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Monitoring spatio-temporal change of rangeland vegetation in Bhutan to inform sustainable rangeland management

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Abstract
Rangelands play a critical role in delivering ecosystem services, including biodiversity conservation, livestock production, and ecological stability in Bhutan's high-altitude landscapes. However, these rangelands are increasingly threatened by climate change, overgrazing, shrub encroachment, invasive species, and the absence of structured management. This study presents the first nationwide, high-resolution, multi-temporal assessment of rangeland extent and condition in Bhutan using Google Earth Engine (GEE)-based multi-sensor data integration. Rangeland dynamics were assessed using Landsat 8, Sentinel-2, and Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data by comparing reference conditions (2013–2015) with recent observations (2022–2024). Participatory field data were collected through the engagement of local herders using smartphone applications, generating1,548 training points and 2,624 validation points to support ground truthing. The overall classification accuracy achieved was 65.09% with a Kappa coefficient of 0.53, reflecting moderate mapping reliability. Sentinel-2 imagery and a Random Forest classification algorithm based on FAO's Land Cover Classification System (LCCS 3) helped delineate three major rangeland types: 3,451 km^2 of herbaceous rangeland, 3,546 km^2 of shrub and bush rangeland, and 2,310 km^2 of mixed rangeland. Relative to the baseline period (2013–2015), shrub and bush rangelands exhibited the most pronounced greening trends, while herbaceous and mixed rangelands showed spatially clustered areas of vegetation decline, indicating class-specific land-use and condition change across Bhutan. Vegetation index analysis showed that 1,425 km^2 of rangelands had increased vegetation index values, while 442 km^2 exhibited declining trends, and 7,159 km^2 remained stable. The results provide a spatially explicit and scalable geospatial infrastructure to inform rangeland monitoring, sustainable grazing, and rangeland restoration in Bhutan.

Keywords Remote sensing, Rangeland mapping, Vegetation dynamics, Rangeland assessment, GEE, Landsat 8, Sentinel-2, Bhutan

1 Introduction

Rangelands are ecosystems comprising semi-natural grasslands, shrublands, savannas, alpine meadows, deserts, and wetlands and are primarily used for grazing [1–4]. These ecosystems cover more than 50% of the Earth's terrestrial surface, and serve as essential natural capital that provides ecosystem goods and services, support biodiversity, sequester carbon, and regulate hydrological processes [5–10]. Over one billion people depend on rangelands for economic provisioning, mainly through pastoralism, agroforestry, livestock grazing, tourism, and the collection and sale of high-value medicinal products [11–13]. However, in many regions, shifting climatic regimes, combined with increasing pastoral pressure are degrading rangeland ecosystems. These pressures contribute to declining biomass productivity, loss of biodiversity, drying of water sources, and increased vulnerability to desertification [14–16]. Such negative changes reduce the ability of rangelands to generate multiple benefits supporting key Sustainable Development Goals (SDGs), particularly those related to food security and poverty reduction [17, 18].

Of the eight Hindu Kush Himalaya (HKH) countries, six contain extensive high-altitude rangelands that are essential for pastoral livelihoods and alpine biodiversity conservation [19–21]. Bhutan's rangeland ecosystems, particularly in montane and alpine zones, play a key role in biodiversity conservation, rangeland-based economies, and transhumance practices [22–24]. Nevertheless, escalating temperatures and increasingly erratic rainfall are altering grazing conditions and contributing to vegetation structure changes that accelerate soil erosion processes [25–27]. These fragile mountain environments, which are highly sensitive to climatic variability, require large-scale remote sensing approaches with robust methodologies to monitor long-term ecological resilience [28–30].

More than 10% of Bhutan's high-altitude population depends on rangelands to sustain their pastoral culture and economy, with livestock products contributing directly to household subsistence [30, 31]. However, balancing economic development with environmental sustainability remains challenging. While Bhutan maintains progressive conservation policies, with 72.3% forest cover, rangeland ecosystems face mounting pressures from land-use shifts and climatic extremes [21, 28, 32]. Localized expansion of roads, settlements, and infrastructure has, in some areas, reduced access to traditional grazing zones and gradually disrupted transhumant herding systems [33–35]. Although some areas exhibit increasing vegetation greenness, this does not necessarily indicate improved rangeland health, as invasive species may outcompete native forage and alter rangeland composition [36, 37].

