Climate Driven Vegetation Shifts Across High-Altitude Zones for Sustainable Ecosystem Resilience of the Garhwal Himalayas over last 50 years using Multi - Temporal Remote Sensing and AI/ML techniques

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Abstract

High-altitude vegetation change dynamics are essential for unraveling the complex interrelationship between climatic variability and energy exchange processes that occur in these sensitive ecosystems. They are also important for understanding the function of vegetation cover as an essential element of global and regional climate systems. Vegetation cover change is time-specific and represents fundamental indicators of Earth system dynamics. This research is an attempt to detect and analyze vegetation cover change patterns in various altitudinal zones (3000 m and above) of the Garhwal Himalayas during the past half century from 1972–73 to 2022–23 and analyze their ecological implications for changes in every decade in between, employing multi-temporal Landsat satellite data, remote sensing, GIS, and AI/ML-based spatial analysis. Decadal and slope-wise (altitudinal) zonal analysis indicates a steep rise in vegetated cover, especially in the 3000–3500 m and 3500–4000 m zones. For example, in the 3000–3500 m zone, vegetated cover rose from 56.42% in 1972–73 to 66.87% in 2022–23 of the areas, whereas in the 3500–4000 m zone, it went up from 43.78% to 59.03%, covering the areas that were previously under snow and barren land. This suggests a clear upward change in vegetation distribution, which is presumably caused by warming climate. The zones above 4000 m remains covered with snow and barren land, but also exhibits moderate vegetation intrusions, indicating a slow alpine ecosystem transformation. Predictive analysis of all the six maps from 1972-73 until 2022-23 to give forecast for 2033 shows significant changes with pine forests, moist alpine pastures, dry alpine scrubs, and barren land are predicted to increase by 65%, 13%, 9%, and 14%, respectively. Conversely, snow cover is anticipated to decline by 33% and Oak forests by 3%, indicating significant environmental shifts in the Himalayas. These results are crucial for formulating specific strategies for sustainable ecosystem resilience in the high-altitude zones of the Garhwal Himalayas.

1. Introduction

Human induced changes and their impacts manifested as climate variability are known to influence ecosystem structure, function, and properties (Laghari, 2013; Pandit, J., & Sharma, A. K. 2023). There is a growing interest to understand the ongoing processes in different eco regions of the world. Western Himalayan eco region is among the fragile and sensitive systems having altitudinal range from 500-8000 m (Owen and Benn 2005) supporting diverse vegetation controlled by orography and climate (Khan et al., 2012; Mehmood et al., 2025).

The recent rise in temperature has started showing its impact at all levels starting from species distribution to habitat functions and eventually on ecosystem structure and functioning (Rai et al., 2010).

There is now increasing evidence of the changes in the current ecosystem structure and spatial organization that are making species vulnerable (Pounds et al., 2006; Anderson and Boyer, 2008; Bernardi et al., 2024; Wilson et al. 2023).

Thomas et al., 2004, Parmesan, 2006, Mukhtar et al. 2025 and García et al. 2025, have reported the consequences of a slight increase in temperature on biotic communities that could range anything from shifting of phenological cycles to changes in species distribution pattern.

The shift in temperature regimes has a direct impact on the precipitation amount, availability of nutrients thereby impacting the population growth and density of ecologically sensitive plant species (Scott and Rouse 1995). These impacts are likely to amplify in future as the changes in current climatic patterns may continue to increase and have repercussions. Understandings of such ecosystem level changes are essential to draw adaptation and mitigation strategies.

In this study, we have tried to evaluate and assess the long-term variations in vegetation cover and its impact on vegetation distribution patterns in high altitude regions of Himalayas.

2. Materials and Methodology

The datasets used in the study were multi-temporal images of Landsat series for the years 1972, 1973, 1979, 1990, 2002, 2003, 2012, 2013, 2022, 2023 and ASTER DEM data. The multispectral bands in Landsat series – MSS, TM, ETM, Landsat 8 and 9 consisting of Green, Red, Near Infra-Red (IR) and SWIR wavebands were used for delineating the snow cover and other land cover classes.

