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Original Research

Above Ground Biomass Estimation for Alpine Grasslands of Kashmir Himalayas Using Remote Sensing and Field-Data

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ABSTRACT

This study presents a comprehensive analysis of Alpine pastures in the Kashmir Himalayas through a multidisciplinary approach, combining remote sensing and field-based assessments for biomass estimation and time series analysis of the (NDVI) Index for the growing season from May to October 2022. The Alpine and Subalpine region of Kashmir was delineated using ALOS PALSAR Digital Elevation Model, and Landsat 8 imagery was classified using a maximum likelihood algorithm, revealing a total grassland area of 160,974 hectares. After grassland delineation Biomass estimation was carried out based on data collected from 18 pastures, each of which was subjected to a stratified sampling approach to establish four 1 m² quadrats, with two designated for grazed areas and two for ungrazed areas, this yielded average biomass yields of 20.87 t/ha and an average dry weight biomass of 5.16 t/ha. Pastures like Daksum (28.36 t/ha), Tragbal (28.22 t/ha), Krush (27.83 t/ha), Lung Marg (27.03 t/ha), observed high biomass availability, while moderate levels were found in locations like Gangbal (22.75 t/ha), Hangel Marg (22.68 t/ha), Dagwan (21.76 t/ha), Gumri (20.82 t/ha), Bangus (20.66 t/ha), Pir Galli (18.52t/ha), Maalish (18.21 t/ha), In contrast, lower biomass values were recorded in Mohand Marg (11.47 t/ha), and Thajwas (9.81 t/ha). These findings were complemented by (NDVI) metrics, which varied across sites. For example, high NDVI values were observed for sites such as Pir Gilli, Bangus, and Kud Marg, indicating a healthier vegetative profile with less impact of grazing during the grazing season. In contrast, pastures like Mohand Marg, Thajwas, Razdan, and Tragbal recorded moderate NDVI values, suggesting a moderate level of grazing impact. Pasture sites with lower NDVI values and high standard deviation, such as Hangel Marg and Gumari, witnessed high seasonal variability, suggesting a high grazing impact, besides other natural factors responsible, like early snowfall. The study emphasizes the need for ongoing, multifaceted ecological assessments for the sustainable management and conservation of these critical Alpine ecosystems.

Introduction

Grasslands are vital ecosystems that cover approximately 40% of the Earth's land area and hold 30% of its biomass stock, play crucial roles in biogeochemical cycles, energy transfer, and climate change dynamics, and are a significant part of terrestrial ecosystems, contributing to the overall balance and functioning of the planet (Erb et al., 2018; Bar-On, Phillips, and Milo 2018; FAO 2018; FAO 2019; Piao, Fang, and He 2004; Morais, Teixeira, Figueiredo, and Domingos 2021). Grazing-based systems, despite their relatively minor contribution to global food production, accounting for less than 1% of dietary calories (Herrero et al. 2015; Woods et al. 2015), play crucial roles in supporting livelihoods and providing essential ecosystem services (DeFries and Rosenzweig 2010). As a result, there is a growing recognition of the significance of pasture lands for sustainable intensification, aiming to enhance productivity and efficiency in these systems (Thornton and Herrero 2010; Palermo, de A. d'Avignon, and Freitas 2014; Bogaerts et al. 2017). Aboveground biomass is of significant importance within the carbon cycle of an ecosystem and is commonly used to observe and assess changes in ecosystem structure and functionality (Tan et al. 2010; Yang et al. 2010; Alvarez et al. 2012). The aboveground biomass of grassland serves as the primary food source for grazing live-

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stock, including sheep and cattle. It forms the foundation for the advancement of grassland animal husbandry and is a significant indicator for estimating the carrying capacity of grassland ecosystems. Precise simulation and prediction of the spatial and temporal dynamics of aboveground biomass in grassland ecosystems can contribute to the preservation of grassland ecosystems, facilitate the rational planning of livestock production, and enhance the sustainable management of these ecosystems (Li, He, and Fu 2016; Cao, Wu, and Zhang 2019).

The historical emphasis on cattle farming in mountain economies can be attributed to the availability of abundant grazing areas. During the summer season, pastures are intensively used for grazing purposes, while forage is preserved and allocated for winter feed supply (Garcia-Gonzalez, Hidalgo, and Montserrat 1990). However, the production of grass is subject to various physical constraints. The land use changes (Jamal, Malik, and Ahmad 2022) and topography of the land impedes soil formation and the accumulation of nutrients. It limits the expansion of farms, resulting in the division of land and geographical isolation. The lack of spatial continuity, stemming from the structure of land ownership, hampers mechanization due to low land extension and accessibility (Vaccaro and Beltran 2010).

Grasslands with various ecological features are distributed across different geographic areas in India, accounting for approximately 24% of its total geographical area (Singh, Laienroth, and Milchunas 1983). Grassland vegetation in the Indian Himalaya covers approximately 35% of the region's geographical area and includes various types such as warm temperate grasslands, subalpine and cool temperate grassy slopes, alpine meadows in the greater Himalayas, and steppe formations in cold arid or alpine dry shrub regions (Rawat 1998; Roy and Singh 2013; Rawat and Adhikari 2015). In the Western Himalaya, alpine grasslands prevail above the tree line, primarily on the southern slopes (Rawat 2005). Plant communities and species composition in diverse grasslands differ according to elevation, and the palatability of forage varies from one region to another (Sundriyal 1995; Wilson et al. 2012). These grassland ecosystems represent distinct categories with differences in origin, structure, and composition. Similar to grasslands elsewhere in the world, these formations sustain a diverse array of wild herbivores, domestic livestock, and support various agropastoral cultures (Körner, Nakhutsrishvili, and Spehn 2006; Becker, Körner, Brun, Guisan, and Tappeiner 2007). However, grasslands in the Himalayas are considered particularly vulnerable to climate change and human induced modifications (Paudel and Andersen 2010).

The alpine and subalpine meadows, locally termed "margs" or "bahaks or dokhs," are prominent features of the Jammu and Kashmir region (Singh, Dev, Deb, Chaurasia, and Radotra 2015; Haq et al. 2022; Mugloo et al. 2023). These pastures are an important biological resource, have a significant impact on socioeconomic and environmental aspects, and act as natural buffers, safeguarding against erosion and contributing to flood resilience in the Himalayas, which is important in climate change adaptation debate (Rather, Shafi Bhat, and Andrabi 2017; Malik and Hashmi 2021; Malik 2022; Malik 2022a; Malik 2022b; Malik and Hashmi 2022; Wani and Malik 2023; Malik and Ford 2024). While previous studies predominantly focused on assessing aboveground herbaceous species production within a restricted area of the Kashmir Valley (Saleem et al. 2019; Dev et al. 2018), these investigations were limited to pastures accessible by roads. There has been a notable absence of research encompassing the entire Kashmir Valley region, examining (AGB), and providing comprehensive documentation of the region (Rather et al. 2022; Bhat et al. 2023 and Singh et al. 2024). The present study aims to conduct a comprehensive assessment of its current condition. Such an assessment serves as a foundation for devising suitable pasture management strategies. The challenge of restoring degraded grasslands, which leads to decreased productivity, underscores the necessity of this assessment (Zhang, Liu, Zhou, and Fang, 1998; Ahmad, Mir, Bhat, and Singh 2018).

