RESEARCH PAPER

FOUR DECADES OF TREE COVER AND GRASSLAND DYNAMICS IN THE FOOTHILLS OF THE WESTERN HIMALAYAS – CHAMOLI DISTRICT OF UTTARAKHAND, INDIA

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ABSTRACT. The study investigates the dynamics of land use and land cover changes and their impacts on tree cover and grasslands in the Chamoli district of Uttarakhand over four decades (1983-2023). Using multi-temporal satellite data analysis, the research examines vegetation patterns across different elevation zones ranging from 683m to 7801m. The findings reveal significant variations in tree cover, with an initial increase from 224,027 hectares in 1983 to fluctuations leading to 323,554 hectares by 2023. Tree cover showed remarkable expansion at higher elevations, particularly in the 4149-5152m zone, increasing from 147 hectares to 44,189 hectares. This indicates significant upward migration. Grassland areas demonstrated considerable variability, expanding from 93,647 hectares in 1983 to 118,330 hectares in 2023. The study identifies a clear spatial pattern with consistently higher vegetation density in the southern region, while the northern portion exhibits notably lower coverage. This north-south vegetation gradient persists throughout the temporal sequence, suggesting underlying environmental and human influences. The research also highlights concerning trends in other land cover types, including an increase in barren land and a massive decrease in snow cover, indicating significant changes. These transformations have important implications for local ecosystems, biodiversity, and communities dependent on these landscapes. The findings contribute to understanding the complex interactions between climate change, land management practices, and vegetation dynamics in high-altitude regions, providing valuable insights for conservation strategies and sustainable resource management.

KEYWORDS: Land use, Vegetation, Treeline, Livelihood, Grassland, Resource, Management, Conservation

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INTRODUCTION

Climate change and human activities have significantly altered mountain ecosystems worldwide, particularly affecting vegetation patterns and land use dynamics (Rawat & Schickhoff 2022). Land use and land cover (LULC) are changing in the Himalayan region, which has a major effect on the local landscape. Examining how the landscape has altered over the last several decades shows important trends that shed light on how ecological conditions and biophysical markers have evolved (Flantua et al. 2007). Changes in vegetation migration to higher altitudes indicate warming temperature conditions in the region, leading to changes in vegetation composition and biodiversity (Grace et al. 2002; Holtmeier and Broll 2005; Holtmeier and Broll 2007; Harsch et al. 2009; Harsch et al. 2011; Holtmeier and Broll 2012). Trees and plant species that previously thrived at lower elevations have established themselves at higher altitudes (Kullman 2001; Liu et al. 2002; Jobbagy and Jackson 2003; Payette 2007). The altered landscape affects resource availability for both ecosystems and humans in the region. These ecological changes have direct socio-economic implications for the dependent population (Bagchi et al. 2004; Hansen et al. 2008). Local traditions are particularly impacted (Kumar et. al. 2025). The livelihoods of pastoral communities may be affected if grazing patterns need to change in response to shifts in vegetation and water supplies (Mishra 2001).

Worldwide, changing climates and land use practices are causing forests to encroach more into grasslands, reducing biodiversity, and altering ecosystem functions and services. Such alterations affect the socio-economic conditions of the people involved (Schickhoff et al. 2005). Higher altitudes, being more sensitive to changes, are experiencing rapid shifts. Himalayan ecosystems are particularly vulnerable to climate-induced vegetation changes. Shrubs and other vegetation are moving upwards in mountain regions. Forests encroaching into alpine meadows lead to changes in land cover and fragmentation of alpine habitats (Anderson et al. 2020). The rich biodiversity of the Himalayas helps to support local people's livelihoods through their reliance on resources from the natural ecosystem (Joshi and Negi 2011). The local community's livelihood depends mainly on traditional practices related to livestock and farming (Lefroy et al. 2000; Von Wiren-Lehr 2001). Any land-use change in forests or nearby ecotones will affect forestry, pastoralism, agriculture, livestock, Non-Timber Forest Products (NTFPs), livelihood services, and biodiversity. Land use and land-cover changes directly or indirectly influence the natural landscape, which in turn affects the services provided by the ecosystem (Quéttier et al. 2007). However, in the Himalayan states, livestock density and pastoralism are declining in many areas, which allows vegetation to move upslope in some regions (Suwal et al. 2016). These changes will significantly impact the livelihoods of forest-dependent communities. Climate change has a profound effect on vegetation growth. Therefore, the role of climate in changing the vegetation structure of any region cannot be ignored (Duffy et al. 2015). Vegetation growth is encouraged by warm climatic conditions. Higher elevations that previously lacked vegetation will develop growth and regeneration due to favourable and suitable conditions (Payette et al. 2007; Pepin et al. 2015). Globally, meta-analyses of treelines have shown that treelines in most regions are advancing poleward or upwards. Thus, regional responses of treelines can be linked to changing local or regional elements that influence treeline positions. An upward shift of vegetation has been observed in about 52% of studies worldwide (Harsch et al. 2009). Studies along the treeline ecotone in the western Himalayas indicate both an increase and a decrease in vegetation along the treeline zone (Rai et al. 2012). A common method for monitoring vegetation shifts involves analysing remotely sensed data (Purekhovsky et al. 2025).

Remote sensing helps to overcome the difficulties posed by direct observation in poorly accessible terrain. Remote sensing investigations indicated an upward shift of the treeline up to 388 m in Uttarakhand between 1970 and 2006 (Singh et al. 2012). The shift in altitudinal structure and change in vegetation has been attempted in the western Himalayas based on remote sensing tools (Singh et al. 2012; Sah et al. 2023). However, the lack of methodological errors and sufficient ground observation verification made these studies less accepted. Recent studies have documented significant land use and land cover (LULC) changes across Uttarakhand (Singh and Singh, 1987). The Garhwal Himalayan region has experienced substantial forest fragmentation, with the loss of forest cover and the loss of grassland cover in the Rudraprayag district (Forest Survey of India, 2019). Studies have documented shifts of 23-998 m in species' upper elevation limits and a mean upward displacement rate of 27.53±22.04 m/decade in Himalayan ecosystems (Rana et al. 2019). Key species exhibiting these elevational shifts include Abies spectabilis, Betula utilis, and Rhododendron campanulatum (Rawal et al. 2025). More temperature-sensitive functional groups, such as dwarf shrubs, herbs, grasses, bryophytes, and lichens in the Himalayas, have migrated northwards to cooler climates (Rana et al. 2019). It is essential to comprehend these interrelated changes to create plans to lessen the negative effects of these changes, guarantee sustainable livelihoods, and preserve the ecosystem. The land use and land cover patterns in high-altitude regions have changed significantly, and this is especially evident in the Himalayan region. The Chamoli district presents a unique case study for understanding these dynamics with its diverse elevation gradient range. The changes at various altitudes limit the quantity and quality of forage, which directly impacts land use practices and local livelihoods (Tasser and Tappeiner, 2002). This study examines four decades (1983-2023) of land use and land cover changes in Chamoli, focusing particularly on tree cover and grassland dynamics. The research aims to quantify these changes across different elevation zones.

Study Area

Chamoli district is in the Garhwal Himalayas of Uttarakhand, India. It is a high-altitude mountainous area known for its varied topography, rich biodiversity, and ecological importance. The district is located between 30°05'N to 31°25'N latitudes and 79°10'E to 80°30'E longitudes. It covers an area of approximately 8,030 km^2. The terrain features steep slopes, deep valleys, and high-altitude meadows (Bugyals). Elevations range from 800 m to over 7,800 m, including peaks such as Nanda Devi (7,816 m). Chamoli has a temperate to alpine climate. The lower valleys receive moderate rainfall during monsoons, while higher elevations experience heavy snowfall in winter. The region is home to treeline ecotones, where the transition between subalpine forests and alpine meadows takes place. Major vegetation types include oak, rhododendron, and coniferous forests at lower altitudes, which gradually change to alpine grasslands. Chamoli is ecologically vital, shown by its diverse land use types. Chamoli is a critical site for studying treeline shifts, meadow dynamics, and ecological responses to climate change.