Despite their vast extent and importance, reliable, up-to-date, and reproducible mapping of rangeland condition using multi-temporal remote sensing remains limited [38, 39], particularly in complex mountain landscapes such as Bhutan [40–42]. Conventional rangeland monitoring techniques often rely on field-based assessments [9], single-year rangeland maps, or coarse-resolution satellite imagery, which fail to adequately capture localized degradation patterns and long-term ecological changes [43, 44]. In this regard, there is a clear need for analytical approaches that combine high spatial resolution with multi-temporal satellite observations while avoiding over-reliance on generalized definitions of rangeland condition change [9, 45]. Research has shown that combining multi-temporal satellite data provides an effective framework for large-scale evaluation of rangeland health, vegetation dynamics, and climatic interactions [46, 47].

1.1 Study area

The study area covers the entire territory of Bhutan, 38,394 km², ranging from about 200 m in the southern lowlands to roughly 7,500 m in the northern high mountains, as shown in Fig. 1. Bhutan is a mountainous country located in the eastern Himalayas bordered by India to the south, east, and west, and by China to the north [48, 49]. Seasonal variations in temperature and precipitation across the country are strongly influenced by the South Asian monsoon system [50]. These climatic gradients directly affect rangeland productivity and feed availability for both domestic animals and wildlife. In high-altitude locations where agriculture is limited, Bhutan's rangelands support notable cattle grazing and yak herding systems [22] and sustain large and diverse wildlife populations. However, shifting precipitation patterns, temperature fluctuations, and increasing demand for grazing resources are increasingly influencing these fragile high-elevation environments. Although forests account for 72.3% of Bhutan's land cover, rangelands still play a vital role in pastoral livelihoods, food security, and biodiversity protection [51].