Material and Methods

Study area

The study site is located in the alpine and subalpine regions of the Kashmir Himalayas, spanning between 33°21′ and 34°55′N latitude and 73°30′ and 75°35′E longitude, within the northwestern part of the Himalayan biodiversity hotspot (Fig. 1).

With an elevation ranging from 2208 m above mean sea level (amsl) to 5375 m (amsl), the area experiences a temperate climate (Moonis 1978). The unique interplay of altitude, soil conditions, and topography contributes to a diverse array of flora, featuring various vegetation formations. At lower altitudes, one finds an abundance of broad-leaved species, including *Populus deltoides* and *Juglans regia,* while coniferous species such as *Pinus wallichiana*, *Cedrus deodara, Abies pindrow*, and *Picea smithiana* dominate the higher elevations. Throughout the Kashmir Himalaya, extensive herbaceous vegetation formations, collectively known as "grasslands," cover the landscape. These grasslands boast an array of tussock-forming herbs, sedges, and grasses, with particular emphasis on key species such as *Aconitum, Gentiana, Iris, Pedicularis, Potentilla, Primula*, and *Ranunculus*. Notably, leguminous plants like *Astragalus, Lotus, Medicago*, and *Trifolium* also play a crucial role in these ecosystems (Dad et al. 2010; Ahmad, Mir, and Bhat 2021). Historically, these grasslands have served as summer pastures for both local communities and nomadic groups. However, recent shifts in government priorities aim to explore alternative non-pasture activities, such as tourism and recreation, within these areas. Consequently, the study was conducted across 18 distinct sites, each characterized by unique site histories and management practices, in order to acquire a deeper understanding of the dynamics of these grasslands and their associated management approaches.

Data acquisition and preparation

The study utilized a combination of remote sensing techniques, land use classification, and field observations to estimate the aboveground biomass in alpine pastures above 2500 m (Fig. 2). By using the ALOS PALSAR an acronym for Advanced Land Observing Satellite—Phased Array type L-band Synthetic Aperture Radar, a widely employed satellite sensor for terrain mapping with a finer resolution of 12.5-meter DEM to delineate the pasture area, this high-resolution data enabled precise identification of the target altitude range. Subsequently, Landsat 8 OLI Surface reflectance having a 30-metre resolution was acquired using cloud filtering to ensure that the imagery obtained for the study area contains less than 2 percent cloud cover from the USGS database and was pre-processed. Prior to land use classification, satellite image preprocessing is critical to accurately relating the gathered data to biophysical phenomena (Chander and Markham 2003). The acquired satellite imagery was geo-referenced and rectified to fit the UTM zone 43 N, adhering to the WGS84 datum (Table 1). Following the assessment of data quality, the imagery was processed using ERDAS Imagine 9.1 for radiometric and geometric corrections, such as image enhancement, layer stacking, mosaicking, and sub-setting according to the study area. NDVI Sentinel satellite data, boasting a finer resolution of 10 meters and a revisit time of 10 days, was employed for vegetation analysis and precise monitoring of phenological changes during the growing months from May to October 2022. The selection of data for this analysis was meticulously re-

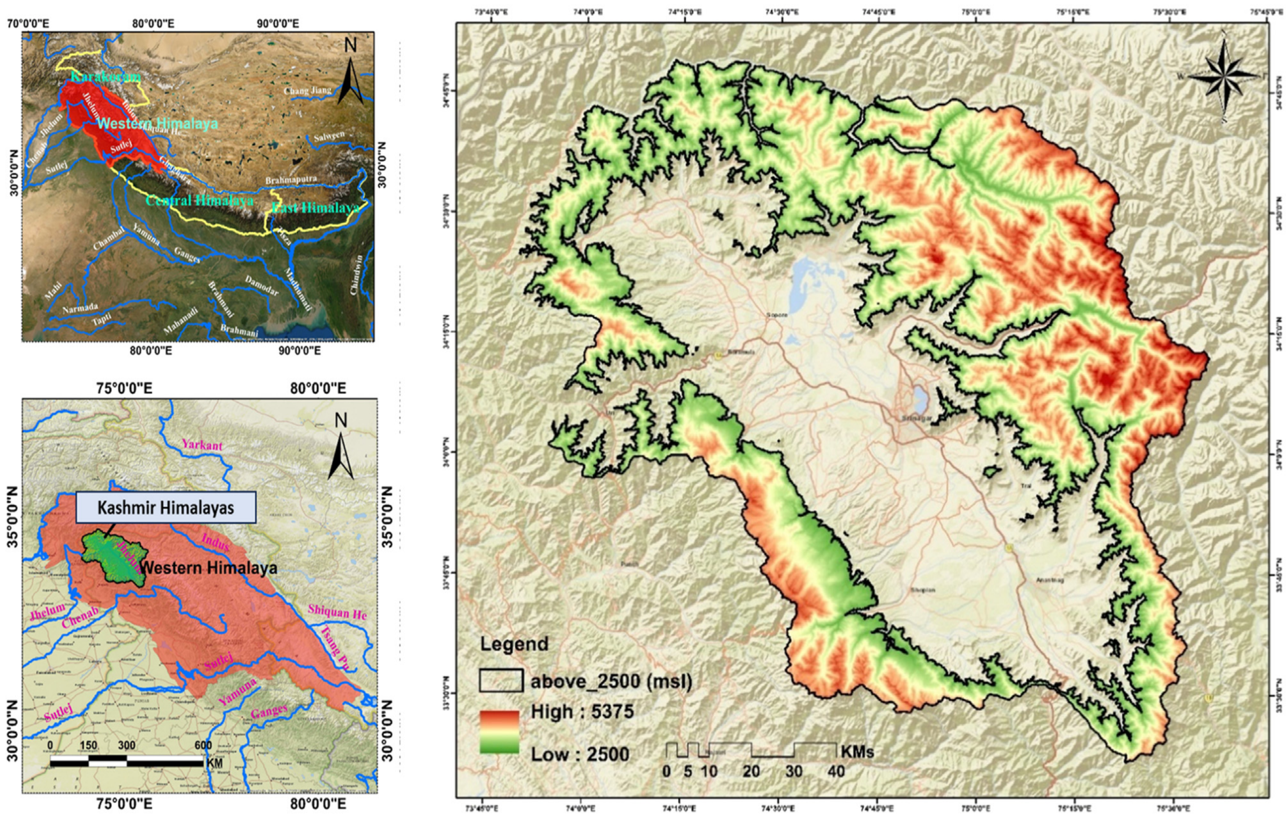

Figure 1. Alpine and sub-alpine area of Kashmir region 2500 m ASL.