Methodology

The study uses a combination of remote sensing and GIS techniques to analyse changes in land use and land cover, vegetation density patterns, and treeline and grassland cover over time. Multi-temporal satellite images from 1983, 1993, 2003, 2013, and 2023 were used to detect changes in vegetation cover, grasslands, and treelines. Digital Elevation Model (DEM) data is also used to extract topographic parameters such as elevation. DEM processing and GIS-based spatial analysis help in understanding terrain characteristics that influence vegetation and land cover dynamics. To ensure consistency and accuracy in data analysis, satellite images were pre-processed, including stacking, mosaicking, and clipping, based on the study area. A pixel-based classification method, the Spectral Angle Mapper (SAM), is applied to classify different land cover types. Various research indices are employed to assess vegetation health and landscape changes. The Normalised Difference Vegetation Index (NDVI) was used to evaluate vegetation density. Additionally, the Soil-Adjusted Vegetation Index (SAVI) was computed to further assess vegetation conditions. Land use and land cover classification was performed to differentiate between grasslands, forests, and other landscape features. Vegetation positions in each period were identified using image classification algorithms. Spatial interpolation was conducted to estimate vegetation positions between observed points. GIS techniques were used to overlay vegetation data with other spatial datasets such as land use, land cover, and topography. Grassland and treeline positions were extracted using classification results. The spatial and temporal distribution and shifting trends of meadows and treelines over different periods were analysed. Digital elevation models were obtained to analyse elevation-related factors affecting vegetation dynamics. The methodological framework can be seen in Figure 2 below.

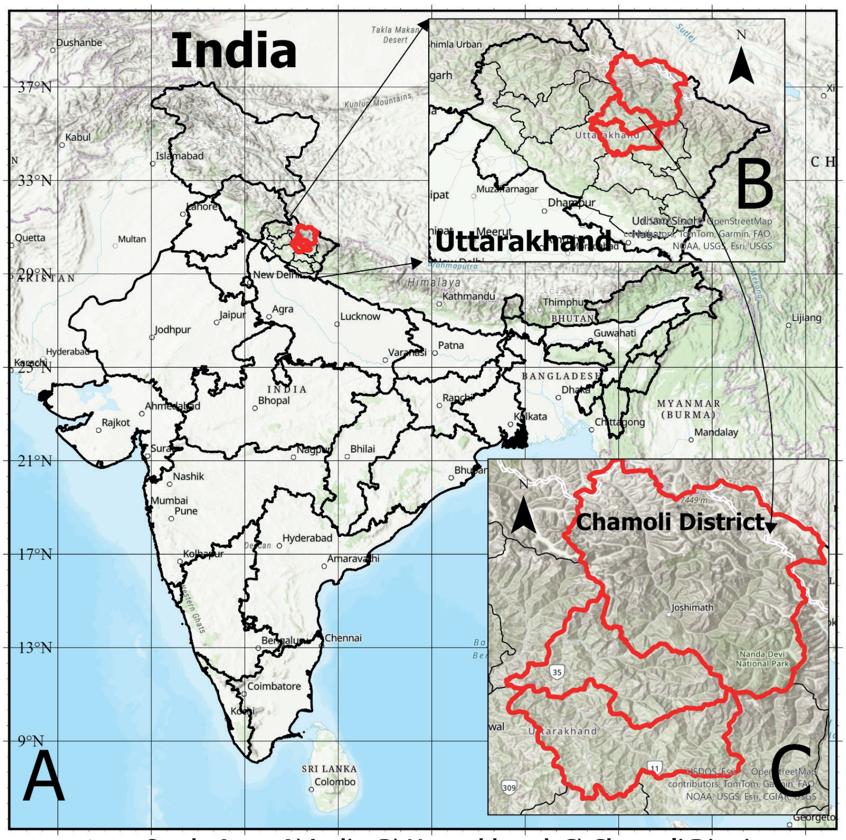

Fig. 1. Study Area, A) India, B) Uttarakhand, C) Chamoli District

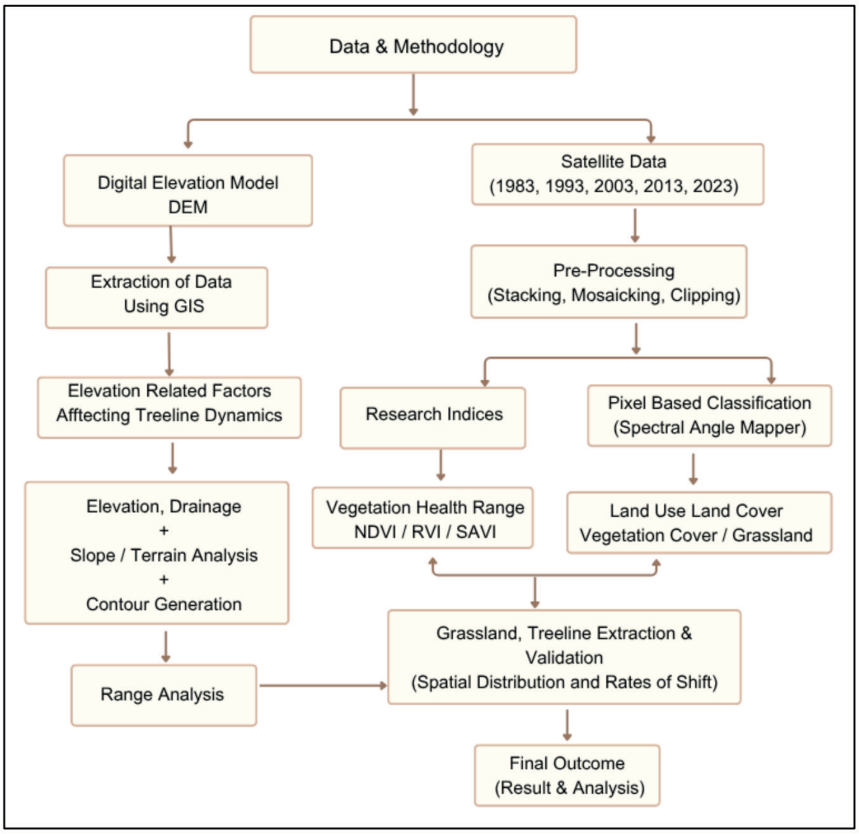

Fig. 2. Methodological Framework

Methods for assessing the quality of the classification

To ensure the reliability and accuracy of the LULC classification results, a comprehensive accuracy assessment was performed. The assessment process followed standard remote sensing classification evaluation protocols to provide a thorough evaluation of classification performance. Reference data for accuracy assessment were collected through a combination of high-resolution satellite imagery interpretation, field surveys, and existing land cover databases. Ground truth points were systematically distributed across the study area using a stratified random sampling approach to ensure representative coverage of all land cover classes, including agricultural land, tree cover, grasslands, built-up areas, snow cover, water bodies, and bare land. Reference points were selected based on the number of land cover classes.

Error Matrix Construction

The accuracy assessment was conducted using confusion matrices for each temporal period (1983, 1993, 2003, 2013, and 2023). The error matrix is a square array where rows represent reference data (ground truth) and columns represent classified data. This matrix provides the basis for calculating various accuracy metrics by comparing classified pixels with their corresponding reference classifications on a class-by-class basis.

