationship between precipitation and vegetation response. The Pearson correlation coefficient (r) was used to assess the strength and direction of the precipitation–SAVI relationship:

$$r = \frac{\sum(P_i - \bar{P})(S_i - \bar{S})}{\sqrt{\sum(P_i - \bar{P})^2 \sum(S_i - \bar{S})^2}}$$

where P_i is monthly precipitation and S_i is monthly SAVI.

The coefficient of determination (R^2) was derived to evaluate the proportion of SAVI variability explained by precipitation. Additionally, scatter plots with linear trend lines were generated to visualize the relationship.

Spatial Analysis and Mapping

Spatial maps of monthly precipitation and SAVI were generated to examine their geographic distribution across the study area. Zonal statistics were used to compute district-level averages, while pixel-level maps were used to identify intra-district variability.

The spatial correspondence between precipitation patterns and vegetation response was analyzed qualitatively and quantitatively to identify areas where rainfed agriculture is efficient.

Implementation

All data processing, analysis, and visualization were implemented in the Google Earth Engine platform using JavaScript-based scripts. The platform enabled automated processing of large satellite datasets, reproducibility of results, and integration of climatic and remote sensing information.

Results

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Spatial and Temporal Variability of Precipitation and Vegetation

The analysis revealed substantial spatial and temporal variability in both precipitation and vegetation conditions across the four study districts (Tomdi, Uchquduq, Nurota, and Konimex). Monthly precipitation totals exhibited strong seasonality, with the majority of rainfall concentrated in the spring months (March–May), while summer months showed minimal rainfall.

The spatial distribution of precipitation showed relatively higher values in the foothill and mountainous areas of Nurota compared to the flatter and more arid landscapes of Tomdi and Uchquduq. Konimex exhibited intermediate precipitation levels.

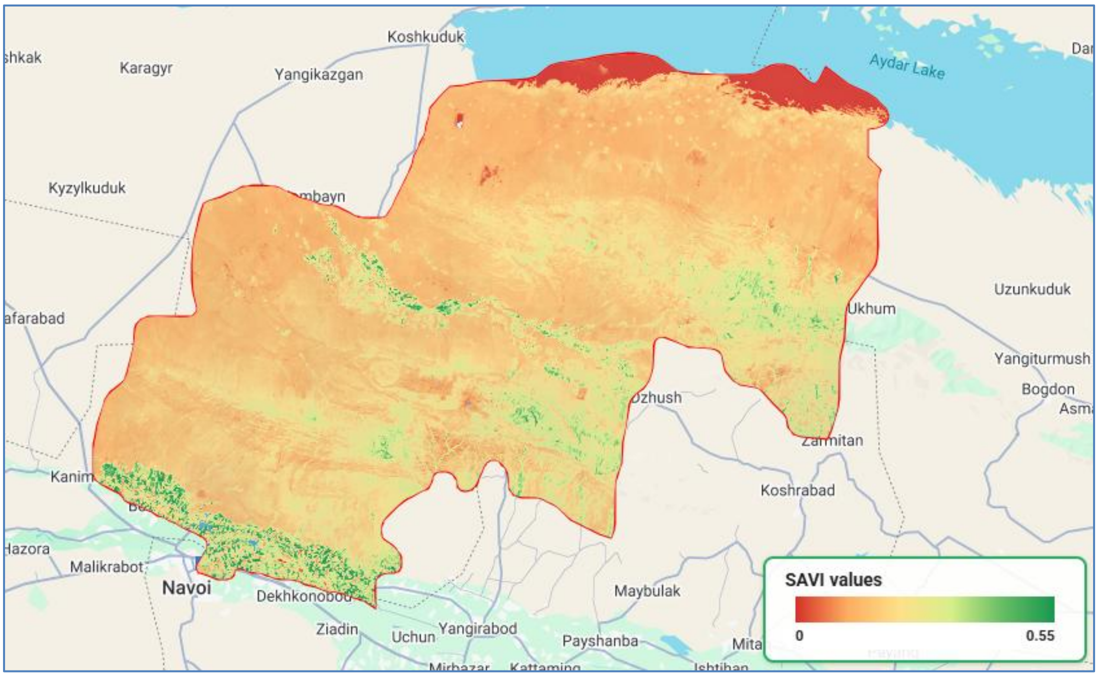

Fig.1. Spatial distribution of monthly Soil-Adjusted Vegetation Index (SAVI) derived from Landsat 8 for the Nurota district (April, 2025).