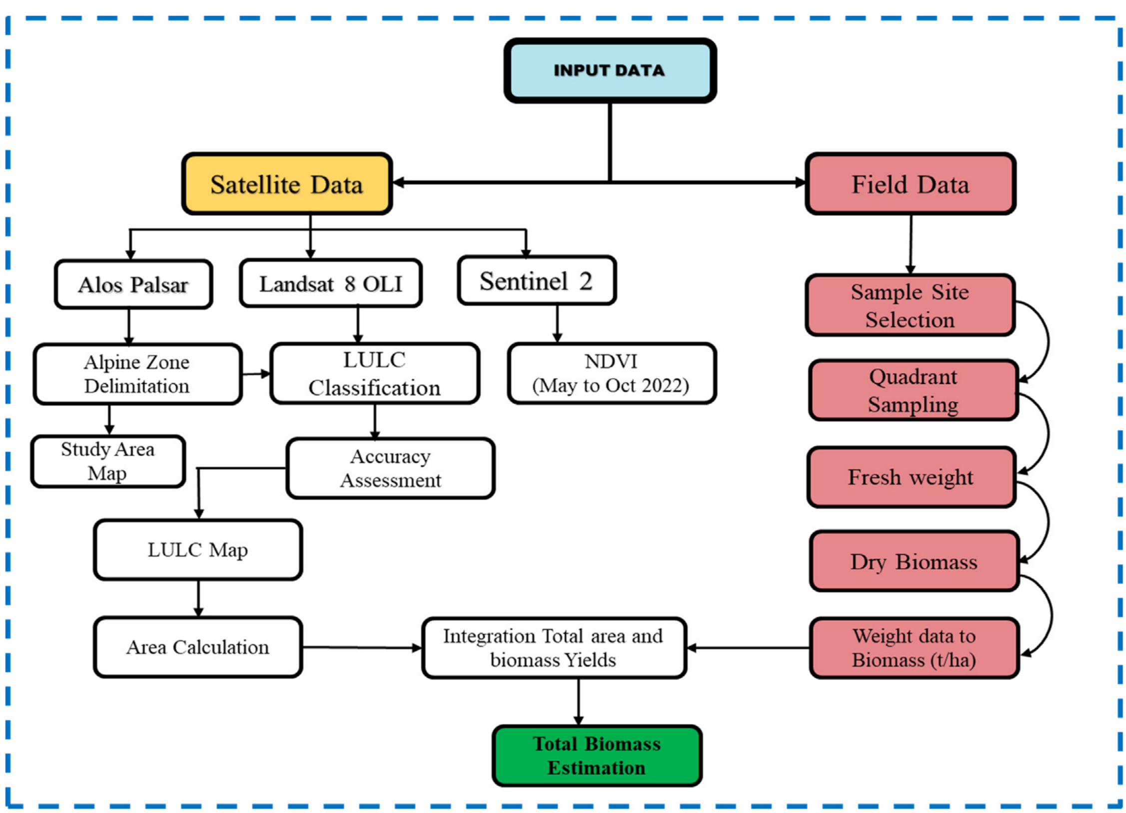

Figure 2. Methodology flow chart.

Table 1
List of data sources used in the study.

Sensor	Year	Path/Row	Source	Acquisition	Resolution (m)	Bands	Use
ALOS PALSAR	2015	149/36	USGS	4 June	12.5	L	Study area delineation
Landsat 8 OLI	2019	149/36	USGS	16 May	30	2,3,4,5, 6	LULC
Sentinel 2	May–Oct 2022	149/36	GEE	5 Days revisit	10	4, 8	NDVI