Accuracy Metrics Calculation

Quantitative accuracy measures were derived from the error matrices. Overall Accuracy was calculated as the percentage of correctly classified pixels relative to the total reference pixels, providing a general measure of classification performance. Producer's Accuracy, computed for each class, represents the probability that reference pixels are correctly classified, while User's Accuracy indicates the likelihood that pixels assigned to a class truly belong to it. The Kappa Coefficient, ranging from 0 to 1, was employed to evaluate the agreement between classified and reference data beyond chance, with values approaching 1 denoting higher accuracy.

Results and Discussion

Temporal Changes and Deviation in LULC

Over the past four decades, land-use and land-cover changes reveal critical environmental and socio-economic dynamics (Table 1). Temporal analysis shows that tree cover fluctuated significantly. It initially increased from 224,027 hectares in 1983 to 346,453 hectares in 2003, reflecting successful reforestation and natural regeneration efforts. However, this was followed by a decline to 273,528 hectares in 2013. By 2023, tree cover had partially recovered to 323,554 hectares, showing renewed conservation efforts (an increase of 44.43 percent). Grassland areas have varied over the past 40 years. The area increased from 93,647 hectares in 1983 to 120,103 hectares in 1993, followed by a decline to 78,081 hectares in 2003. By 2013, grassland areas had expanded significantly to 199,293 hectares, but then decreased again to 118,330 hectares in 2023 (an overall increase of 26.36 percent). These fluctuations can be attributed to changes in agricultural practices, grazing pressure, and land management policies. Agricultural land saw an increase from 12,300 hectares in 1983 to 20,147 hectares in 1993. This was followed by a gradual decline to 16,148 hectares in 2013. By 2023, agricultural land had slightly recovered to 17,050 hectares (an increase of 38.62 percent). These changes reflect shifts in land use due to urbanisation, land degradation, and possibly changes in agricultural practices. Built-up areas have expanded dramatically, indicating urbanisation and infrastructure development. From 216 hectares in 1983, the area of built-up land increased to 9,349 hectares by 2023. This growth corresponds to population increases, economic development, and the expansion of urban areas. It highlights the socio-economic transformation in the district. Water bodies have experienced minor fluctuations over the decades. Starting at 2,985 hectares in 1983, the area stabilised around 2,917 hectares by 2023. These slight variations suggest natural changes in water levels influenced by climate conditions, human consumption, and water management practices. The area of barren land has increased substantially, rising from 69,784 hectares in 1983 to an alarming 209,677 hectares in 2023 (an increase of 200.47 percent). This increase indicates severe land degradation, likely due to deforestation, soil erosion, and possibly the abandonment of agricultural lands.

The dramatic rise in barren land highlights the urgent need for sustainable land management practices. Snow cover has significantly declined over the past four decades, from 377,885 hectares in 1983 to just 99,606 hectares in 2023, a drastic decrease of 63.64 percent. This reduction highlights the impact of warming trends, which have resulted in decreased snowfall and accelerated glacial melting. The sharp decrease between 2013 and 2023 shows the severity of climate change effects on high-altitude ecosystems. A temporal analysis of Chamoli district's landscape over 40 years reveals critical environmental challenges and socio-economic developments. This change is a particularly concerning point regarding environmental degradation and the impact of climate change. Fluctuations in tree cover and grassland areas highlight the dynamic nature of ecological responses to a changing climate. The temporal analysis of land use and land cover over the last four decades reveals notable trends and shifts. Water bodies, with slight fluctuations, showed a decrease of 2.28 percent. Barren land has seen a dramatic increase of 200.47 percent. Tree cover has increased by 44.43 percent. Built-up areas have expanded tremendously by 4228.35 percent. Grassland areas have experienced varying trends with an overall increase of 26.36 percent. Snow cover has dramatically decreased by 73.64 percent. Agricultural land has increased by 38.62 percent.

Figure 3 shows the spatial distribution of land cover changes across five temporal periods in the study area (1983-2023). The multi-temporal analysis reveals distinct patterns of vegetation dynamics. These maps demonstrate

Table 1. Land Use/Land Cover percentage change, 1983-2023

LULC Classes	Area in Hectares					LULC Change (Percentage)				
	1983	1993	2003	2013	2023	1983-1993	1993-2003	2003-2013	2013-2023	1983-2023
Water bodies	2,985	3,015	3,056	2,668	2,917	1.01	1.35	-12.68	9.32	-2.28
Barren Land	69,784	1,00,912	91,845	1,17,622	2,09,677	44.61	-8.99	28.07	78.26	200.47
Tree Cover	2,24,027	2,86,714	3,46,453	2,73,528	3,23,554	27.98	20.84	-21.05	18.29	44.43
Built-up Areas	216	483	464	5,691	9,349	123.61	-3.84	1,125.29	64.28	4,228.35
Grassland	93,647	1,20,133	78,081	1,99,293	1,18,330	28.25	-34.99	155.24	-40.63	26.36
Snow Cover	3,77,885	2,49,255	2,39,413	1,66,976	99,606	-34.04	-3.95	-30.26	-40.35	-73.64
Agricultural Land	12,300	20,147	19,616	16,148	17,050	63.8	-2.63	-17.68	5.58	38.62

the temporal evolution of landscape patterns and potential land use transformations within the defined geographic boundary.

Elevation-Based Changes

The analysis based on elevation shows that several land cover types, including tree cover, grasslands, snow cover, water bodies, barren land, built-up areas, and agricultural land, have changed (Table 2). At an elevation of 683–2051 metres in 1983, grasslands covered 28,105 hectares, while tree cover was 91,268 hectares. By 1993, grasslands had reduced significantly to 12,316 hectares, and tree cover increased to 107,170 hectares. This trend continued in 2003, with grasslands slightly recovering to 13,430 hectares and tree cover reaching its highest at 126,178 hectares. In 2013, grasslands surged to 38,351 hectares, possibly due to conservation efforts or reduced agricultural pressure. However, they decreased again to 24,135 hectares in 2023. Built-up areas increased substantially from 216 hectares in 1983 to 7,763 hectares in 2023, reflecting urban expansion. Water bodies and barren land remained relatively stable with minor changes. At 2052–3053 metres elevation, grasslands increased from 22,831 hectares in 1983 to a peak of 52,801 hectares in 2013 before declining to 38,596 hectares in 2023. Tree cover followed a different pattern, increasing significantly from 111,228 hectares in 1983 to 142,469 hectares in 2003, then stabilising around 128,104 hectares by 2023. Barren land fluctuated considerably, with a slight increase in 1993 and a rapid increase by 2023. Built-up areas saw a gradual increase from 1993, indicating the spread of human settlements. Agricultural land fluctuated but generally remained at lower levels compared to other land cover classes. At the elevation of 3054–4159 metres, grassland cover showed notable variations. It initially increased to 56,752 hectares in 1993, decreased to 45,470 hectares in 2003, and then rose to 48,655 hectares by 2023. Tree cover showed substantial growth from 21,229 hectares in 1983 to 70,282 hectares in 2003, stabilising around 55,860 hectares in 2023. Snow cover and barren land also fluctuated, with significant decreases in snow cover by 2023.