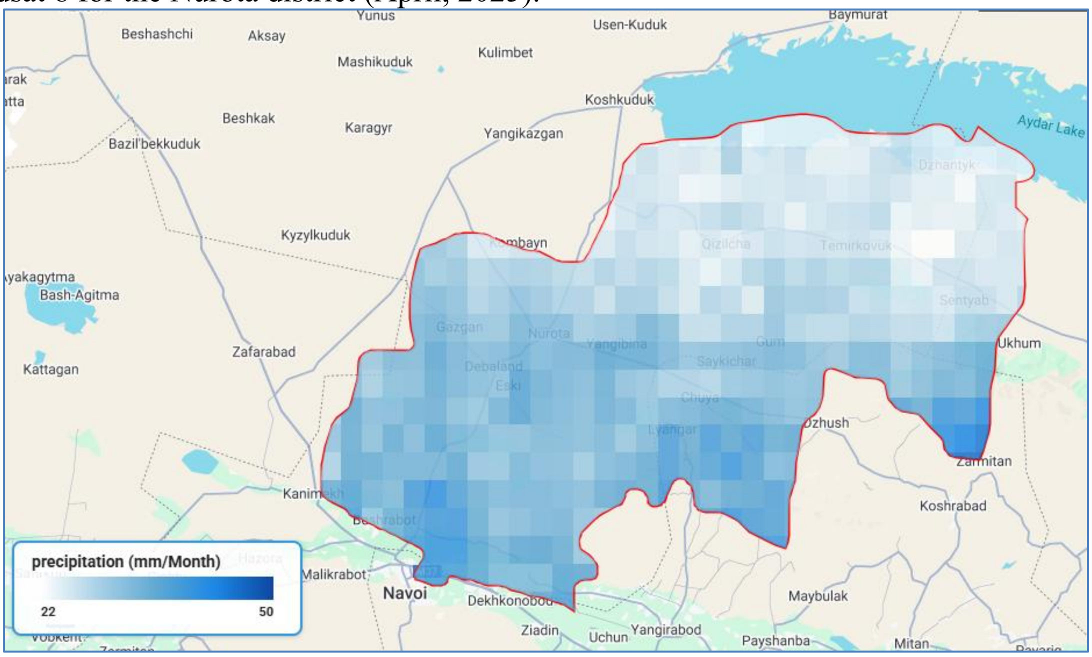

Fig.2. Spatial distribution of monthly precipitation (CHIRPS) for the Nurota district (April,

2025).

The Soil-Adjusted Vegetation Index (SAVI) displayed corresponding spatial and temporal patterns. Higher SAVI values were observed during periods of increased precipitation, indicating enhanced vegetation growth and biomass accumulation. Conversely, low precipitation months were associated with reduced SAVI values, reflecting moisture stress in vegetation.

Relationship Between Precipitation and Vegetation Response

A statistically significant positive relationship was identified between monthly precipitation and monthly mean SAVI across all districts. Scatter plot analysis demonstrated that increases in rainfall were generally followed by increases in vegetation greenness, indicating that precipitation is a dominant limiting factor for vegetation productivity in these rainfed landscapes.

Table 1. Regression and correlation table of precipitation and vegetation cover in the districts of Navoi region for 2025.