The comprehensive methodology that was deployed in this study is depicted in the Figure1. ASTER DEM data was used to generate the altitudinal zones from 3000 meters upwards and were used to analyze the impact of vegetation cover changes in the region.

2.1 False Colour Composites

The false cover composites generated during this study for the years 1972, 1979, 1990, 2002, 2013, and 2023 are depicted in Figure 2.
Digital Image processing using hybrid classification was conducted on Landsat 8 and 9 images of 2012-13 and 2022-23.

2.2 Altitudinal Zone Maps

An altitudinal zone raster was created from ASTER DEM data to observe changes over a specified elevation interval (3000–3500 m, 3500–4000 m, and so on till 7500-8000m, allowing for the stratified analysis of vegetation dynamics. This zonal abstraction was done to study the ecological changes that were differently manifested at different altitudes. Figure 3 and Figure 4 depicts the altitudinal zones and their respective areas in each altitudinal zone.

2.3 Vegetation Type Maps

Vegetation type maps were generated for the years 1972-73, 1979, 1990, 2002-03, 2012-13, and 2022-23. 11 vegetation
cover classes and 3 non-vegetation classes were delineated from the satellite images for all the six vegetation type maps.

2.4 Accuracy Assessment Methodology

Accuracy assessment was carried out for the vegetation type maps that were generated for the six decadal years namely 1972, 1979, 1990, 2002, 2013 and 2023. Initially, a frame for spatial sampling points was established and sample.

2.5 Spatial Temporal Analysis

This study is focused on a detailed spatiotemporal analysis of vegetation and land cover change from a high-altitude Himalayan perspective for five decades, between 1972 and 2023. The analysis included satellite-derived classified thematic raster datasets for six time points: 1972-73, 1979, 1990, 2002-03, 2012-13, and 2022-23. The rasters included
14 land cover categories, such as snow, water bodies, different types of forests, grasslands, and shrubs/scrubs.
Remote sensing and GIS-based analyses of land cover transitions spanning each time period were conducted in Python within a Jupyter Notebook setup; examples of periods analyzed for changes were 1972-73 to 1979, 1979 to 1990,1990 to 2002-03, 2002-03 to 2012-13, and 2012-13 to 2022-23.

In terms of visualization, a heatmap was plotted for every decade-Extensive GPS readings were undertaken in the field to corresponding vegetation type class to confirm the availability of the particular vegetation type in the given region. Further, the maps of 2005 and their GPS observations were also taken into consideration to work both backward and forward in time to obtain the vegetation classes.

2.6 Predictive Analysis

The 2023–2033 land cover projection analysis was carried out to assess the potential changes in vegetation patterns and other land cover types over high-altitude regions due to natural and human-induced drivers. This forecast study utilized high-end Artificial Intelligence (AI) and Machine Learning (ML) algorithms, which were trained on a rich dataset obtained from six major temporal snapshots: 1972– 73, 1979, 1990, 2002–03, 2012–13, and 2022–23.

These multi-decadal data were derived through remote sensing and geospatial analysis methods, and then extensively processed through solid mathematical and statistical modeling techniques to examine long-term land cover changes.

By identifying spatiotemporal patterns in past vegetation changes, the AI/ML models projected future land cover projections with greater reliability. Predictive analysis highlighted possible expansion of a few vegetation classes, like subalpine scrub and degraded forests, but also indicated decline in ecologically important categories like moist alpine pastures and temperate conifers.

By combining AI/ML with historical geospatial data one can successfully undertake landscape change forecasting, fostering long-term environmental sustainability in the time-window from 1972-73 until 2022-23 using seaborn and matplotlib. These probably showed the intensity and direction of people-land-cover changes, focusing on the main land cover changes: decreasing snow cover and increasing alpine pastures as depicted in Figure 11, 12, 13, 14 and 15.