Built-up areas and agricultural land remained minimal, reflecting the harsh conditions and limited human activity at these elevations. Furthermore, at the 4150–5152 metre elevation range, grasslands experienced significant changes, increasing dramatically to 37,174 hectares in 1993 and decreasing to 16,940 hectares by 2023. Tree cover increased from 11,147 hectares in 1983 to 16,190 hectares in 2023. Barren land and snow cover also saw significant fluctuations, with snow cover decreasing sharply by 2023. Built-up areas remained negligible, while agricultural land saw slight increases. The highest elevation range showed minimal grassland cover throughout the decades, peaking at 302 hectares in 1993 and minor growth by 2023. Snow cover remained dominant but decreased significantly from 155,069 hectares in 1983 to 80,374 hectares in 2023. There were no built-up area and agricultural land remained absent, reflecting the extreme environmental conditions. The 3054–4149 metre elevation range witnessed the most significant changes, particularly in tree cover and grasslands. Grasslands increased initially but saw substantial

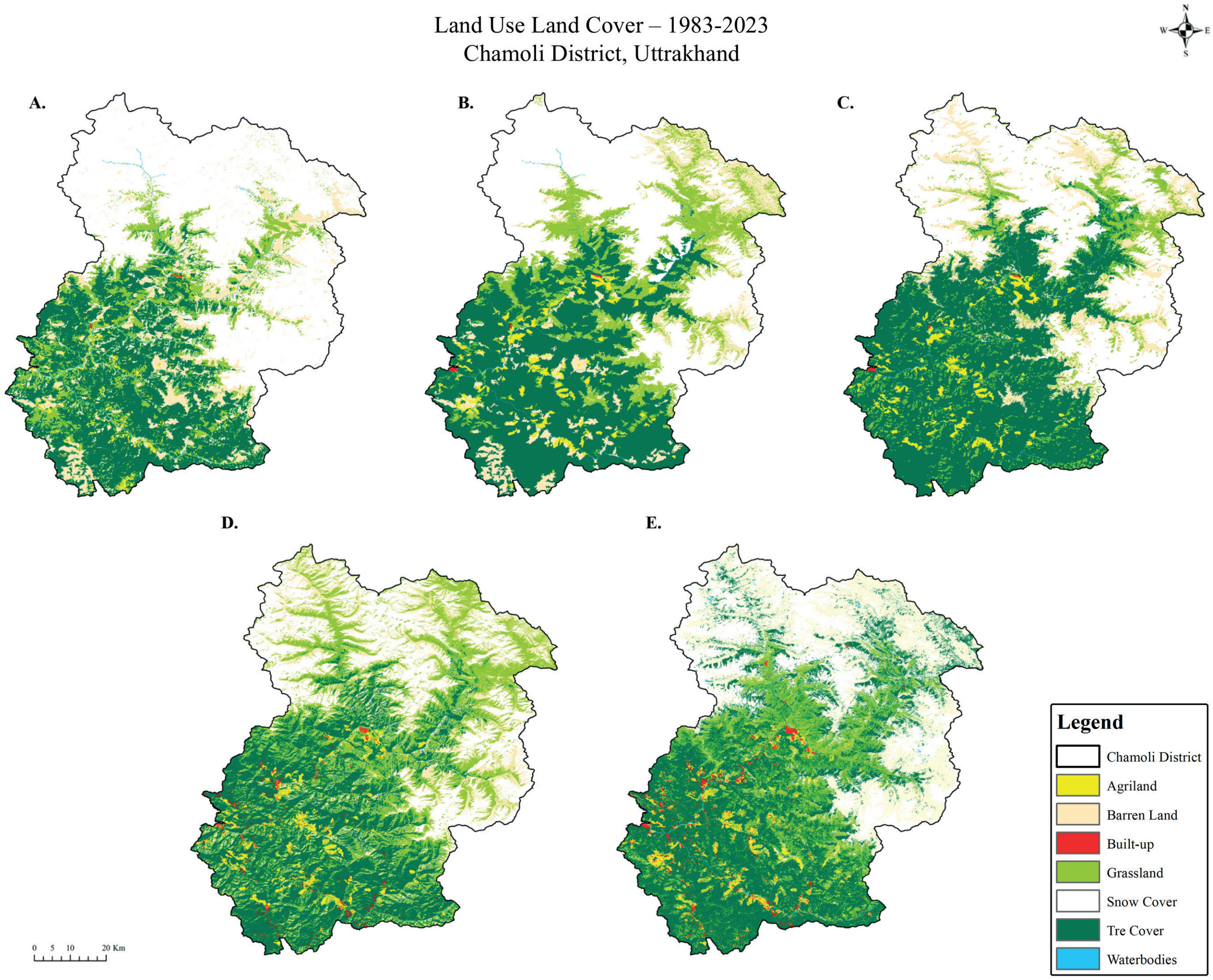

Fig. 3. LULC of Chamoli District: a) 1983, b) 1993, c) 2003, d) 2013 and e) 2023

fluctuations, while tree cover showed considerable growth and stabilisation trends. Snow cover decreased drastically. The analysis reveals that lower elevations have seen significant urbanisation and agricultural activities, while mid to higher elevations have experienced changes in grassland and tree cover, reflecting both natural and anthropogenic influences over the decades.

The changes are visible in high-altitude regions, particularly from elevations above 3000m. Between 3054m and 5152m, both tree cover and grasslands increased significantly in the last four decades. This indicates positive changes in vegetation cover, suggesting climate change impacts and shifts towards higher altitudes. Figure 4 below provides a comprehensive understanding of the prevailing scenario.

LULC Classification Assessment Results

The classification accuracy assessment across 1983, 1993, 2003, 2013, and 2023 demonstrated a steady improvement in reliability. In 1983, the classification achieved an overall accuracy of 82.34% with a Kappa coefficient of 0.79. By 1993, the overall accuracy increased to 85.39% with a Kappa of 0.82. In 2003, the overall accuracy further improved to 88.36% with a Kappa of 0.85. The 2013 classification showed a substantial increase, with an overall accuracy of 91.02% and a Kappa of 0.89. The highest accuracy was recorded in 2023, with an overall accuracy of 93.21% and a Kappa of 0.91. Overall, the results indicate a clear improvement in classification performance over four decades.

Spatio-Temporal Dynamics of Tree Cover

The spatio-temporal analysis of tree cover distribution across different elevation zones was conducted (Table 3). It revealed significant variations over the 40 years from 1983 to 2023. In the lowest elevation zone (683-2052m), tree cover expanded from 91,268 hectares in 1983 to peak at 126,178 hectares in 2003, followed by a slight decline to 116,793 hectares by 2023. The mid-elevation zone (2052-3053m) showed the most substantial tree cover,

Table 2. Elevation-based changes (1983–2023)

Elevation (meters)	Year	Water	Barren	Tree- Cover	Built-up	Grassland	Snow	Agriculture
683 - 2051	1983	2140	18911	91268	216	28105	0	10588
	1993	2184	23384	107170	477	12316	0	15171
	2003	1984	800	126178	463	13430	0	14590
	2013	797	7766	103758	4830	38351	0	12226
	2023	1493	3105	108528	7763	24135	0	12653
2052 -3053	1983	443	14535	111228	107	22831	0	1673
	1993	430	7729	132847	238	13461	0	4816
	2003	443	1701	142469	311	27596	0	4417
	2013	185	12331	111709	834	52801	0	3534
	2023	284	3445	128104	1321	38596	0	2610
3054 - 4149	1983	276	26718	21229	33	37765	40491	139
	1993	277	15319	44361	53	56752	19612	151
	2003	315	27897	70282	127	35470	5668	610
	2013	257	18731	52131	148	65868	2367	1389
	2023	373	21569	55860	187	48655	1130	1726
4150 - 5152	1983	117	7789	11147	27	14697	166415	0
	1993	123	42123	11623	38	37174	97604	0
	2003	113	49519	7307	47	11268	93820	0
	2013	132	47273	13737	59	41877	59800	0
	2023	289	109115	16190	78	16940	18092	0
5153 - 7801	1983	0	1813	66	0	228	155069	0
	1993	0	12275	48	0	302	140441	0
	2003	0	11910	31	0	276	139788	0
	2013	0	31514	42	0	251	104674	0
	2023	379	72442	71	0	103	80374	0