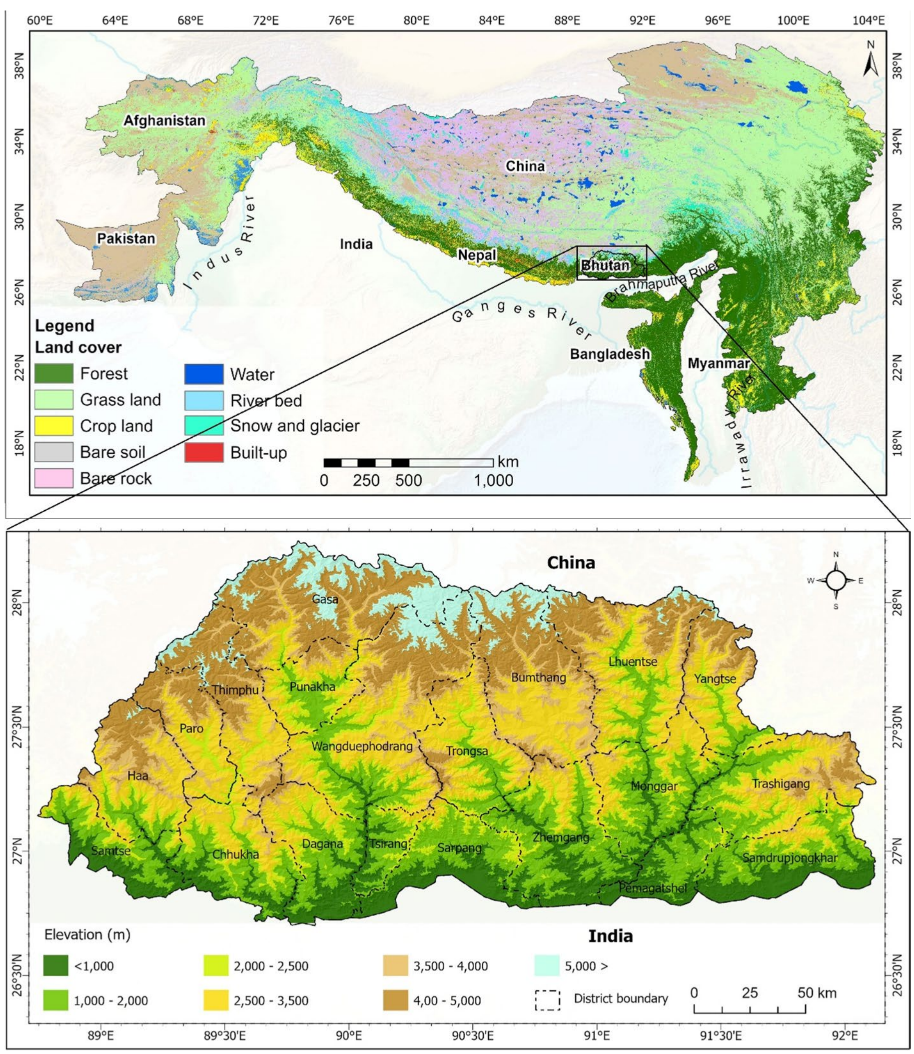

Fig. 1 The study area encompasses the entire country of Bhutan, which was analyzed for rangeland mapping using multi-temporal satellite imagery and geospatial techniques. The reference maps include the ICIMOD-developed https://rds.icimod.org/Home/DataDetail?metadataId=1972511 HKH land cover and the elevation of Bhutan.

1.2 Data and methods

1.2.1 Data used

Rangeland mapping was conducted using Sentinel-2 Surface Reflectance Level-2 A imagery (10 m resolution), processed in Google Earth Engine. Sentinel-2 data, available since April 2017, provided high-resolution imagery for the 2024 rangeland mapping. Using Landsat 8 OLI/TIRS Collection 2 atmospherically corrected surface reflectance data, accessible since April 2013, we investigated historical rangeland vegetation changes in Bhutan. Publicly available for scientific study, Landsat images were available at several processing stages, including radiometric, geometric, and atmospheric adjustments [52]. Using GEE access [53], we investigated these data by selecting Landsat 8 imagery from 2013 to 2024 for Bhutan that have WRS-2 path 137, row 41; path 138, row 41. Using these two remote sensing datasets, this paper maps rangeland vegetation trends in Bhutan from 2013 to 2024. The radiometric consistency and atmospheric correction capabilities of Landsat 8's Operational Land Image (OLI) and Thermal Infrared Sensor (TIRS) Level 2 Surface Reflectance (SR) facilitated long-term comparisons.

To assess the impact of precipitation on rangeland productivity, Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) was incorporated. By integrating 0.05° satellite products with in-situ station data, CHIRPS provides a gridded rainfall time series for trend analysis. Including infrared Cold Cloud Duration (CCD) improves earlier "smart" interpolation techniques and high-resolution precipitation forecasts [54]. Ground reference points collected and shared by local communities were used to improve the accuracy and validation of the rangeland map using Collect Earth.

1.3 Sentinel-2 image analysis for rangeland mapping

Sentinel-2 images (10 m resolution) handled in GEE were used for rangeland mapping. The rangeland classification system and description can be found in Table 1, derived from the FAO's Land Cover Classification System (LCCS 3) [55]. Consultations among stakeholders improved the classification system by specifying three main rangeland categories applicable to Bhutan and the HKH region. The CEO platform was used in 1,548 reference data collection [56].

For accuracy assessment and authentication of the developed rangeland map, a mobile phone-based application was designed to function efficiently without requiring an internet connection. The app is used by local community members, particularly those who regularly visit grazing areas with their yaks, to collect reference data. Once herders return home and regain internet access, the collected data are uploaded to the central system. The user-friendly app allows herders to capture georeferenced information, including vegetation health, soil conditions, and livestock movement, directly from their mobile devices. Integrating field-based observations with spatial mapping improves the

Table 1 Rangeland classification systems generated with LCCS 3 tools developed by the FAO

Sl no	Rangeland class	LCSS
1	Herbaceous rangeland	Closed to open (> 15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
2	Shrub and bush rangeland	Closed to open (> 15%) shrubland (< 5 m) Herbaceous closed to open vegetation /
3	Mixed Rangeland	Closed to open (> 10%) vegetation (grassland, shrubland, woody vegetation)

reliability of rangeland assessments and provides valuable data for enhanced rangeland mapping efforts.