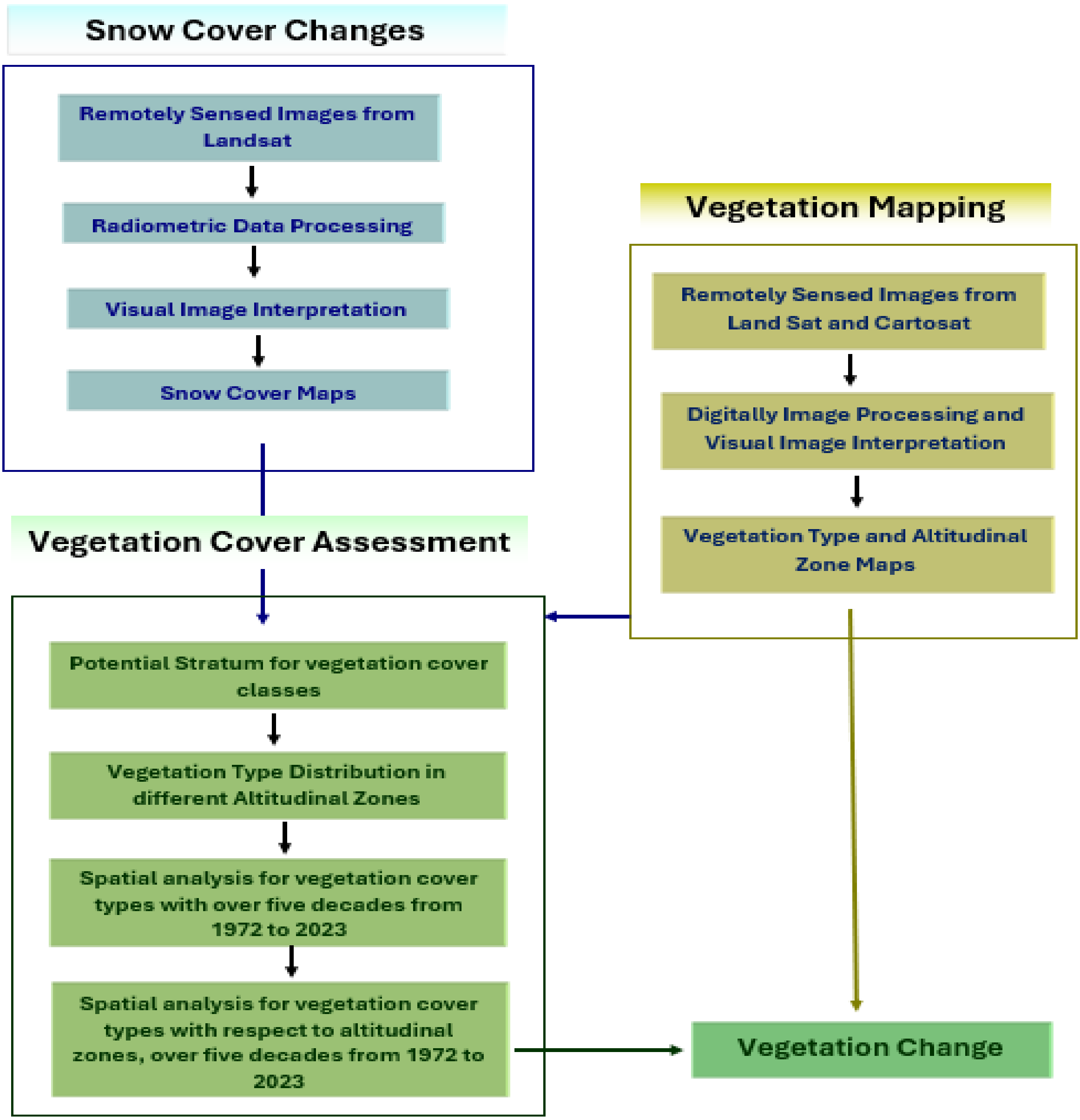

Figure 1: Approach and Methodology

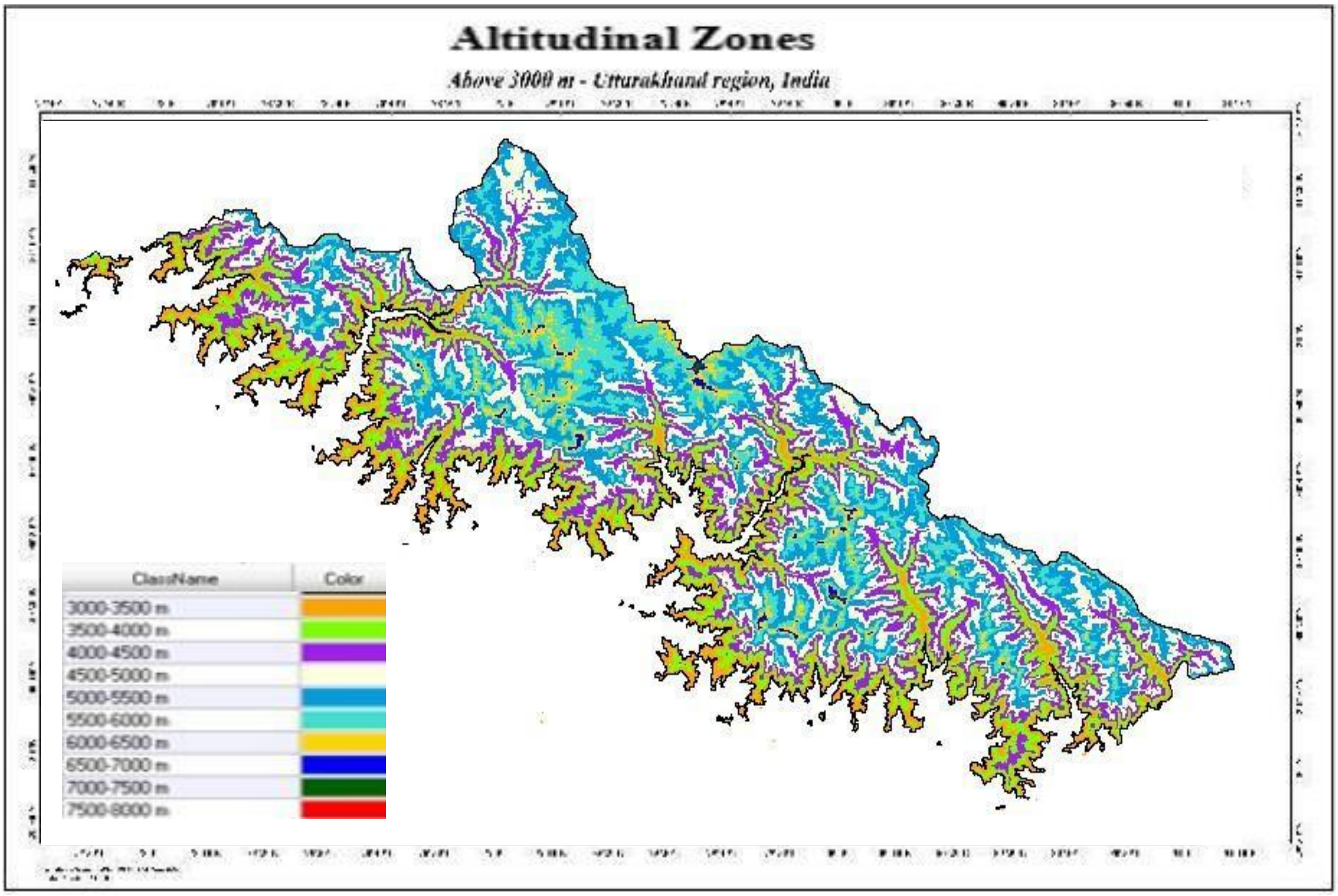

Figure 2: Altitudinal Zones

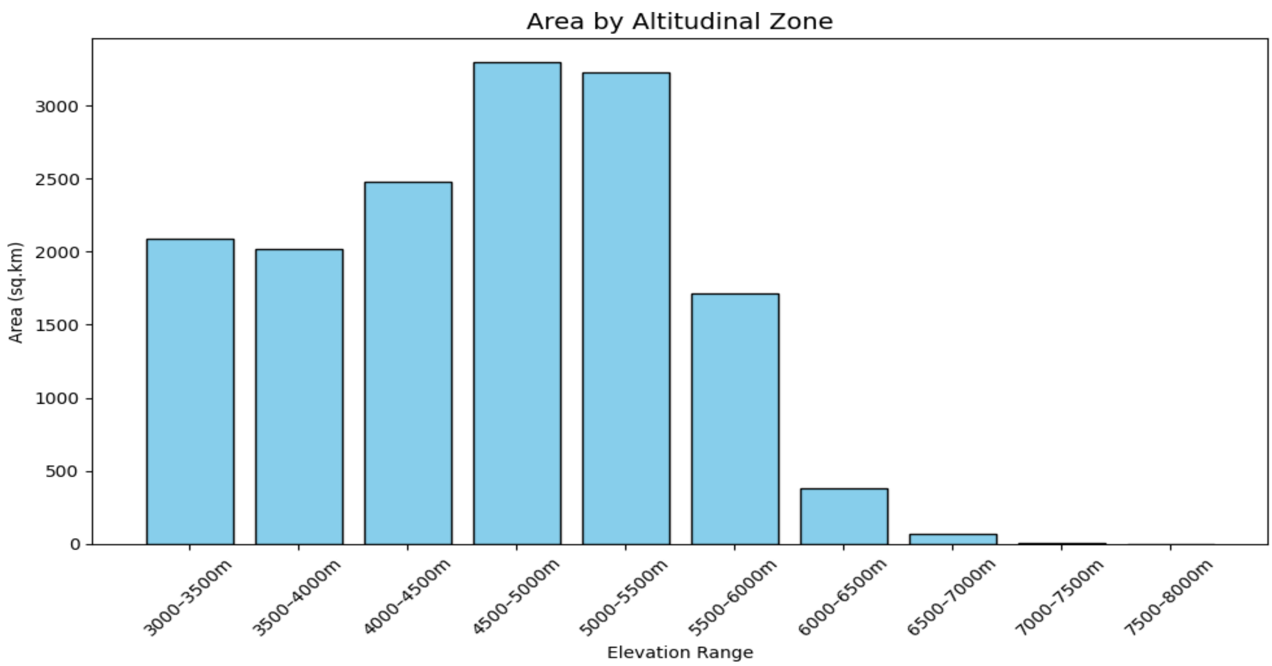

Figure 3: Area covered by each Altitudinal Zone

3. Results

The change analysis of vegetation cover classes from 1972 through 2013 clearly depicts the profound changes in vegetation cover that can be considered to be directly influenced by changes in snow and other land cover changes in high altitudes of Garhwal Himalayas. The trends of decadal evaluation of snow cover dynamics of last 4 decades, especially minimum snow cover has shown drastic reduction in the surface area.

Various studies from multi-temporal satellite data have also confirmed the trend of decreasing snow cover (Singh et al. 2012; Dhankar and Asha 2013; Rathore et al., 2015). The decrease in snow cover as also documented by other studies as well as this study have resulted in exposing the land cover that was earlier under snow (Kaur et. al, 2009; Schmidt and Nüsser, 2012). The snow melt areas either changed into barren land or to different vegetation cover classes as depicted in the Table 3. However, it was observed that in 2023 there was a slight increase in the snow cover.

Similar changes in vegetation cover due to snow cover changes in Himalayas have also been reported by other research studies (Shreshta et. al., 2012; Telwala et. al., 2013; Dolezal et. al., 2016; Anderson et. al., 2020). The most obvious changes that were observed were emergence of dry alpine scrub and moist alpine pastures in very high-altitude regions, while subalpine vegetation as well as pine, showed considerable increase in the cover especially in the areas that were earlier under snow.

3.1 Overall vegetation cover change dynamics

3.1.1 Vegetation Changes (1972–2023)

Over the past 50 years, high-altitude vegetation landscapes have changed significantly due to climate fluctuations and human-induced drivers.