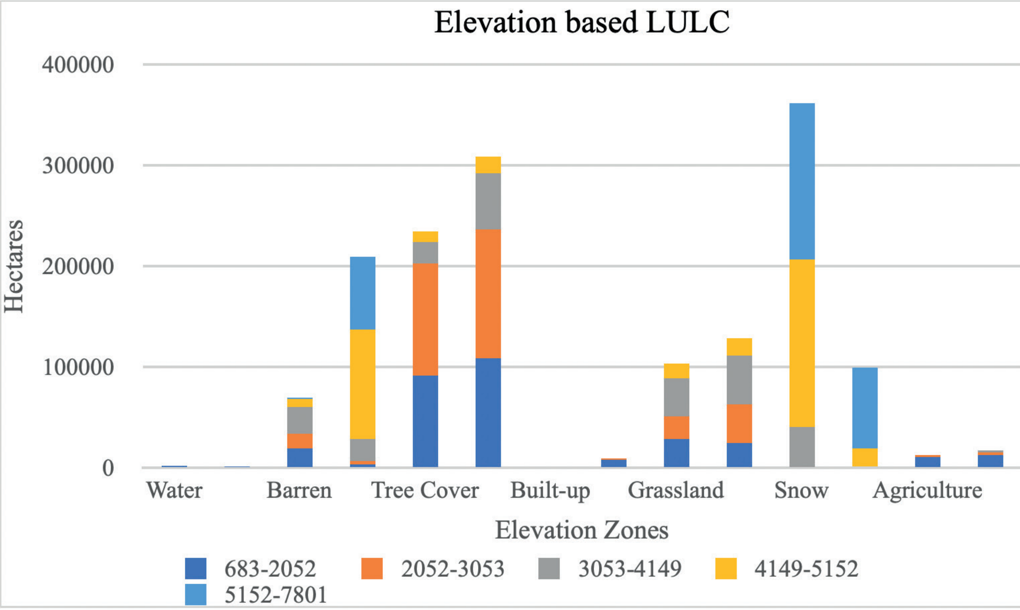

Fig. 4. Elevation-based changes in land-use patterns, 1983 and 2023

increasing from 111,228 hectares in 1983 to a maximum of 142,468 hectares in 2003, before stabilising around 115,942 hectares in 2023. Notable changes occurred in higher elevations, particularly in the 3053-4149m range, where tree cover more than tripled from 21,229 hectares in 1983 to 70,281 hectares in 2003, though moderating to 52,967 hectares by 2023. The most dramatic transformation was observed in the 4149-5152m zone, with tree cover expanding from merely 147 hectares in 1983 to 44,189 hectares by 2023, indicating significant upward treeline migration. The highest elevation zone (5152-7801m) also experienced notable changes, from 66 hectares in 1983 to 3,870 hectares in 2023, suggesting potential climate-driven vegetation responses at extreme altitudes.

Figure 5 shows how tree cover has changed in the area between 1983 and 2023. The different colours on the map indicate the spatial changes over these years.

Temporal Dynamics of Grasslands

The distribution of grassland across different elevations in the district was analysed. The analysis revealed significant changes in grassland distribution over time and across various altitudes (Table 4). At lower elevations (683-2052 metres), the grassland area decreased from 28,105 hectares in 1983 to 12,316 hectares in 1993. This decline is likely due to human activities such as agriculture, urbanisation, and other development. However, grassland cover substantially recovered by 2013, reaching 38,351.36 hectares. This was followed by a reduction to 24,134.64 hectares of grassland in 2023, showing a 14 percent decrease over 40 years. This suggests continued pressure from human activity or other environmental changes. Grassland cover followed a similar pattern in the mid-elevation range (2052-3053 metres). It decreased from 22,831 hectares in 1983 to 13,461 hectares in 1993, and then increased to 52,800.87 hectares by 2013. It decreased again to 38,595.93 hectares in 2023, representing a 69 percent increase. These fluctuations indicate a dynamic interaction between human land use and natural processes, with periods of both recovery and decline influenced by grazing practices, forestry activities, and climatic factors. Higher elevations (3053-4149 metres) showed considerable variation, with an increase in grassland area from 37,765 hectares in 1983 to 56,752 hectares in 1993. This was followed by a decrease to 25,469.78 hectares in 2003. Grassland cover expanded significantly to 65,868.20 hectares by 2013 and declined to 48,654.96 hectares in 2023, a 29 percent decrease. These changes reflect the impact of climate change, human-environment relationships, and grazing pressures on the extent of grasslands at these altitudes.

In the highest elevation ranges (4149-5152 metres and 5152-7801 metres), grassland areas showed extreme volatility. The grassland cover increased significantly in 1993 but decreased considerably in subsequent years. By 2023, only 16,939.94 hectares remained in the 4149–5152-metre range, representing an 18 percent increase from the 1983 period. At the 5152–7801-metre range, there was a drastic

Table 3. Elevation-wise Area of Tree Cover (in hectares)

Elevation Wise Area of Tree Cover (In Hec.)					
Elevation (in m)	1983	1993	2003	2013	2023
	Tree Cover	Tree Cover	Tree Cover	Tree Cover	Tree Cover
683-2052	91268	107170	126178.35	116175.42	116793.72
2052-3053	111228	132847	142468.52	115253.22	115942.00
3053-4149	21229	44361	70281.71	52520.22	52967.29
4149-5152	147	1623	7306.70	5736.95	44189.70
5152-7801	66	1.3	31.38	1.75	3870.85

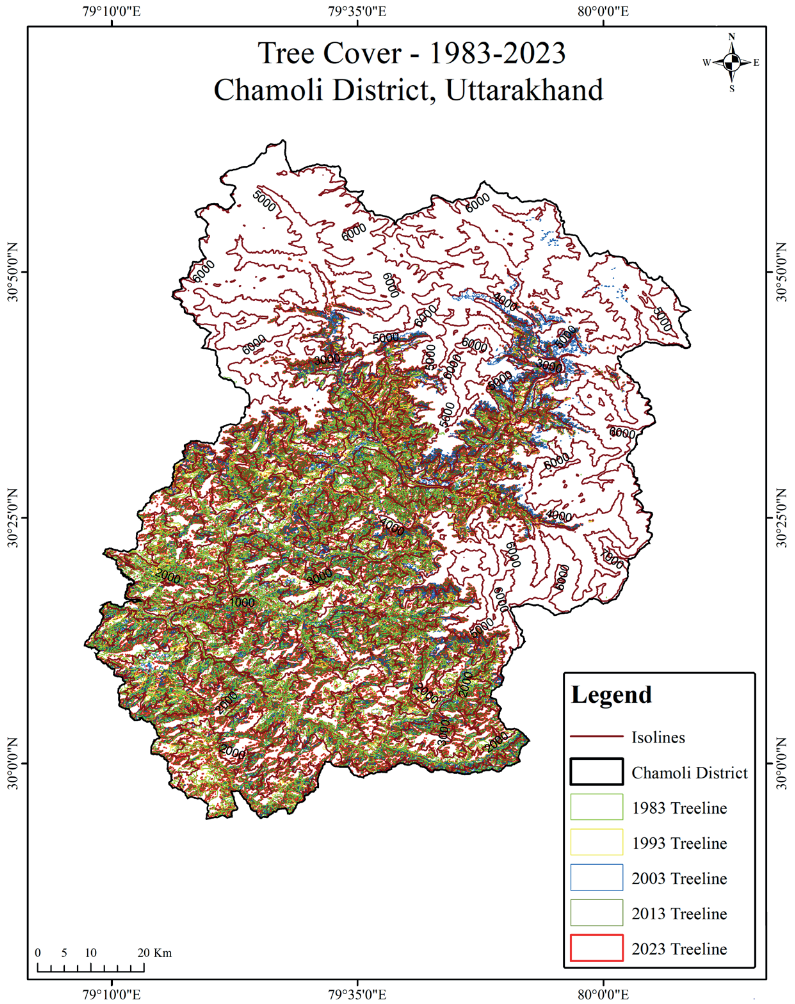

Fig. 5. Tree cover and pattern, Chamoli district

Table 4. Elevation-wise area of grassland (in hectares).