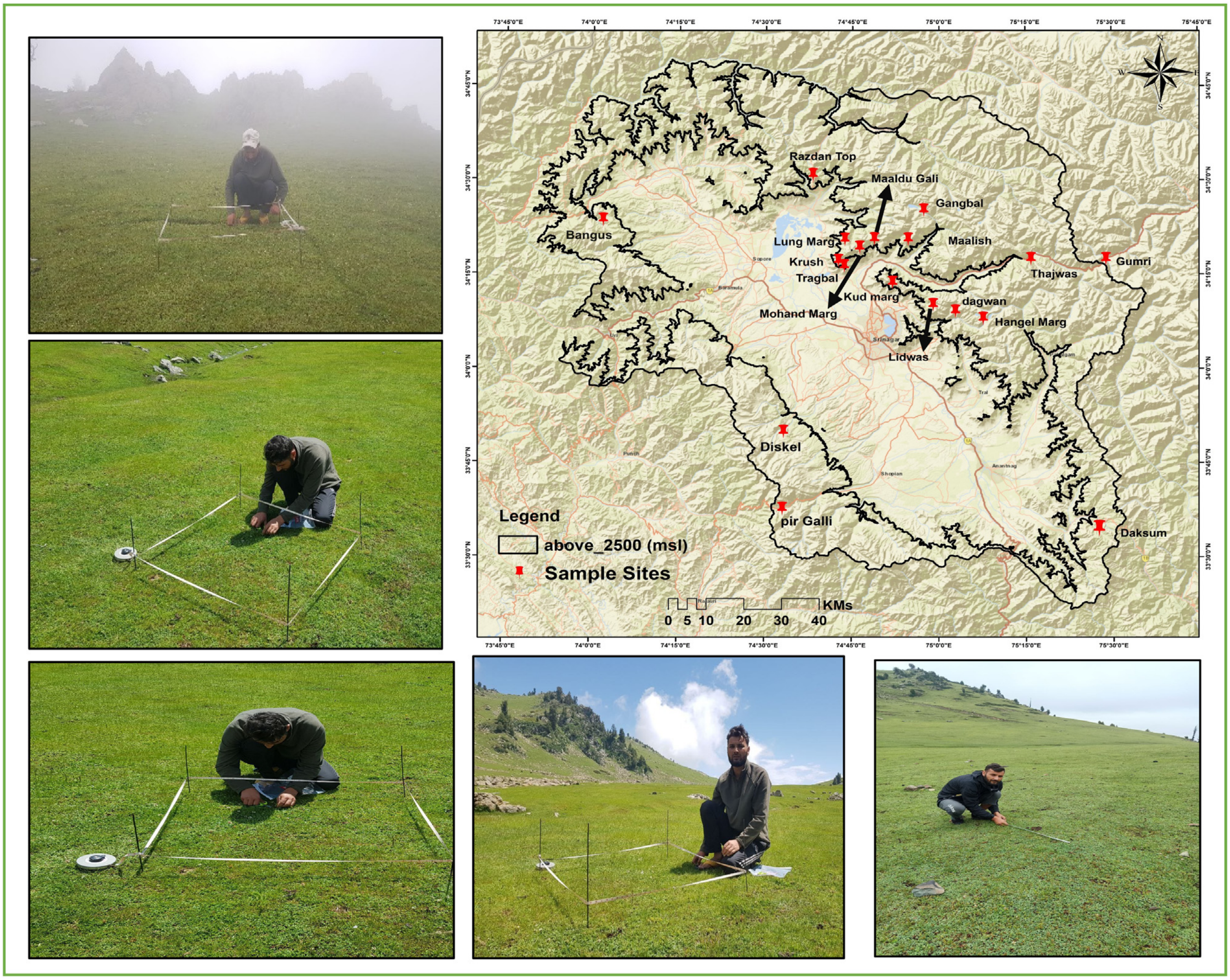

Figure 3. Location of sampled pastures and photographs taken during the field visit.

fined by applying cloud filtering techniques to ensure unobstructed observations, thereby making the year 2022 the specific choice for this study.

Collection of herbaceous plant samples

To collect aboveground biomass data, herbaceous plant samples were collected using the direct field plot harvest technique for fresh weight, and to measure dry biomass, samples were oven-dried at 105 °C until a constant weight was achieved. A total of 72 field observations were conducted over a period of two years, from 2021 to 2022. Four 1 m^2 (1 m x 1 m) quadrants (Mueller et al. 1974; Kent and Coker 1992) were laid down per site: two from grazed areas near their wooden huts where they stay and two from the ungrazed area of pasture, and all herbaceous plant species were harvested from above ground (Fig. 3). displays the location of sampling sites, which were selected to ensure the representation of all major grasslands across the study region.

Generation of land use/land cover

Land use/land cover classification is a well-established method for extracting meaningful information from satellite imagery. In this study, we used false color composite (FCC) imagery to generate accurate LULC data for the sub-Alpine and Alpine regions of Kashmir. Amongst the array of available LULC classification techniques, we opted for a supervised classification method employing the maximum likelihood classifier algorithm and random forest classifier to produce reliable LULC maps by precisely taking 80 training samples for each class to ensure robust model training using ArcMap 10.8 software. The classification process identified six distinct LULC classes, including Open Forest, Exposed Rock, Forest, Shrubland, Grasslands, and Snow-covered region. To address any initial classification errors, we employed post-classification techniques, including ground truths derived from classified scenes. These measures were undertaken to refine and enhance the accuracy of the LULC classification outputs, thereby contributing to a

Table 2
Accuracy results of land use land cover (LULC) maps derived from satellite data.

Class	OF	ER	F	S	G	SI	Row Total	User Accuracy (%)
OF	*68*	*1*	*1*	*2*	*0*	*0*	*72*	*94.44*
ER	*1*	*76*	*0*	*0*	*2*	*0*	*79*	*96.2*
F	*3*	*0*	*80*	*5*	*0*	*0*	*88*	*90.91*
S	*2*	*0*	*2*	*62*	*4*	*2*	*72*	*86.11*
G	*0*	*3*	*0*	*0*	*66*	*6*	*75*	*88*
SI	*0*	*0*	*0*	*0*	*0*	*92*	*92*	*100*
Column total	*74*	*80*	*83*	*69*	*72*	*100*	*478*	
Producer accuracy (%)	*91.89*	*95*	*96.39*	*89.86*	*91.67*	*92*		

Diagonal italic numbers show accurate classifications for each LULC class (OF): Open Forest, (ER): Exposed Rock, (F): Forest, (S): Shrubland, (G): Grassland, (SI): Snow/Ice. Sum of diagonal: 444; Total: 478 overall accuracy: 92.89%; Kappa coefficient (K) 0.91.

more robust and precise analysis of land use and land cover dynamics within the study area.

Accuracy assessment

Accurate assessment of land use/land cover classification plays a crucial role in evaluating the reliability and suitability of the generated maps for specific purposes (Rwanga et al. 2017). several techniques, including the Kappa coefficient and error matrix, have been widely utilized to assess the accuracy of LULC maps (Talukdar et al. 2020; Verma, Raghubanshi, Srivastava, and Raghubanshi 2020). In this study, we employed the Kappa coefficient and error matrix to evaluate the producer's and user's accuracies. Producer's accuracy, which measures the proportion of correctly classified instances for each land cover class relative to the total instances of that class in the ground truth data, and user's accuracy, which indicates the proportion of correctly classified instances relative to the total instances classified as that class, were calculated for each land cover class of the LULC maps of the alpine and sub-alpine regions of Kashmir using a sample of 478 randomly selected points. The study utilized a random stratified sampling method to select 478 points from the classified image, which were then validated using a combination of field visits and Google Earth Pro, particularly in areas with limited access or no field data. The classification achieved an overall accuracy of 92% with a Kappa value of 0.91 (see Table 2), which is considered acceptable and indicative of a strong agreement, as supported by prior research (Anderson et al. 1976).

Normalized difference vegetation index

The Normalized Difference Vegetation Index is an integral metric for quantifying the density of green vegetation using the spectral reflectance properties at specific wavelengths, pivotal for differentiating vegetated from non-vegetated areas. For Sentinel satellite data, NDVI is calculated using the specific bands that correspond to red and near-infrared, typically band 4 (Red) denoted as ρ_v and band 8 (near-infrared) denoted as ρ_{iv} for Sentinel-2 data. The NDVI was calculated (Eq. (1): Rouse, Haas, Schell, and Deering 1974).

$$\text{NDVI} = \frac{\rho_{iv} - \rho_v}{\rho_{iv} + \rho_v} \quad (1)$$

The NDVI response ranges from −1.00 to 1.00, with negative values typically indicating clear water bodies, and values between 0.00 and 0.25 indicating exposed soil surfaces, including straw residue. NDVI values between 0.25 and 0.40 signify soils with vegetation presence, while values above 0.40 indicate vegetated surfaces. Higher NDVI values approaching 1.00 indicate stronger vegetation profiles (Formaggio and Sanches 2017).