Once the procedure of image correction was competed, the composite for 2024 was created and covariates were generated based on the Sentinel-2 composites. These covariates mainly included Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Soil-Adjusted Vegetation Index (SAVI), Atmospherically Resistant Vegetation Index (ARVI), Normalized Difference Moisture Index (NDMI), Green Chlorophyll Index (GCI), Normalized Difference Water Index (NDWI), and Bare Soil Index (BSI). Pre-processed Sentinel-2 data underwent the application of a supervised Random Forest classifier [57, 58].

1.4 Rangeland vegetation condition assessment

Two time periods, a baseline (2013–2015) and a recent period (2022–2024), were analyzed to assess rangeland vegetation changes. This made it possible to identify temporal fluctuations in rangeland vegetation dynamics. The study used three widely applied indices —NDVI, EVI, and SAVI — extracted from Landsat 8 images. These satellite-derived indices provide a comprehensive understanding of land surface characteristics and the condition of rangeland vegetation. NDVI is particularly effective in detecting sparse vegetation greenness patterns; EVI improves sensitivity to canopy structure and reduces atmospheric distortions; while SAVI is effective for minimizing soil brightness effects.

To examine rangeland vegetation patterns, mean values of vegetation indicators were calculated for every year between 2013 and 2024. The main objective was to identify areas showing relative vegetation increase, stability, or decline across time. The absolute change in indices was calculated as:

$$\Delta\,\mathrm{Index} = \mathrm{Index}_{2022-2024} - \mathrm{Index}_{2013-2015}$$

Simple comparisons of absolute changes may not be useful, given the variations in baseline vegetation conditions throughout different areas. A drop from 0.8 to 0.7 in NDVI has different ecological consequences than a drop from 0.3 to 0.2. The computed relative percentage change elucidated this variability and ensured that vegetation dynamics could be correlated across diverse environments. This was accomplished through the following formulations:

$$NDVI_{change\,(\%)} = \frac{NDVI_{2022-2024} - NDVI_{2013-2015}}{NDVI_{2013-2015}} \times 100$$

$$EVI_{change\,(\%)} = \frac{EVI_{2022-2024} - EVI_{2013-2015}}{EVI_{2013-2015}} \times 100$$

$$SAVI_{change\,(\%)} = \frac{SAVI - SAVI_{2013-2015}}{SAVI_{2013-2015}} \times 100$$

Understanding rangeland conditions, the study classified the variations in vegetation indices into relevant categories. Using threshold values as shown in Table 2, this classification was performed to divide the indices into five different categories ranging from notable vegetation recovery to extreme degradation. Using a conditional argument, GEE assigns a category depending on the ΔIndex value attached to every pixel. Areas showing increased vegetation index values may reflect favorable climatic conditions,

Table 2 Classification of rangeland alterations in Bhutan utilizing NDVI, EVI, and SAVI indices, identifying changes

Rangeland change category	Threshold (Δ Indices)	Description
Significant increase	> 0.10	Strong vegetation recovery, or improved vegetation greenness.
Moderate increase	0.05 to 0.10	Moderate vegetation growth, seasonal or due to conservation efforts.
Stable	-0.05 to 0.05	No notable change in vegetation, health or range cover remains unchanged.
Moderate decrease	-0.10 to -0.05	Gradual vegetation declines, potential stress due to environmental or rangeland use factors.
Significant decrease	< -0.10	Strong vegetation loss, due to drought, or overused.

reduced grazing pressure, conservation measures, or expansion of non-native/invasive vegetation. Areas with a minor improvement showed delayed development, most likely from seasonal fluctuations or efficient rangeland management techniques. Stable areas showed little or no change, suggesting equilibrium conditions. Areas showing a modest drop suggested mild drought, overgrazing, or land-use changes. Areas showing notable reductions reflected anthropogenic disturbance, soil erosion, or rangeland conditions.

To investigate how precipitation affects changes in rangeland, CHIRPS rainfall data were analyzed. The mean precipitation (mm) for both periods was computed, clipped to Bhutan's boundary, and compared with vegetation indices to identify spatial and temporal variations in rangeland conditions.