District name	Statistical analysis	
	R^2	Pearson r
Nurota	0.48	0.69
Konimex	0.23	0.48
Tomdi	0.09	0.31
Uchquduq	0.02	-0.15

The strength of the relationship varied by district. Nurota exhibited the strongest correlation, likely due to its orographic precipitation and more favorable soil and topographic conditions. Tomdi and Uchquduq showed weaker but still positive relationships, reflecting the influence of arid conditions and higher evapotranspiration rates. Konimex showed moderate sensitivity to rainfall.

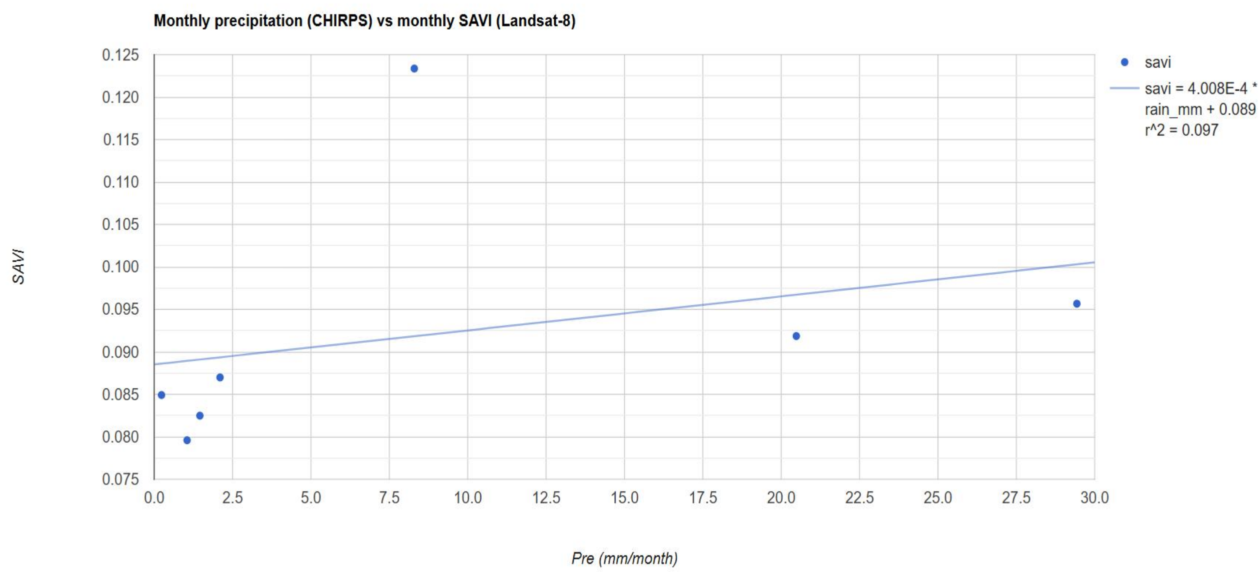

Fig.3. Cross-regression analysis of monthly average precipitation and vegetation cover data for 2025, Tomdi district.