Results and Discussions

Land Use Land Cover analysis, focusing exclusively on the alpine and sub-alpine regions of Kashmir, particularly targeting areas above 2500 meters in elevation, brings to light the distinct land cover classes present in these high-altitude regions. Previous investigations have mapped LULC shifts in numerous catchments across the Kashmir valley, showcasing significant transformations (Ahmad et al. 2021; Saleem et al., 2021; Ahmed et al. 2022 and Imdad et al. 2023). It is commonly observed that transitions in LULC occur within Kashmir's catchments, transitioning from unirrigated systems such as forests and barren land to irrigated systems driven by agricultural and horticultural activities, which promote enhanced crop production and economic benefits (Pandey, Koutsias, Petropoulos, Srivastava, and Dor 2021; Ritse et al. 2020). However, the current study's scope is delineated to conducting a LULC analysis for the alpine and sub-alpine zones of Kashmir (Figs. 4 and 5). The comprehensive analysis of six diverse land cover types, including (1) Open Forest, (2) Exposed Rock, (3) Forest, (4) Shrubland, (5) Grasslands, and (6) Snow covered a total area of 8,79,033 hectares within the alpine and sub-alpine regions of Kashmir.

Table 3
Area coverage of land use and land cover in square hectares and percentage.

Class Name	Area in Hectares	Percentage (%)
Open Forest	98,147	11.17%
Exposed rock	3,45,269	39.28%
Forest	1,69,367	19.25%
Shrubland	93,117	10.59%
Grassland	1,60,974	18.32%
Snow	12,159	1.38%
Total	8,79,033	100.00%

The distribution of land cover types revealed a diverse landscape. Open forests occupied an area of 98,147 ha, corresponding to 11.17% of the total study area, while exposed rock formations extended significantly across 3,45,269 ha, accounting for 39.28% of the total land cover. Forest areas, measuring 1,69,367 ha, constituted 19.25% of the total area, and shrublands covered 93,117 ha, representing 10.59% of the landscape (Table 3). Additionally, grasslands spanned 1,60,974 ha, making up 18.32% of the total area. In contrast, snow-covered regions were relatively limited, encompassing 12,159 ha, or 1.38% of the total area. This comprehensive assessment of land cover types offers valuable insights into the distribution and diversity of ecosystems within the studied regions, underscoring the importance of balanced conservation and management strategies in these areas.

These findings provide valuable insights into the distribution and proportion of various land cover classes in the high-elevation regions. Such assessments are crucial for understanding the ecological dynamics and potential environmental changes in fragile mountainous ecosystems.

Above ground biomass

The investigation of rangelands in the Kashmir Valley, covering 19 different site types (including both grazed and protected

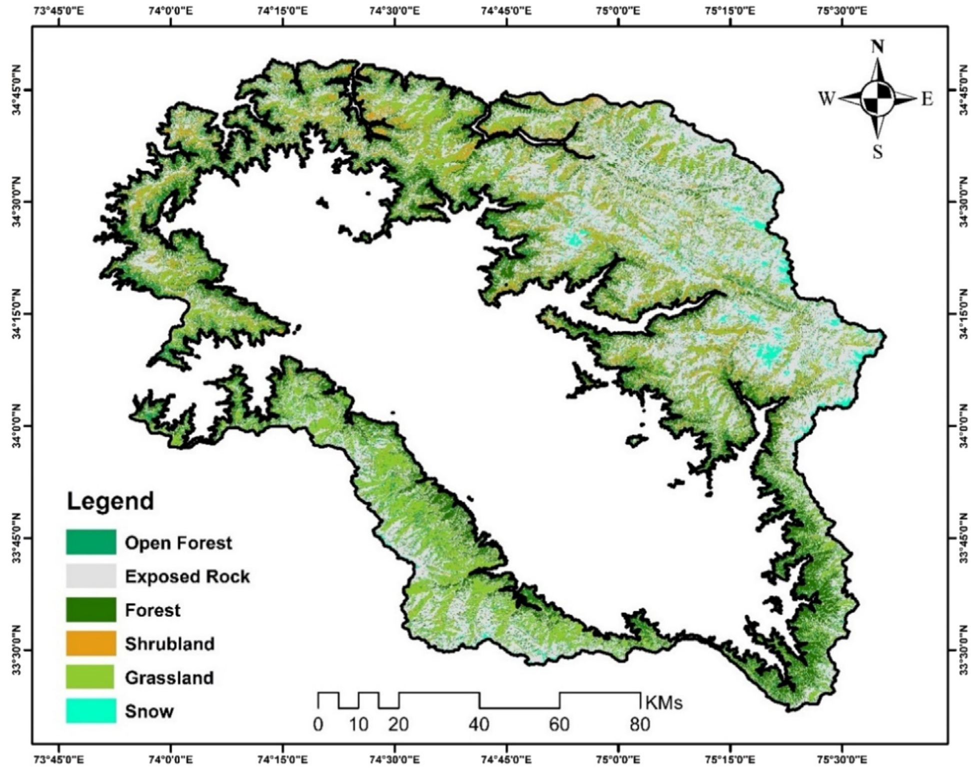

Figure 4. Land use maps of Alpine and sub-Alpine region of Kashmir.

Table 4
Show green herbage and dry biomass in metric tons/ha in the pastures of alpine region of Kashmir.

Name of Sites	Latitude	Longitude	Elevation (m)	Green Herbage		Dry Biomass
				Mean ± SD	S.E	
Mohand Marg	34.3223528	74.7724611	3351	11.47 ± 2.70	1.35	2.87
Tragbal	34.2726278	74.7281792	2720	28.22 ± 3.70	1.85	7.06
Krush	34.2867028	74.7112833	2990	27.83 ± 3.03	1.52	6.96
Lung Marg	34.3428861	74.7301856	3229	27.03 ± 4.80	2.4	6.76
Maaldu Gali	34.3445222	74.8151528	3450	14.91 ± 3.77	1.88	3.73
Kud Marg	34.2287194	74.8675036	3270	17.16 ± 2.99	1.49	4.29
Gangbal	34.4210556	74.9573361	3536	22.75 ± 2.59	1.3	5.69
Dagwan	34.1527583	75.0480000	3640	21.76 ± 3.11	1.56	5.44
Maalish	34.3439139	74.9123722	3680	18.21 ± 3.79	1.9	4.55
Thajwas	34.2915425	75.2663667	2790	9.81 ± 3.77	1.88	2.45
Razdan Top	34.5144556	74.6371000	3365	23.95 ± 6.02	3.01	5.99
Gumri	34.2908667	75.4822667	3550	20.82 ± 4.93	2.46	5.20
Daksum	33.5866278	75.4392444	2549	28.36 ± 4.54	2.27	7.09
Lidwas	34.1697444	74.9845390	3367	25.25 ± 1.80	0.9	6.31
Hangel Marg	34.1332333	75.1287139	3875	22.68 ± 2.13	1.07	5.67
Diskel	33.8324056	74.5550167	3257	15.52 ± 2.89	1.44	3.88
Pir galli	33.6280167	74.5519972	3453	18.52 ± 3.32	1.66	4.63
Bangus	34.393169	74.032183	2830	20.66 ± 4.84	2.42	5.16

areas, as well as fresh and dry biomass), provided valuable insights into their biomass production. Figure 6 and Table 4 presents the AGB in the pastures of Kashmir, in metric ton/ha. The analysis of fresh weight from different grassland sites provides variations in biomass production across these sites, with an average biomass yield of 20.64 t/ha.