A positive percentage indicates an increase in vegetation index values, while a negative value indicates a decline. To better understand the relationship between precipitation and vegetation indices, CHIRPS precipitation data were processed in GEE. Summing five-day CHIRPS rainfall measurements generated annual total precipitation, and a mean reducer was used to compile precipitation data over Bhutan. NDVI and EVI data were extracted from Landsat 8 images to capture vegetative response over time. Python was also used to examine the dataset from 2013 to 2024 for relationships between precipitation and vegetation indices. Regression plots were generated to visualize these relationships.

The threshold values used to classify rangeland vegetation change (Table 2) were defined based on a combination of established vegetation change detection literature, empirical testing within the Bhutan rangeland context, and expert judgment informed by regional ecological conditions. Thresholds between − 0.05 and + 0.05 represent stable conditions, accounting for normal inter-annual climatic and phenological variability. Changes between ± 0.05 and ± 0.10 indicate moderate vegetation change, while values exceeding ± 0.10 denote significant vegetation change, reflecting stronger climatic stress, grazing pressure, or land-use disturbance. These thresholds were applied consistently across NDVI, EVI, and SAVI to ensure comparability across vegetation density gradients and soil background conditions.

2 Results

2.1 Rangeland classification

The rangeland classification for Bhutan achieved an overall accuracy of 65.09% with a Kappa coefficient of 0.53 (Tables 3 and 4), indicating a moderate level of agreement. Producers' accuracy was highest for Other land cover (97.79%), followed by Shrub and Bush

Table 3 Error matrix for Bhutan rangeland map

Classified data	Herbaceous	Shrub and bush	Mixed	Other	Classified total
Herbaceous	189	1	0	7	197
Shrub and bush	187	303	58	14	562
Mixed	485	45	200	2	732
Other	66	16	35	1016	1133
Classified Total	927	365	293	1039	2624

Table 4 Accuracy totals for Bhutan rangeland map

Class name	Reference totals	Classified totals	Number correct	Producers accuracy	Users accuracy
Herbaceous	927	197	189	20.39%	95.94%
Shrub and bush	365	562	303	83.01%	53.91%
Mixed	293	732	200	68.26%	27.32%
Other	1039	1133	1016	97.79%	89.67%
Classified Total	2624	2624	1708		

Overall Classification Accuracy = 65.09%

rangeland (83.01%), and Mixed rangeland (68.26%), reflecting relatively strong class representation in the reference dataset.

In contrast, user's accuracy varied substantially among classes, with Herbaceous rangeland (95.94%) and Other land cover (89.67%) showing strong reliability, while Shrub and Bush (53.91%) and particularly Mixed rangeland (27.32%) exhibited lower classification confidence. The conditional Kappa values further confirm this pattern, with Herbaceous ($\kappa = 0.96$) and Other ($\kappa = 0.88$) demonstrating very strong agreement, whereas Shrub and Bush ($\kappa = 0.53$) and especially Mixed rangeland ($\kappa = 0.25$) indicates considerable classification uncertainty.

Interpretations involving the Mixed rangeland class should therefore be treated with caution, as its low user accuracy and conditional Kappa reflect difficulty in separating this class from transitional vegetation types. The results indicate that combining structurally similar rangeland classes, such as Shrub and Bush with Mixed rangeland, could potentially improve overall classification reliability in future mapping efforts.

2.2 Spatial distribution and area of rangelands

The generated rangeland map shows that the total area of herbaceous rangeland is 3,451 km², shrub and bush rangeland covers 3,546 km², and mixed rangeland comprises 2,310 km², while the remaining 29,284 km² falls under other land cover classes. Rangeland types are unevenly distributed across Bhutan's twenty districts (Fig. 2). The district with the most extensive herbaceous rangeland is Gasa (1,147 km²), followed by Wangdue Phodrang (537 km²) and Bumthang (491 km²). Likewise, shrub and bush rangeland is most prominent in Gasa (536 km²), with substantial coverage in Wangdue Phodrang (477 km²) and Thimphu (308 km²). Mixed rangeland is most extensive in Thimphu (417 km²), Paro (310 km²), and Haa (255 km²) districts.