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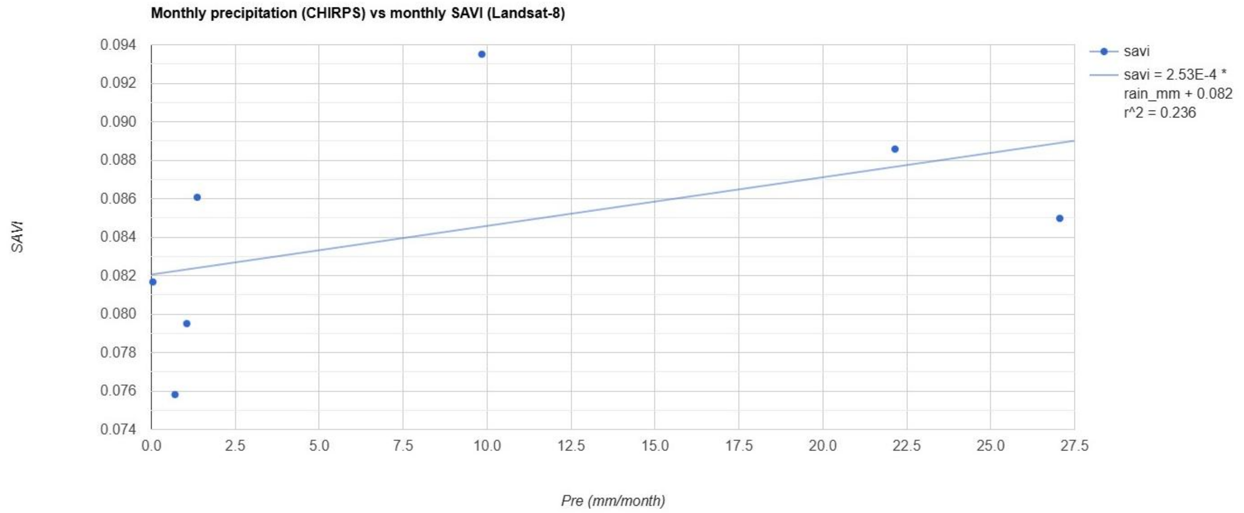

Fig.4. Cross-regression analysis of monthly average precipitation and vegetation cover data for 2025, Konimex district.

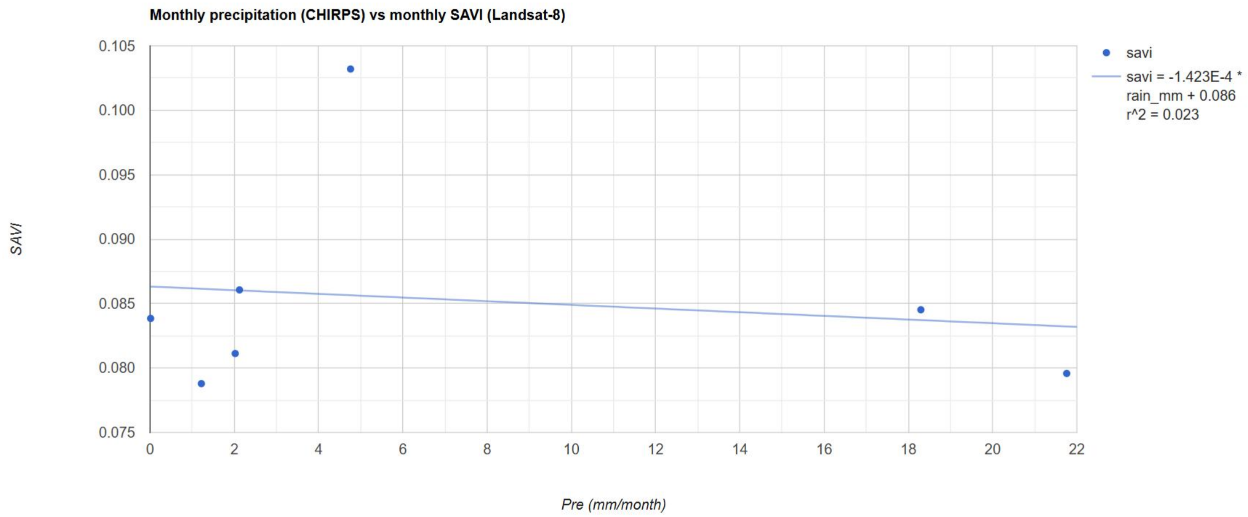

Fig.5. Cross-regression analysis of monthly average precipitation and vegetation cover data for 2025, Uchquduq district.