Snow cover reduced drastically from 68.19% (10,416.12 sq. km) in 1972 to 27.46% (4,189.78 sq. km) in 2023, indicating a major cryosphere recession caused by temperature rise. Dry Alpine Scrub increased from 0.81% to 13.98%, showing the spread of drought-resistant shrubs under warmer and drier conditions.

Temperate Conifers and Fir initially increased but declined after 2013, implying vegetation stress or ecological succession. Oak forests expanded from 2.86% to 4.66%, reflecting ecological resilience and possible adaptation to favorable climates.

3.1.2 Altitudinal Land Cover Changes

• **Period 1972–1979:**
Significant snow decline, especially at 4500–5500 m altitudes. Over 58.2% of snow transformed into barren land or moist alpine pastures, marking early cryosphere retreat and ecological stress.

• **Period 1979–1990:**
Continued snow shrinkage; 61.3% of snow in Zone 3 (4000–4500 m) became barren land, 22.5% turned into moist alpine pastures, and 9.8% into fir.
In Zone 2 (3500–4000 m), more than 55% of snow shifted upward into fir and temperate coniferous vegetation, showing upward migration due to warming.
Zone 5 (5000–5500 m) saw 37.8% barren land emerging from degraded forest and oak. Small glacial lakes formed from melting snow.

• **Period 1990–2002:**
The period of strongest change across all zones.
In Zone 8 (6500–7000 m), 91.5% snow turned barren; Zone 7 (6000–6500 m) saw 65.2% converted to moist alpine pastures; Zone 5 lost 42.7% snow to barren land. 36.3% of moist alpine pastures in Zone 6 changed into subalpine vegetation, while dry alpine scrub expanded by 18.3% in Zone 5.

• **Period 2002–2013:**
The most intense snow loss was recorded across all zones.
In Zones 1–3, 84.2–89.8% of snow converted to barren land, indicating rapid glacier melting and near disappearance of seasonal snow. Vegetation gain was below 15% per zone, showing harsh environmental conditions for regrowth.

• **Period 2013–2023:**
Fewer but complex transitions were observed.
In Zone 6, snow reduced by 66.4%, mostly converting to barren land.
32.7% of blue pine and subalpine vegetation recolonized barren areas (partial recovery).
However, 18.5% of subalpine vegetation in Zone 5 turned barren, showing ecosystem instability.

3.1.3 Predictive Analysis (2023–2033)

AI/ML-based analysis predicts major vegetation shifts by 2033.
Pine forests expected to increase by 65%, showing high climate resilience. Deodar and Fir projected to rise by 11% and 6%, respectively. Temperate Conifers may decline by 4% and Oak forests by 3%, possibly replaced or migrated upward. Subalpine Shrubs and Dry Alpine Scrubs will rise by 10% and 9%, indicating ecosystem alteration. Moist Alpine Pastures → Subalpine Vegetation change will be highest at 19.27% in Zone 6, and 15.09% in Zone 8, showing strong upward snowline and vegetation shift.

Table 1: Vegetation Changes 1972-2023 – Area in Square Kilometers

S.NO	LAND COVER CLASSES	1972	1979	1990	2002	2013	2023
FOREST CLASSES							
1	TEMPERATE CONIFERS	809.89	790.93	837.71	888.23	891.72	858.9
2	FIR	95.46	89.42	81.95	98.42	102.30	107.52
3	DEODAR	145.011	130.09	175.68	186.91	188.75	140.25
4	OAK	436.50	404.66	499.97	534.42	548.27	610.7
5	PINE	5.46	9.68	10.20	14.02	16.08	8.85
6	HIMALAYAN MOIST TEMPRATES	26.76	23.95	29.26	31.74	33.36	33.04
7	DEGRADED FOREST	0	1.24	1.092	1.48	4.49	5.67
SHRUB/SCRUB CLASSES							
8	SUBALPINE VEGETATION	768.23	922.06	851.19	945.71	1032.32	804.04
9	DRY ALPINE SCRUBS	123.91	339.48	362.15	334.58	872.69	932.63
GRASSLAND CLASSES							
10	MOIST ALPINE PASTURES	1153.78	1775.27	1853.85	2028.83	2225.13	2297.22
11	TEMPERATE GRASSLANDS	193.68	193.53	187	210.93	215.39	218.66
NON-VEGETATION CLASSES							
12	SNOW	10417.75	7908.79	6878.61	7596.90	4250.46	4189.78
13	WATER BODY	10.44	28.13	24.68	57.50	59.32	60.25
14	BARREN LAND	1089.82	2658.89	3483.46	2346.91	4836.01	4988.73