2.3 Relative change in rangeland vegetation (2013–2024)

The relative change in rangeland vegetation between 2013 and 2024 was classified into five change categories, and the three rangeland classes are shown in Fig. 3. The results indicate that stable vegetation index conditions accounted for the largest proportion of

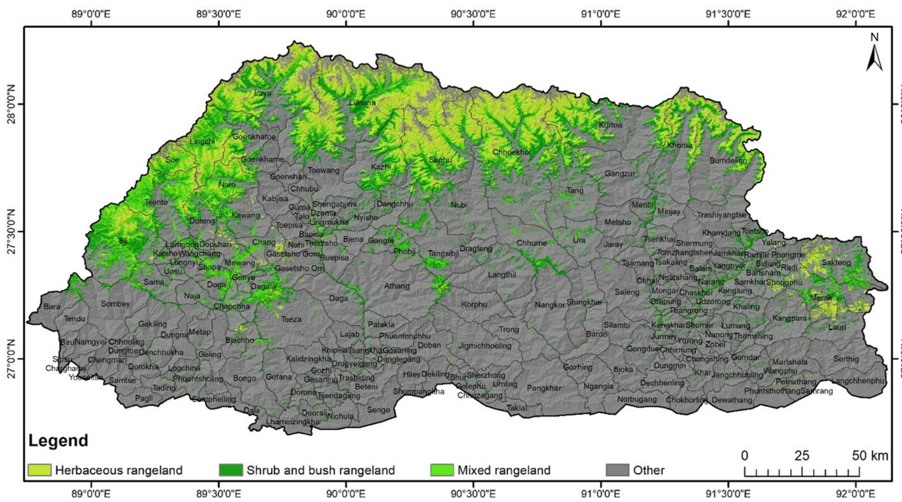

Fig. 2 Sentinel-2 image-based rangeland map of Bhutan

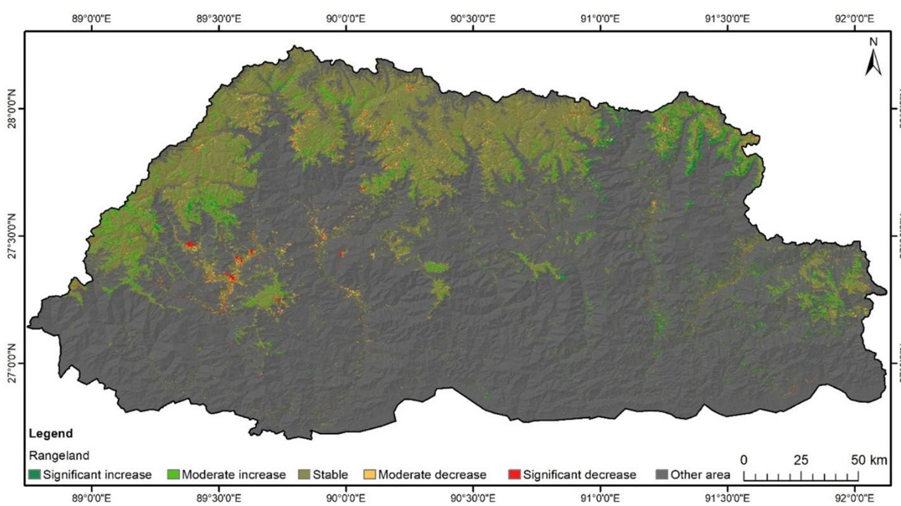

Fig. 3 The relative change in rangeland vegetation in Bhutan was categorized into five distinct classes based on the derived index values

rangeland area, with 7,159 km² remaining within the stability threshold, indicating areas where surface vegetation greenness was largely maintained over time. Notable changes were detected across several.

rangeland categories. With 181 km² mapped as a significant increase and 593 km² as a moderate increase, shrub and bush rangelands exhibited the largest positive shifts in vegetation index values. Similarly, mixed rangeland showed 67 km² with a significant increase and 303 km² with a moderate increase in vegetation indices, reflecting localized greenness enhancement rather than confirmed ecological recovery.