These sites have been categorized into three distinct groups by employing a quantile-based method to divide the biomass data into groups that yielded high, medium, and low amounts. By using the distribution of mean AGB values, this approach divides the dataset into thirds. Sites are categorized as medium-yielding if they are above the 66th percentile, high-yielding if they are below the 33rd percentile, and low-yielding if they are between the 33rd and 66th percentiles. In the high biomass yield group, we find sites such as Daksum (28.36 t/ha), Tragbal (28.22 t/ha), Krush (27.83 t/ha), Lung Marg (27.03 t/ha), Lidwas (25.25 t/ha), and Razdan Top (23.95 t/ha). These sites are characterized by substantial AGB production, which can be attributed to favorable conditions for grassland productivity. Such high yields are primarily a result of effective rangeland management practices, and sustainable grazing patterns employed by pastoralists. The medium biomass yield group includes sites like Gangbal (22.75 t/ha), Hangel Marg (22.68 t/ha), Dagwan (21.76 t/ha), Gumri (20.82 t/ha), Bangus (20.66 t/ha), Pir Galli (18.52t/ha), Maalish (18.21 t/ha), and These sites exhibit moderate AGB yields, suggesting reasonable productivity and forage availability for grazing animals (Fig. 6). Conversely, the low biomass yield group encompasses sites such as Kud Marg (17.16t/ha), Diskel (15.52 t/ha), Maaldu Gali (14.91 t/ha),

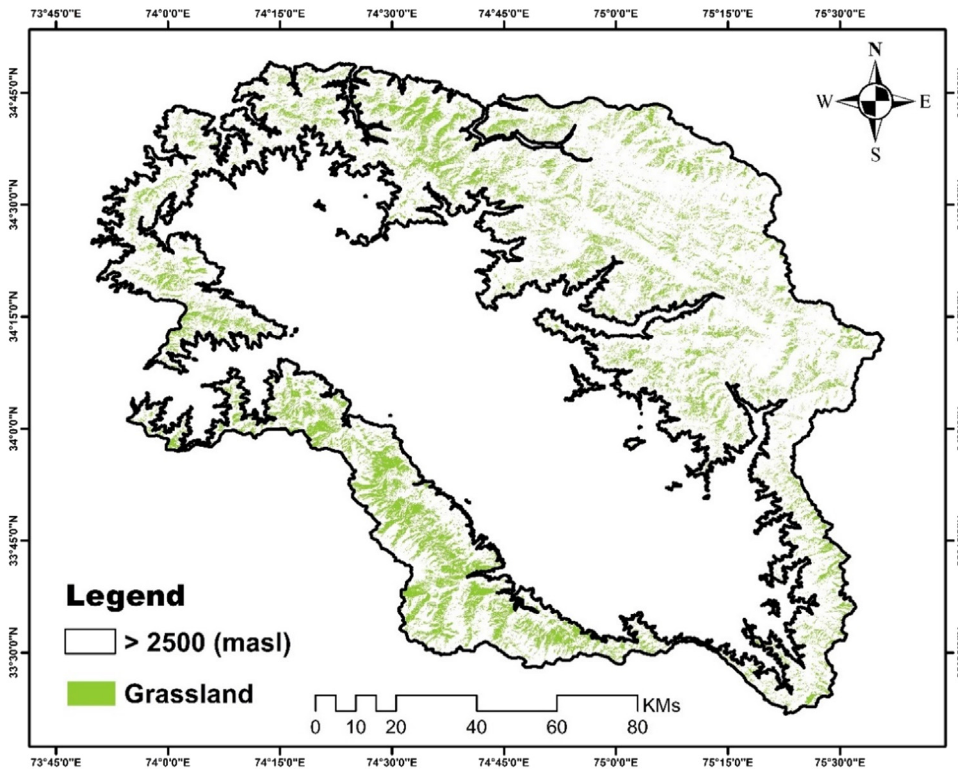

Figure 5. Land use maps of Alpine and sub-Alpine region of Kashmir.

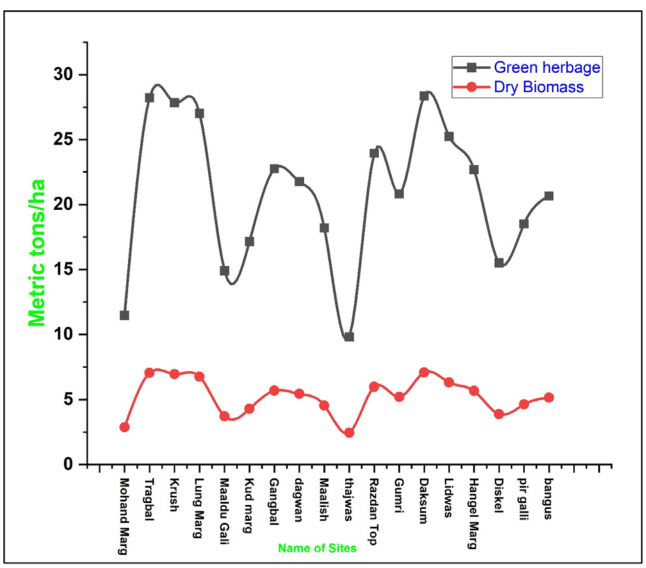

Figure 6. Biomass yields different pasture sites.

Mohand Marg (11.47 t/ha), and Thajwas (9.81 t/ha). These locations exhibit notably diminished biomass yields, suggesting less favorable conditions for grassland growth. The principal reasons for these lower yields are twofold. First, overgrazing is a prominent issue, especially given the proximity of Sonamarg, a key transit point on the way to Minamarg and the largest grazing site for pastoral nomadic Bakerwals. Second, the presence of a substantial number of horses and donkeys during the summer season, mainly due to tourist activities, adds to the pressure on the grasslands, further contributing to the reduced biomass yield in these areas. These factors, in combination with potential soil quality limitations and climatic constraints, contribute to the observed lower biomass yields. These findings underscore the importance of effective management of rangelands in protected sites across the Kashmir Valley. The data associated with each site type provides a clear depiction of the variations in biomass yields across the grasslands of the Kashmir region.