Vegetation Cover Area Changes 2023-2033

Figure 4: Heat Map of Vegetation cover area changes (2023-2033)

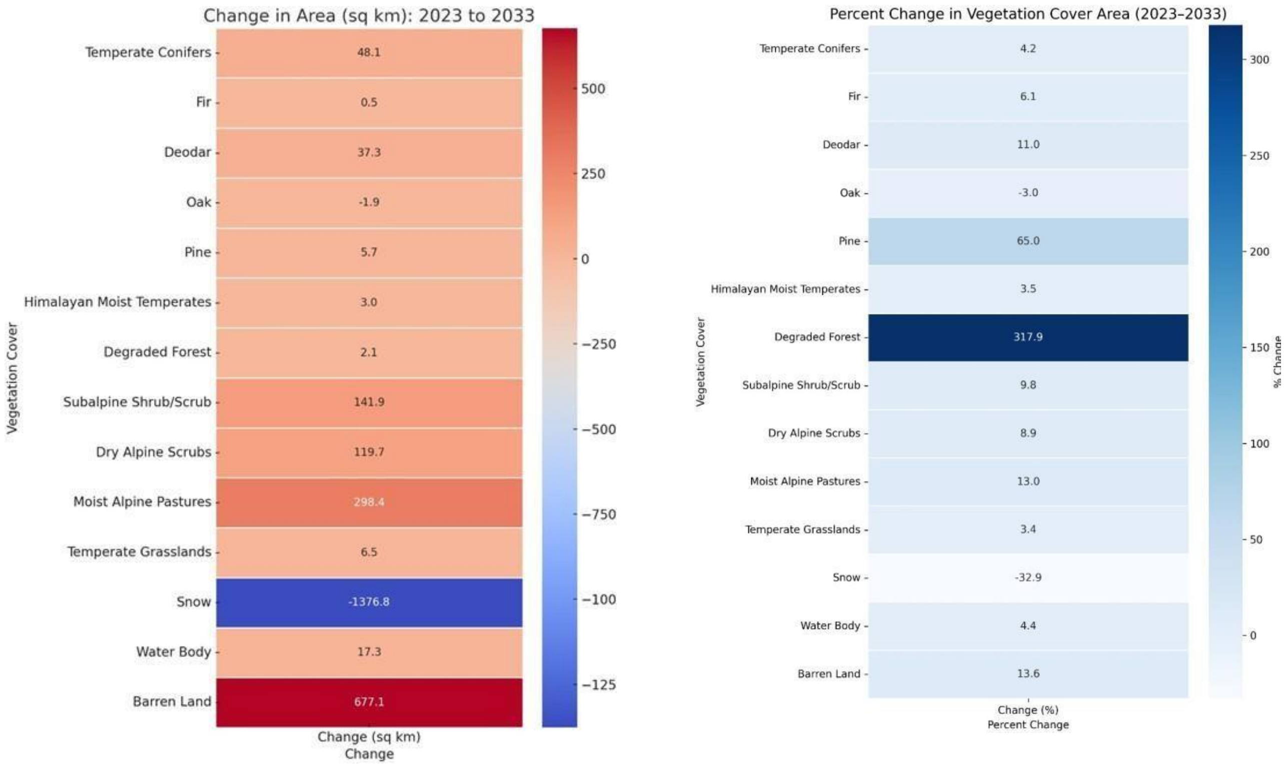

Figure 5: Predictive Analysis of Vegetation cover area changes (2023-2033)

Discussion and Conclusion

The increase in temperature in alpine and sub-alpine regions is causing climate-induced vegetation cover changes (Miehe, 1996; Guisan and Theurillat, 2000; Walther et al., 2005; Lenoir et al., 2008; Cuesta et al., 2023; Liu et al., 2023). This study evaluates long-term changes in vegetation and other land cover classes in the high-altitude regions of the Garhwal Himalayas, Uttarakhand, establishing a 50-year trend of changes in vegetation and snow cover.