Area of Grassland Based on Elevation (in Ha.)						
Sr. No.	Elevation (in m)	1983	1993	2003	2013	2023
1	683-2052	28105	12316	13429.86	38351.36	24134.64
2	2052-3053	22831	13461	27595.86	52800.87	38595.93
3	3053-4149	37765	56752	35469.78	65868.20	48654.96
4	4149-5152	14697	37174	11268.36	31877.32	16939.94
5	5152-7801	228	302	276.30	250.99	103.27

reduction to 103.27 hectares. These trends suggest that harsh climatic conditions and land-use changes, such as grazing and environmental degradation, have severely impacted these higher altitude grasslands, making them less sustainable over time. The overall trends reflect how conservation efforts, agricultural practices, and climatic changes have shaped grassland distribution over four decades. The data suggest that lower and middle elevations have seen more significant human impact, whereas higher elevations show more resilience to change but still experience fluctuations due to environmental conditions. (A detailed examination of vegetation density can be seen in Appendix B, Table 1 and Figure 1). The trend of grasslands shifting upwards in elevation can be seen in the map below (Fig. 6) from 1983 to 2023. This upward migration can be observed through the changing colour patterns across the district. Each colour on the map corresponds to grassland elevation in different decades, indicating the distribution and movement of grasslands. In 1983, grasslands were primarily concentrated in lower and mid-elevation regions. However, over the years, a noticeable upward shift in grassland cover can be observed. In the earlier years, grasslands were more extensive at lower elevations, as shown by the significant green areas in the lower and central parts of the district in 1983. Over the decades, there has been a clear trend of grasslands receding from these lower regions, with a corresponding increase in grassland areas at higher altitudes. The yellow areas (representing 1993) and the orange areas (representing 2003) show a gradual migration of grasslands towards higher elevations. By 2013, as shown by the light blue areas, grasslands continued to extend further up, occupying regions that were previously not covered by grasslands. The most recent decade, 2023, represented by the red areas, shows a prominent presence of grasslands at the highest elevations.

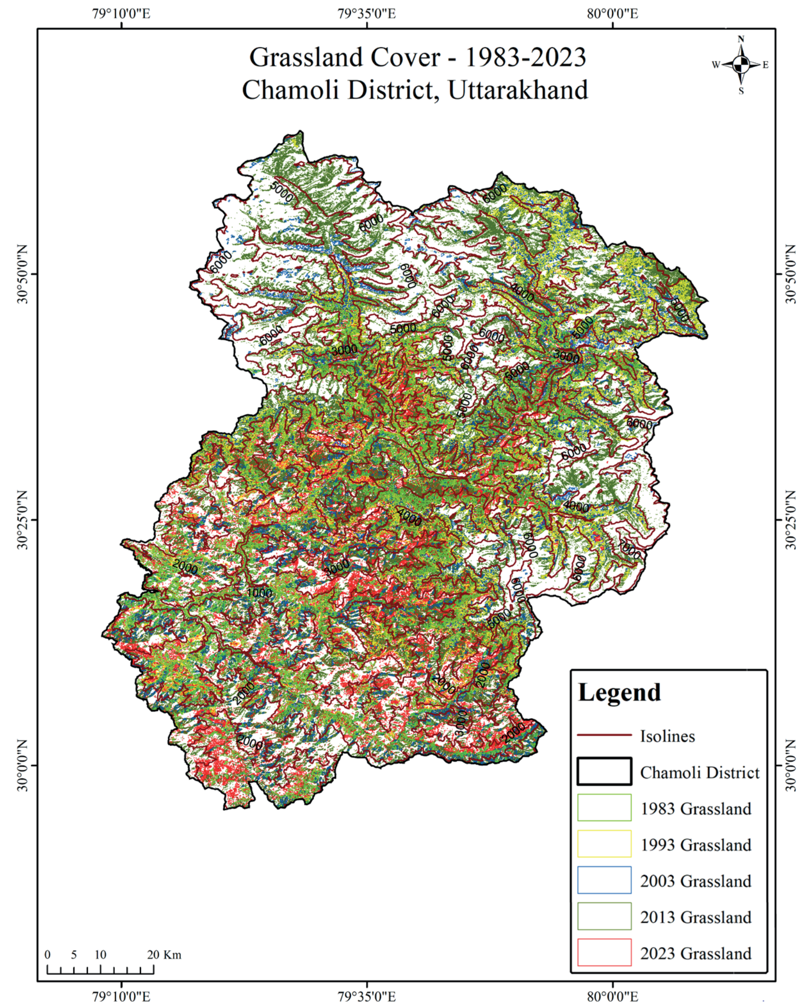

Fig. 6. Temporal trend of grasslands, 1983–2023

This trend highlights how grasslands have progressively moved from lower to higher altitudes over the past four decades. This shift can be attributed to various factors, including climate change, which has altered temperature and precipitation patterns, making lower elevations less suitable for grasslands. Additionally, increased human activities such as agriculture and urbanisation at lower elevations have contributed to this upward movement, pushing grasslands to higher altitudes where conditions are more favourable for their growth. A clear pattern can be seen with grasslands adapting to changing environmental conditions by shifting upwards over the years.

DISCUSSION

Land use and land cover patterns in high-altitude regions have changed significantly (Rawat and Schickhoff 2022). One of the critical influences of these changes is on tree cover and grasslands. The four-decade analysis of LULC changes in the district reveals complex spatio-temporal dynamics with significant implications for mountain ecosystems and local communities. Our findings demonstrate a paradoxical landscape transformation characterised by simultaneous forest recovery and environmental degradation. The substantial increase in tree cover over the study period, particularly at higher elevations, aligns with observations by Kumar and Khanduri (2024), who documented upward shifts in vegetation zones across the Himalayan region. The fluctuating patterns of tree cover, with initial increases followed by periods of decline and partial recovery, align with findings from other Himalayan regions where conservation efforts have competed with development pressures. Similar to observations by Rawat and Schickhoff (2022), who documented complex vegetation dynamics in high-altitude Himalayan ecosystems, our study found that tree cover increased by 44.43 percent over the study period. This indicates some success in reforestation initiatives despite intervening challenges.

These findings also support Tewari et al. (2017) and Walia et al. (2025) conclusion that Himalayan forests experience cyclic patterns of degradation and regeneration influenced by both natural processes and management interventions. The dramatic expansion of tree cover in the 4149–5152 m elevation zone (from 147 to 44,189 hectares) represents clear evidence of treeline advancement, consistent with Harsch et al.'s (2009) global meta-analysis of treeline responses to climate warming. This also corresponds with Schickhoff et al. (2015), who documented treeline shifts in response to warming trends across the Himalayas. The increased vegetation at extreme altitudes suggests a warming-induced habitat expansion for tree species, consistent with global observations of upslope migration of plant communities (Lenoir et al. 2008). However, this must be viewed alongside concerning degradation trends. The 200.47 percent increase in barren land and the 73.64 percent decrease in snow cover indicate severe environmental stress in the region. These findings point towards Immerzeel et al. (2020) research highlighting accelerated glacial retreat across the Hindu Kush Himalaya, with profound implications for water security and ecosystem stability. The reduction in snow cover is particularly alarming as it threatens the hydrological regime that supports downstream communities and ecosystems (Bolch et al. 2019). The fluctuating patterns of grassland distribution across elevation gradients (with overall increases of 26.36 percent) reflect a dynamic interplay between climate forcing and anthropogenic pressures. This supports Tasser and Tappeiner's (2002) findings that mountain grasslands undergo complex transitions influenced by both land management practices and environmental changes. The upward shift of grasslands observed in our study is similar to the findings of Parmesan and Yohe (2003), who documented elevation shifts in numerous plant species globally in response to warming. The fluctuating grassland coverage, with overall increases at mid-elevations but volatility at higher elevations, has also been documented by Suwal et al. (2016), who documented elevation-dependent responses of alpine vegetation to climate change. These grassland shifts directly impact traditional pastoral livelihoods, as noted by Kassahun et al. (2008), who documented how changing vegetation patterns disrupt transhumance practices.