Despite these positive shifts, several areas exhibited declining vegetation index values. Although 116 km² showed a significant decreases, over 326 km² exhibited a moderate decreases, indicating spatially variable vegetation stress. Shrub and bush rangeland recorded the greatest decline, with 150 km² classified as moderate decreases and 54 km² as significant decreases. Herbaceous rangeland, while largely stable, also exhibited localized declines, with 80 km² categorized as moderate decreases and 23 km² as significant

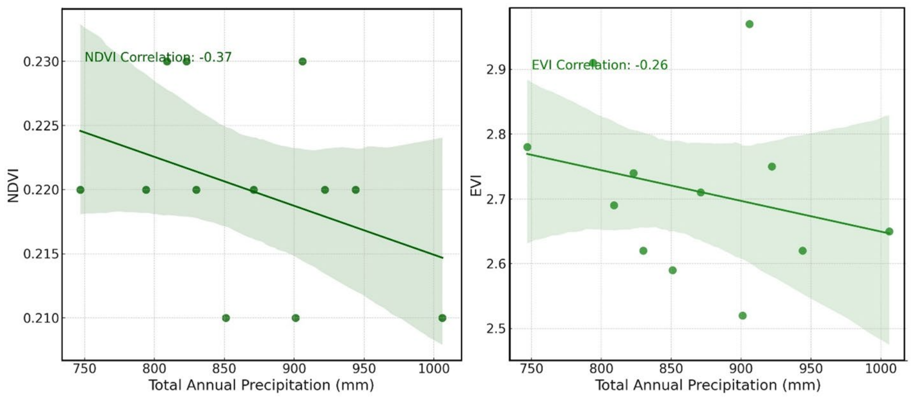

Fig. 4 Relationship between CHIRPS precipitation variability and vegetation dynamics (NDVI and EVI) in Bhutan

decreases, indicating potential impacts from grazing pressure, climatic variability, or land-use stress.

2.4 Vegetation-climate interaction in Bhutan

Precipitation impact analysis on NDVI and EVI reveal an overall negative correlation between annual precipitation and vegetation indices from 2013 to 2024 (Fig. 4). NDVI shows a moderate negative correlation with precipitation ($r = -0.37$), indicating that higher rainfall does not necessarily correspond to increased vegetation greenness. This pattern is likely influenced by topographic constraints, excessive soil moisture reducing root oxygenation, persistent cloud cover limiting radiation, grazing pressure, and phenological effects. Likewise, EVI exhibits a weaker negative correlation ($r = -0.26$), suggesting that although precipitation supports biomass development, other environmental and anthropogenic factors exert stronger control over rangeland vegetation dynamics.

These results highlight the complex and non-linear interactions between rangeland vegetation and climate in Bhutan. The observed vegetation responses suggest that precipitation alone does not govern rangeland greenness, and that soil conditions, grazing intensity, vegetation composition, and land-use pressures play dominant roles in shaping spatial and temporal vegetation patterns. This complexity underscores the need for integrated rangeland management strategies that account for both climatic variability and human-induced pressures.

3 Discussion

The findings of this study provide spatially explicit evidence of rangeland vegetation greenness dynamics across Bhutan between 2013 and 2024, using multi-temporal Landsat 8 and Sentinel-2 imagery analyzed in Google Earth Engine. The dominance of stable vegetation index conditions across large rangeland areas suggests that, at a national scale, surface greenness has been largely maintained over the last decade, despite localized zones of both positive and negative change. These patterns are consistent with observations from other Himalayan rangeland systems where climatic variability and grazing pressure act simultaneously on vegetation dynamics [24, 59, 60].

The spatial concentration of increasing vegetation index values within shrub and bush rangelands indicates that these systems are undergoing the most dynamic transformation [61, 62]. However, as also highlighted by participatory field observations, greenness increases should not be directly interpreted as rangeland recovery [63, 64]. This is because shrub expansion, invasive plant proliferation, and weed encroachment can elevate vegetation indices while simultaneously reducing forage quality and functional grazing potential [36, 37, 65]. Similar shrub-driven greening trends have been documented across high-altitude rangelands of the Hindu Kush Himalaya, often linked with altered grazing regimes and climatic stress [19, 29, 61]. Participatory field inputs provided critical contextual interpretation of the remotely sensed results, especially regarding the discrepancy between greenness and functional rangeland condition [66]. Herders consistently noted that areas showing increasing greenness were, in some cases, dominated by unpalatable shrubs and invasive weeds, which negatively affect livestock mobility, fodder availability, and wildlife habitat quality [39, 67]. This finding reinforces the limitation of index-based greenness as a proxy for ecological condition in complex mountain rangelands, and highlights the importance of integrating species-level information and grazing suitability assessments in future rangeland monitoring efforts [9, 68].