The analysis of dry biomass, as derived from the provided data, reveals important insights into the productivity and potential ecological significance of various sites. The dry biomass represents the amount of organic matter that remains after the removal of moisture content. The dry biomass across various sites reveals significant variability in grassland productivity. High-yielding sites like Daksum, Tragbal, Krush, Lung Marg, Lidwas, and Razdan Top, with dry biomass exceeding 5.57 tons/ha, suggest favorable conditions for vegetation growth Table 4. These conditions could be attributed to optimal soil quality, adequate precipitation, and effective pasture management practices, including sustainable grazing patterns. In contrast, sites like Thajwas and Mohand Marg, which show considerably lower dry biomass values below 2.5 tons/ha, are experiencing less favorable conditions and adverse anthropogenic impacts. Notably, these lower-yielding sites are also popular tourist destinations, attracting significant numbers of horse riders leading to intense grazing pressures. Additionally, some locations, such as Pir Galli, situated along migratory routes of the Bakerwal pastoral community from the Jammu plains to summer pastures, face a substantial influx of livestock, contributing to overgrazing. Furthermore, there is an observed relationship between elevation and biomass yields, with sites at higher elevations tending to have lower yields compared to those at lower elevations. This variation underscores the ecological impact of altitude on grassland productivity. The compiled dry biomass data is crucial for assessing the ecological health of these grasslands.

Normalized difference vegetation index

The NDVI serves as a pivotal metric for assessing various ecological variables, such as vegetation health, land cover classifi-

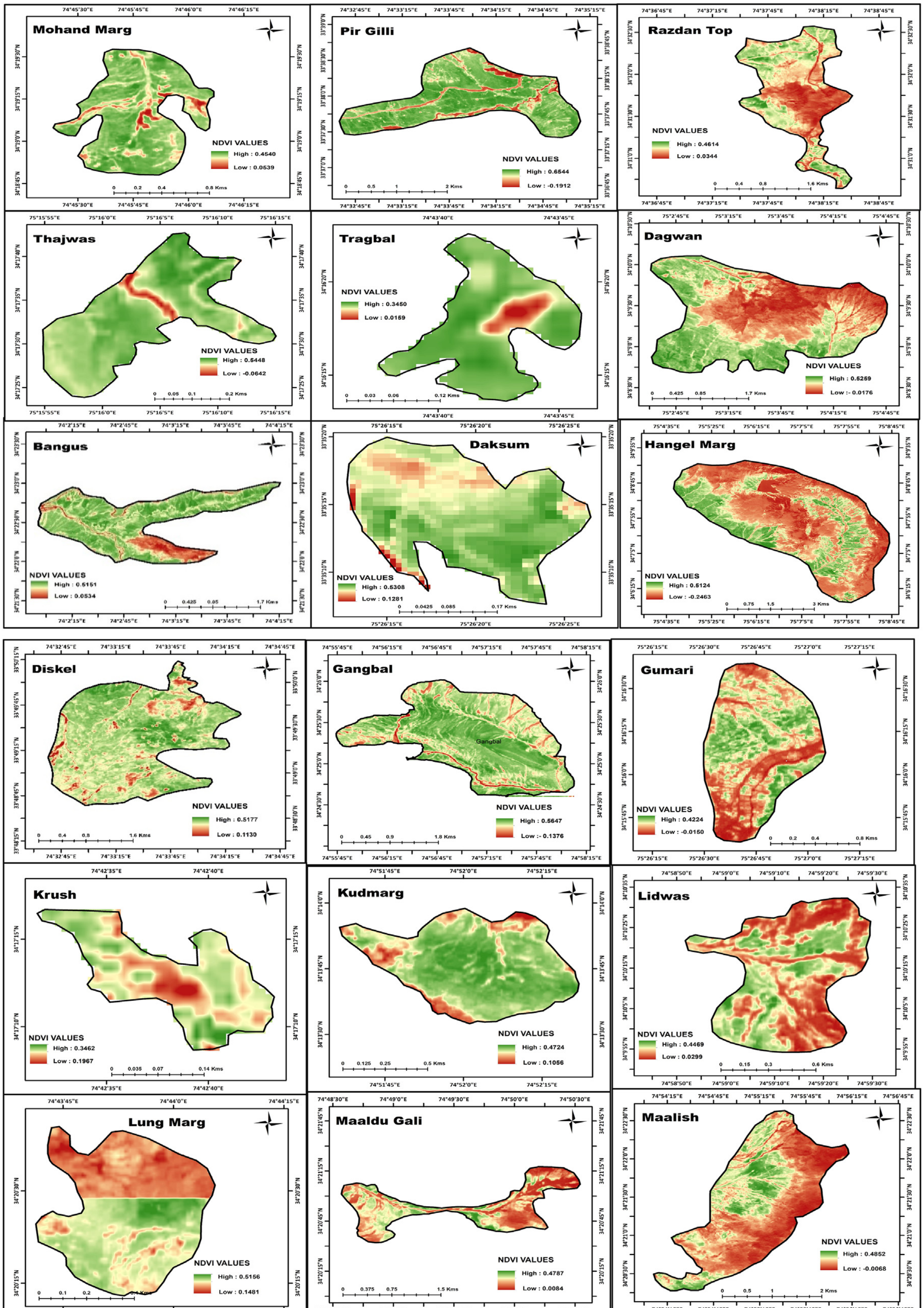

Figure 7. Normalized Difference Vegetation Index maps for selected pasture sites (May–Oct 2022).