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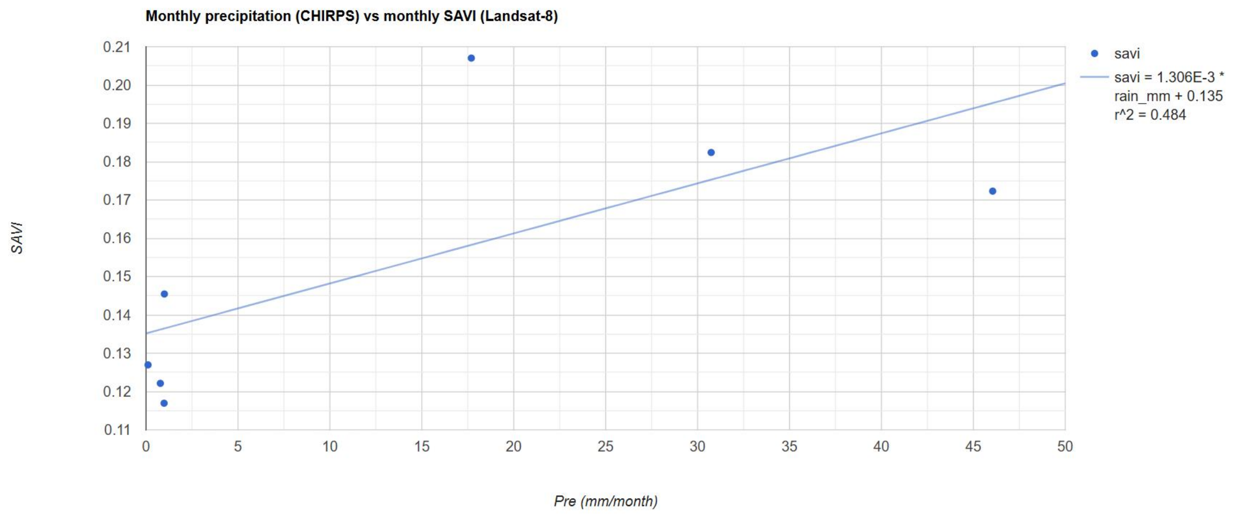

Fig.6. Cross-regression analysis of monthly average precipitation and vegetation cover data for 2025, Nurota district.

Linear regression models confirmed that precipitation explained a substantial portion of the observed variance in SAVI, with the coefficient of determination (R^2) indicating moderate to strong explanatory power depending on the district.

Spatial Patterns of Rainfed Agriculture Potential

The spatial overlay of precipitation and SAVI maps revealed distinct zones of higher rainfed agricultural potential, particularly in areas with favorable landscape characteristics such as gentle slopes, finer-textured soils, and proximity to moisture-retaining landforms.

Nurota and parts of Konimex demonstrated consistently higher vegetation response to precipitation, suggesting greater suitability for rainfed agriculture. In contrast, large portions of Tomdi and Uchquduq exhibited low and highly variable SAVI values, indicating vulnerability to drought and limited potential for stable rainfed production.

Implications for Landscape-Based Land Use Planning

The observed precipitation–vegetation relationships provide a scientific basis for improving landscape-based land management and land-use planning for rainfed agriculture. Areas with strong and stable precipitation–SAVI relationships are suitable candidates for agricultural intensification and targeted land improvement measures. Conversely, areas with weak or unstable relationships may require conservation-oriented strategies, soil moisture retention practices, or alternative land uses.

Conclusion

This study demonstrated that the relationship between natural precipitation and vegetation condition, expressed through the Soil Adjusted Vegetation Index (SAVI), can be effectively assessed using remote sensing data. The results for the districts of Nurota, Konimex, Tomdi, and Uchquduq indicate a generally positive correlation between monthly rainfall and SAVI values during the vegetation period, confirming the key role of precipitation in controlling vegetation dynamics in rainfed landscapes. However, the strength of this relationship varies spatially, reflecting differences in soil properties, topography, and land use practices among the districts.

This spatial heterogeneity highlights the importance of adopting landscape-based land management and planning approaches rather than applying uniform solutions across the region. Overall, the integration of satellite-derived vegetation indices and precipitation data provides a reliable and scalable framework for improving land-use planning in rainfed agricultural systems. The proposed approach supports evidence-based decision-making aimed at enhancing land productivity and sustainability under increasing climate variability.

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