The dramatic expansion of built-up areas, by 4228.35 percent, represents the most striking anthropogenic transformation. This reflects the rapid urbanisation patterns observed throughout the Himalayan region by Dame et al. (2019), and Anees et al. (2021). This expansion exerts pressure on surrounding ecosystems and traditional land use systems, contributing to the fragmentation of natural habitats. These multifaceted changes have significant implications for local livelihoods, particularly for traditional pastoral communities. As noted by Bhusal and Awasthi (2024), shifting vegetation patterns disrupt transhumance practices that have sustained mountain communities for generations. The upward migration of vegetation zones forces adaptation in grazing patterns and resource use, potentially undermining traditional ecological knowledge systems (Mishra 2001). The interdependence between land use and land cover patterns has resulted in a landscape that is less supportive of traditional grazing practices, further threatening the livelihoods of communities that rely on these lands for sustenance. For sustainable management of the landscapes, integrated approaches that balance conservation with livelihood needs are essential. This requires technical interventions for land restoration and meaningful engagement with local communities. Their traditional knowledge can inform adaptive management strategies (Saxena et al. 2002). Future research should focus on investigating vegetation responses to climate change scenarios and developing adaptive management frameworks that incorporate both scientific data and traditional ecological knowledge. This integrated approach will be crucial for building resilience in mountain social-ecological systems facing rapid environmental change.

CONCLUSION

The land use and land cover of the district have changed significantly over the last few decades. Consequently, major alterations have occurred in the district's landscape and ecology. Tree cover is most prominent at lower altitudes, decreasing as altitude increases. Built-up areas and grasslands are expanding across various zones, particularly at mid-altitudes. Snow cover dominates higher altitudes, between 5153–7801 m, but has shown a declining trend in recent years. The findings suggest that tree cover has fluctuated considerably, indicating successful natural and human-driven conservation efforts. Grassland areas have also shown variability over the past 40 years. Both tree cover and grassland areas have increased in recent decades. These fluctuations in tree cover and grassland areas emphasise the dynamic nature of ecological responses. The elevation range of 3054–4149 metres experienced the most significant changes. Lower elevations have seen considerable urbanisation and agricultural development, while mid to higher elevations have undergone changes in grassland and tree cover, reflecting both natural and human influences. These changes are noticeable in high-altitude regions, especially above 3000 metres. This suggests vegetation is shifting to higher altitudes. These shifts are not uniform and vary within each elevation range. The changes are attributed to various factors, including human activities, climate change, and natural succession processes. These trends highlight the dynamic nature of changes within the district, driven by varying land management practices.

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APPENDIX A

Classification Accuracy Assessment Results

The classification accuracy for the years 1983, 1993, 2003, 2013, and 2023 was assessed using error matrices. Corresponding user's accuracy, producer's accuracy, overall accuracy, and Kappa statistics are presented in Tables 1-5. In 1983, the overall accuracy was 82.34% with a Kappa coefficient of 0.79. By 1993, classification accuracy had improved, showing an overall accuracy of 85.39% and a Kappa coefficient of 0.82. In 2003, the overall accuracy further increased to 88.95% with a Kappa of 0.85. The 2013 classification achieved an overall accuracy of 93.87% with a Kappa coefficient of 0.89. In 2023, the classification reached its highest accuracy, with an overall accuracy of 93.21% and a Kappa coefficient of 0.91. Overall, classification performance demonstrated a clear improvement over the four decades, with both overall accuracy and Kappa values increasing steadily. The early years (1983–1993) recorded relatively higher misclassifications in barren land and built-up areas, whereas later years (2013–2023) achieved much higher reliability, particularly for tree cover, snow, and water categories.

Table 1. Error Metrics for Land Cover Classification – 1983

Error Metrix for Land Cover Classification- 1983										
Reference Data	Classified Data								Total	Producers Accuracy
	Agri. Land	Barren	Built-up	Grassland	Snow	Tree Cover	Water	Total		
Agri. Land	78	6	3	8	0	2	1	98	98	79.59
Barren	7	54	5	11	4	2	0	83	83	65.06
Built-up	3	7	56	4	0	2	0	72	72	77.78
Grassland	12	8	4	118	2	1	0	145	145	81.38
Snow	0	3	0	1	52	2	0	58	58	89.66
Tree Cover	2	5	2	8	3	142	0	162	162	87.65
Water	1	1	0	1	0	0	47	50	50	94.00
Total	103	84	70	151	61	151	48	668	668	Kappa: 0.79
Users Accuracy	75.73	64.29	80.00	78.15	85.25	94.04	97.92	Overall Accuracy: 82.34		

Table 2. Error Metrics for Land Cover Classification - 1993

Error Metrix for Land Cover Classification- 1993										
Reference Data	Classified Data								Total	Producers Accuracy
	Agri. Land	Barren	Built-up	Grassland	Snow	Tree Cover	Water	Total		
Agri. Land	82	4	2	7	0	3	0	98	98	83.67
Barren	5	58	4	9	3	1	0	80	80	72.50
Built-up	2	5	61	3	0	1	0	72	72	84.72
Grassland	10	6	3	125	1	1	0	146	146	85.62
Snow	0	2	0	1	55	1	0	59	59	93.22
Tree Cover	4	4	3	6	2	148	0	167	167	88.62
Water	0	1	0	0	0	0	48	49	49	97.96
Total	103	80	73	151	61	155	48	671	671	Kappa: 0.82
Users Accuracy	79.61	72.50	83.56	82.78	90.16	95.48	100	Overall Accuracy: 85.39		

Table 3. Error Metrics for Land Cover Classification – 2003

Error Metrix for Land Cover Classification- 2003										
Reference Data	Classified Data								Total	Producers Accuracy
	Agri. Land	Barren	Built-up	Grassland	Snow	Tree Cover	Water	Total		
Agri. Land	86	3	2	5	0	2	0	98	98	87.76
Barren	4	63	3	7	2	1	0	80	80	78.75
Built-up	1	3	65	2	0	1	0	72	72	90.28
Grassland	8	5	2	130	1	0	0	146	146	89.04
Snow	0	1	0	0	57	1	0	59	59	96.61
Tree Cover	3	3	2	5	1	152	0	166	166	91.57
Water	0	1	0	0	0	0	48	49	49	97.96
Total	102	79	74	149	61	157	48	670	670	Kappa: 0.85
Users Accuracy	84.31	79.75	87.84	87.25	94.44	96.82	100	Overall Accuracy: 88.36		

Table 4. Error Metrics for Land Cover Classification – 2013

Error Metrix for Land Cover Classification- 2013										
Reference Data	Classified Data								Total	Producers Accuracy
	Agri. Land	Barren	Built-up	Grassland	Snow	Tree Cover	Water	Total		
Agri. Land	90	2	1	3	0	2	0	98	98	91.84
Barren	3	68	2	5	1	1	0	80	80	85
Built-up	1	2	67	2	0	0	0	72	72	93.06
Grassland	6	4	2	134	0	0	0	146	146	91.78
Snow	0	1	0	0	58	0	0	59	59	98.31
Tree Cover	1	1	2	4	1	155	0	164	164	94.51
Water	0	1	0	0	0	0	48	49	49	97.96
Total	101	79	74	148	60	158	48	668	668	Kappa: 0.89
Users Accuracy	89.11	86.08	90.54	90.54	96.67	98.10	100	Overall Accuracy: 91.02		