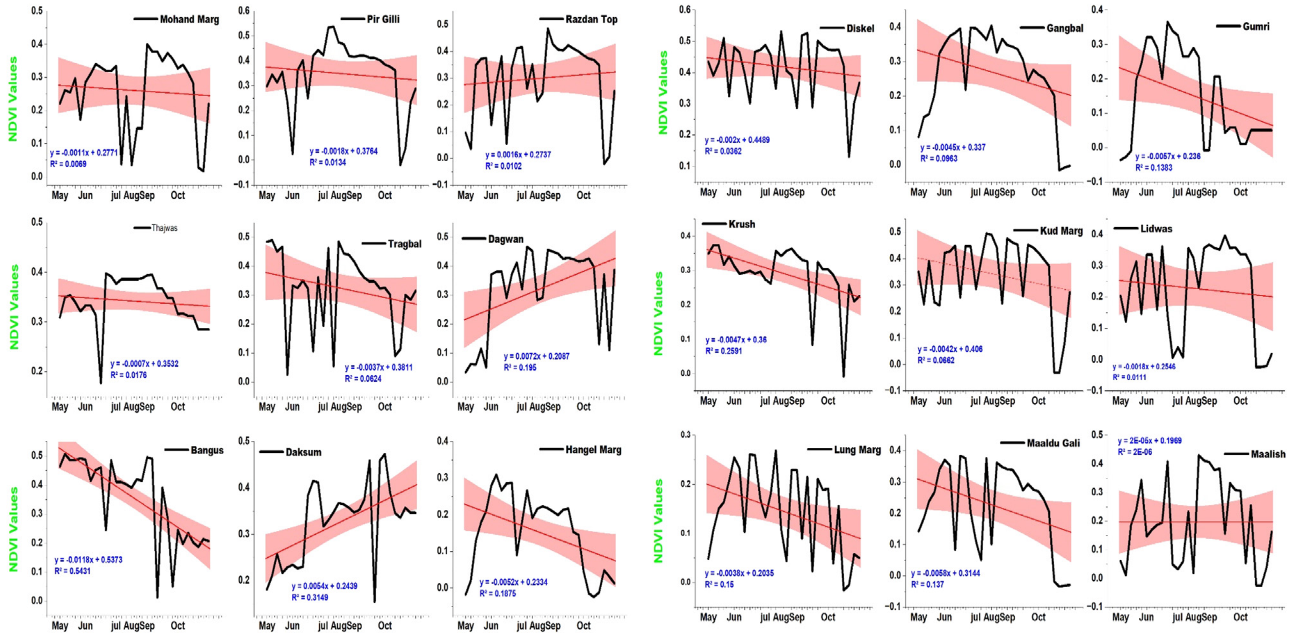

Figure 8. Monthly Normalized Difference Vegetation Index time series graphs (May–Oct 2022).

cations, and phenological shifts (Pettorelli et al. 2005; Drusch et al. 2012). Utilizing high-resolution satellite data from Sentinel 2, a time series analysis was conducted for 18 strategically selected alpine grassland sites within the Kashmir region. The temporal scope focused on the growing period from May to October in the year 2022. The Alpine grasslands in Kashmir serve as a compelling backdrop for assessing vegetation health through NDVI metrics, which are influenced by a myriad of factors ranging from natural climatic conditions to human activities such as grazing.

Figures 7 and 8 visualize the monthly NDVI values for the growing season of 18 alpine grassland sites in the Kashmir region. The analyses, including linear and quadratic regression, highlight both the resilience and the vulnerabilities of these grasslands to ecological stressors such as climate variability and overgrazing. Throughout the growing season, NDVI values generally peak around mid-year (June–July) and reach their lowest points around the beginning and end of the growing season of alpine grasslands. The quadratic regression results revealed that most locations exhibit a statistically significant concave upward trend in NDVI values throughout the growing season. This pattern indicates an increase in vegetation health and biomass during the middle of the growing season, with a decline as the season begins and ends. Such a trend aligns with typical plant phenological cycles in temperate to alpine ecosystems, where growth is maximized during the warmer months (Wang et al. 2020). Positive trends are evident in sites like Dagwan and Daksum, reflecting sustained ecological health and forage availability. In contrast, sites like Bangus, Krush, and Hangel Marg, facing overall declines and seasonal variability, raise concerns about the ecological stressors affecting these grasslands. such as climate variability and overgrazing (Fig. 8).

Conversely, sites with decreasing trends such as Bangus, Gumri, Krush, and Kud Marg, coupled with the seasonal decreases identified in the quadratic analysis, are areas of concern. They reflect an overall decline in vegetation health but also the added challenge of seasonal variability impacting forage availability. Moreover, these sites accommodate significant pastoral populations, exacerbating the potential impact of low forage availability on livestock and leading to overgrazing. Analysis of the NDVI trends within the context of pastoralism unveils essential insights into the interplay between vegetation dynamics and grazing practices across Kashmir's alpine pastures. The varied NDVI trends observed amongst the 18 sites offer a nuanced perspective on vegetation health, directly impacting pastoral communities reliant on these ecosystems for livestock grazing.

Moreover, the convergence of field data and NDVI profiles facilitates a comprehensive analysis of the phenological profile of AGB in grasslands. This integrated approach enables the quantification of total biomass yields, thereby enhancing our ability to gauge the ecological health and productivity of pastoral landscapes. By leveraging NDVI-derived insights alongside on-the-ground observations, it becomes possible to develop sustainable pastoral management strategies (Gao et al. 2023). Studies have shown that AGB can serve as an indicator of pasture quality, affecting livestock nutrition and, consequently, the livelihoods of pastoralists (Dong et al. 2011). For instance, the phenological changes and productivity of grasslands, as captured through AGB assessments, are critical for predicting grazing potentials and planning seasonal movements of pastoral communities (Wang, Price, and Rich 2018).

Conclusion

This study conducted a comprehensive analysis of alpine grasslands in the Kashmir Himalayas using remote sensing techniques and field assessments. We found diverse vegetation formations in the area, highlighting the ecological diversity of the region. The study provides an in-depth exploration of the biomass production and NDVI profiles of grassland ecology in the Kashmir Himalayas, crucial for supporting the livelihoods of pastoral communities for generations. These high-altitude areas, serve as seasonal grazing grounds for herds of sheep and goats, facilitating seasonal migration practiced by over 600,000 people. This connection between the pastoral way of life and the Himalayan landscape is deeply ingrained. Apart from their economic importance, these pastures play a vital role in maintaining Himalayan biodiversity and preserving local cultural diversity. Biomass estimates revealed insights into the ecological dynamics of these pastures.

The total fresh weight biomass, averaging 20.64 t/ha, was approximately 3322,503.36 t, while the total dry weight biomass, averaging 5.16 t/ha, was about 830,625.84 t. These figures highlight the significance of these grasslands for ecological preservation and community sustenance. The NDVI metrics offered complementary insights into seasonal variability in vegetation health, underscoring the importance of informed policy decisions in conserving and sustainably managing alpine pastures in the western Himalayas, especially given the environmental challenges they face. This study thus emphasizes the need for future research and monitoring to understand the nuanced interplay between natural and anthropogenic variables, enabling the sustainable management and coexistence of ecological and cultural aspects in the western Himalayas. The findings emphasize the importance of balanced conservation and management strategies, effective rangeland management practices, and the integration of pastoralist practices for the sustainable management and conservation of these alpine ecosystems. Further research and monitoring efforts are needed to inform adaptive management approaches.

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Ethical Approval

All the ethical standards of research publishing were taken care of during this study.

Authors Contributions

SS and JAR originated the idea and planned to carry out the research work. SS, SA, RA and JAR downloaded and processed data as well as devised the methodology. SS, RA, and SA conducted the field sampling. IHM, JAR, and SA interpreted the results. SS took charge of writing the manuscript, while JAR, IHM, and SA edited and revised it. All authors approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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