4.1 Overall Vegetation Cover Change Dynamics
Mapping was performed through onscreen digitisation using image interpretation (Jenson, 2007) as older MSS, TM, and ETM datasets had spectral issues, while Landsat 8 and 9 data were digitally processed. To maintain consistency, visual interpretation was preferred (Puig et al., 2012; Ghorbani and Pakravan, 2013; Sowmya et al., 2017). The 2005 vegetation map (Roy et al., 2012) with 90% accuracy served as a baseline, while subsequent maps achieved ~89.5% accuracy (Landis & Koch, 1977; Rwanga & Ndambuki, 2017). Snow cover showed a consistent decline from 1972 to 1990, a temporary increase in 2002, and sharp decline again in 2013. This confirms continuous snow retreat and upward vegetation shift in the Garhwal Himalayas. The classification accuracy remained above 90%, aligning with studies suggesting >75% accuracy is strong for change detection (Liu & Zhou, 2004; Fortier et al., 2011; Mishra et al., 2016). The results confirm declining snow cover and associated vegetation pattern shifts. While 3000–4000 m zones showed tree growth (Blue Pine, Fir, Oak), the 4000–5000 m belt saw expansion of shrubs and grasses in snowmelt areas. Above 5000 m, snowmelt created barren zones, consistent with other Himalayan studies (Khan et al., 2012; Telwala et al., 2013; Thapliyal et al.). The study highlights the need to redefine snow and tree lines and assess hydrological security. Further research is needed on snow cover–hydrology interaction and species distribution in newly deglaciated areas to build ecological profiles and develop conservation strategies.

4.2 Altitudinal Variations in Vegetation Cover Dynamics
From 1972–2023, the high-altitude landscape of Uttarakhand transformed drastically under climate change. Nearly 80% of snow between 3000–4500 m converted to barren land or moist alpine pastures between 2002–2013. In the 4500–5000 m zone, 91.5% snow turned barren, and even 5000–5500 m permanent snowfields began retreating. Meanwhile, barren lands transformed into subalpine vegetation and moist alpine pastures at lower zones (3000–4500 m). Vegetation like Fir, Blue Pine, and Alpine Pastures shifted upward into former snow and barren regions, indicating cryosphere retreat, ecosystem compression, and instability. These findings stress the need for climate-oriented land management, glaciological monitoring, and conservation in the Garhwal Himalayas.

4.3 Predictive Analysis of Vegetation Cover Dynamics (2023–2033)
If glacier conservation measures are not undertaken, snow cover will decline sharply, converting into barren land. Predictions show a −1376.8 km² loss in snow cover and a +677.1 km² gain in barren land by 2033. Moist Alpine Pastures (+298.4 km²), Dry Alpine Scrub (+119.7 km²), and Deodar (+37.3 km²) will expand, reflecting upward vegetation shifts. Subalpine Shrub/Scrub (+141.9 km²), Temperate Conifers (+48.1 km²), and Water bodies (+17.3 km²) will also rise moderately. Other classes—Grasslands (+6.5 km²), Fir (+0.5 km²), Himalayan Moist Temperate (+3.0 km²), Pine (+5.7 km²), and Degraded Forests (+2.1 km²)—will show minor increases. Oak forests, however, are projected to decline (−1.9 km²) due to heat stress and succession. These trends suggest relentless ecological reshuffling along elevation gradients, potentially disrupting ecosystem structure, biodiversity, water resources, and long-term sustainability.

4. References

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