Table 5. Error Metrics for Land Cover Classification – 2023

Error Metrix for Land Cover Classification- 2023										
Reference Data	Classified Data								Total	Producers Accuracy
	Agri. Land	Barren	Built-up	Grassland	Snow	Tree Cover	Water	Total		
Agri. Land	92	3	1	2	0	0	0	98	98	93/88
Barren	3	70	2	3	1	1	0	80	80	87.50
Built-up	1	2	67	1	0	1	0	72	72	93.06
Grassland	5	4	2	134	0	1	0	146	146	91.78
Snow	0	1	0	0	57	1	0	59	59	96.61
Tree Cover	2	2	2	4	2	152	0	164	164	92.68
Water	0	1	0	0	0	0	48	49	49	97.96
Total	103	83	74	144	60	156	48	668	668	Kappa: 0.91
Users Accuracy	89.32	84,34	90.54	93.06	95	97.44	100	Overall Accuracy: 93.21		

APPENDIX B

Spatial-Temporal Changes in Vegetation Density

Vegetation density can be used to study vegetation changes, acting as an indicator of environmental conditions and ecological shifts. Figure 1 and Table 1 show a clear altitudinal gradient in vegetation density, with dense forest at lower elevations and sparse or barren areas at higher altitudes. From 1983 to 2003, the general pattern remained consistent, with dense vegetation in southern lowlands and progressively thinner vegetation towards the northern high mountains. By 2013, a decline in dense vegetation was observed in lower and mid-elevation zones. In 2023, vegetation health improved in lower zones, while higher elevations experienced reduced vegetation density. The lower zones showed resilience and recovery, whereas high-altitude regions continued to face ecological stress.

Table 1. Vegetation density and pattern, 1983–2023

Elevation	Vegetation Density (Hectares)- 1983				
	Very Low	Low	Moderate	High	Very High
683 - 2051	1605	6314	44466	64243	31167
2052 - 3053	4329	8044	20877	51127	66087
3054 - 4149	9463	45035	41914	13576	8952
4150 - 5152	15336	147827	5160	78	57
5153 - 7801	17656	129615	241	49	11
Elevation	Vegetation Density (Hectares)- 1993				
	Very Low	Low	Moderate	High	Very High
683 - 2051	486	16999	27203	51562	51546
2052 - 3053	6368	21030	20769	36357	65940
3054 - 4149	14857	28101	41171	20721	14090
4150 - 5152	41289	87824	38597	743	5
5153 - 7801	44778	98360	4981	0	0
Elevation	Vegetation Density (Hectares)- 2003				
	Very Low	Low	Moderate	High	Very High
683 - 2051	538	15591	30507	58360	42801
2052 - 3053	7865	18432	22644	38816	62707
3054 - 4149	15556	30933	41793	17120	13538
4150 - 5152	41667	107084	19379	320	6
5153 - 7801	45669	99381	3070	0	0
Elevation	Vegetation Density (Hectares)- 2013				
	Very Low	Low	Moderate	High	Very High
683 - 2051	24	20738	59729	64369	2936
2052 - 3053	0	30156	64865	53583	1859
3054 - 4149	2	47397	63112	8325	104
4150 - 5152	313	146880	21264	0	0
5153 - 7801	1753	145789	580	0	0
Elevation	Vegetation Density (Hectares)- 2023				
	Very Low	Low	Moderate	High	Very High
683 - 2051	159.38	1799.18	16771.09	60883.38	80112.62
2052 - 3053	12.82	1798.5	29994.15	60050.16	70554.39
3054 - 4149	32.67	24928.79	71805.48	20377.86	10875.35
4150 - 5152	2954.88	148357	29518.86	148.59	0.36
5153 - 7801	5170.91	152745.5	1157.97	0.21	0.03

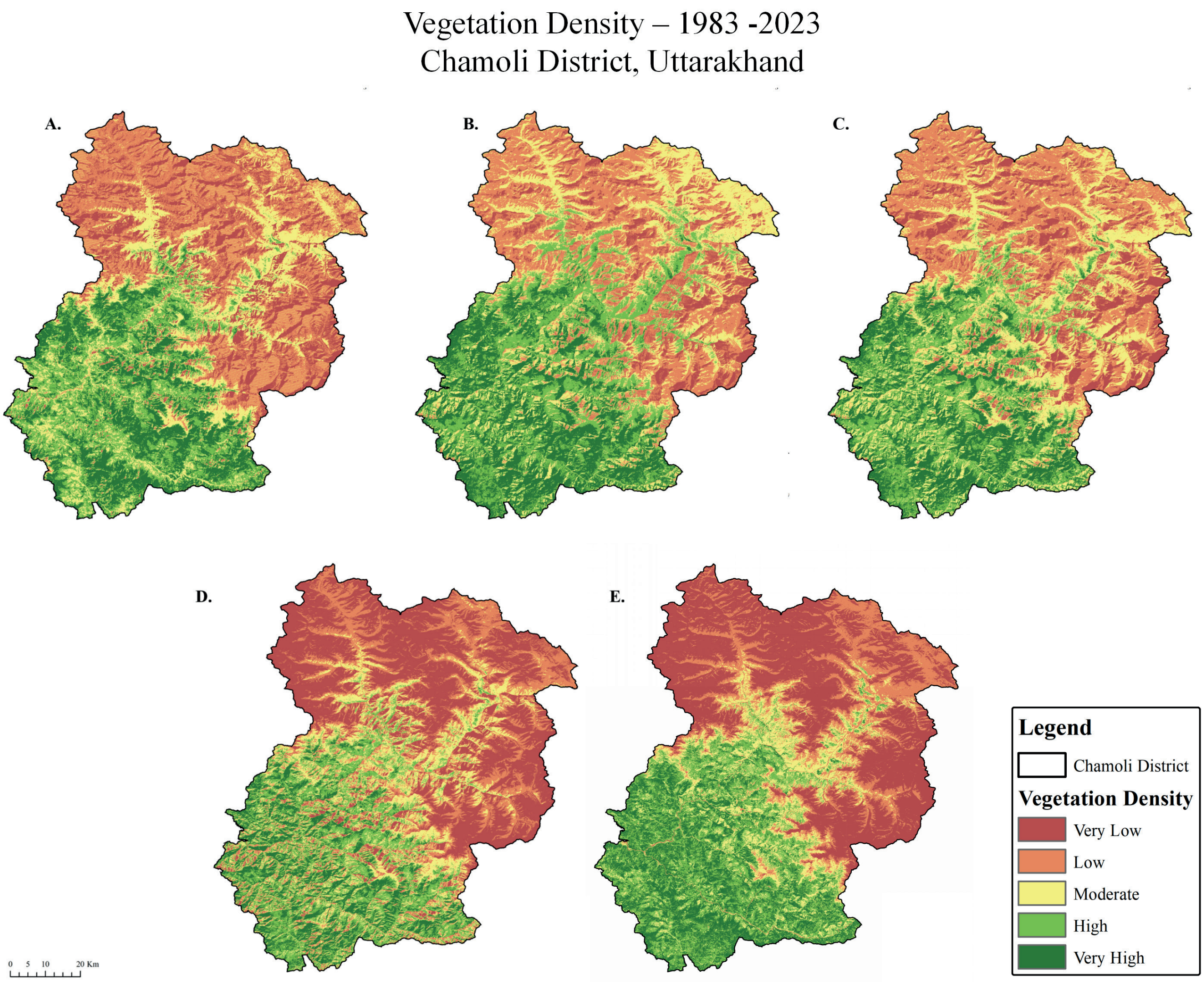

Fig. 1. Vegetation density and pattern: a) 1983, b) 1993, c) 2003, d) 2013 and e) 2023