The negative correlations observed between precipitation and NDVI and EVI further emphasize the non-linear response of Bhutan's rangelands to climatic forcing [25, 26]. While increased rainfall is generally expected to enhance vegetation productivity, excess soil moisture, persistent cloud cover limiting solar radiation, and steep topographic controls likely suppress photosynthetic efficiency in many locations [25, 69]. In addition, heavy grazing pressure during the monsoon season may counteract the potential biomass gains associated with increased rainfall, contributing to the observed negative relationship [70, 71]. Similar inverse or weak rainfall–greenness relationships have been reported from other mountain rangeland systems under complex climatic and land-use interactions [72].

The classification uncertainty associated with the Mixed rangeland category, reflected by its low user accuracy and conditional Kappa, also has important implications for interpretation [45, 61]. Mixed rangelands typically represent transitional vegetation structures, where grass, shrubs, and woody elements co-occur, making them spectrally difficult to separate using medium-resolution imagery. Similar classification challenges have been reported in other heterogeneous mountain landscapes, where mixed vegetation mosaics obscure discrete land-cover boundaries [41, 44]. Interpretations of change patterns in this class should therefore remain cautious, particularly when linking spectral trends to grazing suitability or ecosystem function.

Overall, the Discussion indicates that Bhutan's rangelands are presently characterized by widespread stability in vegetation greenness, localized zones of enhancement driven largely by shrub systems, and spatially clustered areas of decline linked to grazing pressure and climatic variability [4]. These outcomes align with previous studies from Bhutan and the broader HKH region, which similarly report rangeland sensitivity to combined climatic and anthropogenic drivers rather than single-factor control [29, 31, 68, 73].

4 Conclusion

This study provides the first nationwide, high-resolution, multi-temporal assessment of rangeland extent and vegetation dynamics in Bhutan using integrated Landsat 8, Sentinel-2, and CHIRPS datasets within the Google Earth Engine platform. The results show that Bhutan's rangelands are dominated by stable vegetation conditions, with 7,159 km^2

remaining within the stability threshold between the baseline period (2013–2015) and the recent period (2022–2024). A total of 1,425 km^2 exhibited increasing vegetation index values, while 442 km^2 showed declining trends, indicating spatially heterogeneous rangeland condition changes across the country.

Among rangeland classes, shrub and bush rangelands exhibited the strongest positive greenness trends, whereas herbaceous and mixed rangelands contained spatially clustered areas of vegetation decline. These class-specific patterns demonstrate that rangeland change in Bhutan is not uniform and varies significantly by rangeland type and location. The findings also reveal that increases in vegetation indices primarily reflect surface greenness enhancement, which in many areas is associated with shrub expansion and invasive species rather than confirmed ecological recovery, as supported by participatory field validation.

Analysis of climate–vegetation interactions showed weak to moderate negative correlations between precipitation and NDVI/EVI, indicating that precipitation alone does not control rangeland vegetation dynamics in Bhutan. Instead, rangeland greenness is governed by complex, non-linear interactions among climate variability, topography, soil moisture conditions, grazing pressure, and land-use change.

Overall, this study establishes a spatially explicit national baseline for rangeland monitoring in Bhutan and provides quantitative evidence of class-specific vegetation trends and climate interactions. These findings offer a scientific foundation for targeted rangeland restoration, grazing management, and long-term monitoring strategies to enhance rangeland sustainability under changing climatic and land-use conditions.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s44288-026-00434-4.

Supplementary material 1.

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Author contributions

Kabir Uddin: Conceptualization; Methodology; Software; Data curation; Formal analysis; Investigation; Visualization; Validation; Writing – original draft; Writing – review & editing. Yi Shaoliang, Bandana Shakya: Supervision; Writing – review & editing. Srijana Joshi, Tashi Dorji, Ramesh Timilsina, Karma Chorten Dendup: Writing – review & editing.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. Besides that, once the article is accepted, data will be uploaded to the RDS (https://rds.icimod.org/) of ICIMOD for anyone to download. Until the article is accepted, we would not like to share the rangeland map publicly.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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