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Spatio-Temporal Land Cover Change in Chamoli District, Uttarakhand (1990–2026): Methods, Trends, and Research Gaps

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Abstract: *This paper synthesizes evidence on spatio-temporal land use/land cover (LULC) change in Chamoli District, Uttarakhand, from 1990 to 2026, situating local dynamics within broader central Himalayan transitions. Drawing on multi-temporal Landsat and Sentinel-2 imagery, DEM-derived terrain variables, NDVI, fragmentation metrics, and predictive modeling, we reconstruct three phases: a 1990–2010 baseline of declining agriculture and expanding built-up/vegetation; a 2010–2020 transition marked by intensified fragmentation, rapid urban growth, forest loss, and warming-linked hazard exposure; and a 2020–2026 expansion characterized by strong high-elevation greening, grassland spread over deglaciated terrain, increased barren land, and sharp snow decline. Elevation-zone analysis reveals upward migration of vegetation lines (7–28 m yr^{-1}) and disproportionate forest and grassland gains above ~4,100 m, alongside glacier retreat and dense glacial lake concentration in the Dhauliganga–Rishiganga system. Despite methodological advances toward multi-sensor, elevation-aware and prediction-oriented approaches, the district still lacks a fully harmonized 1990–2026 classification series. The results highlight how interacting climate variability, infrastructural growth, and slope-constrained hazards jointly reshape water regulation, slope stability, carbon storage, and settlement safety in a highly sensitive Himalayan landscape.*

Keywords: *Chamoli District; land cover change; spatio-temporal analysis, Forest Cover*

Introduction:

The spatio-temporal land cover change in Chamoli District from 1990 to 2026 is the most suitable study of the transition of the mountain landscape marked by the greening of **high-elevation regions, snow-ice influence, contraction of agricultural land, and the simultaneous growth of built-up area**. This study examines spatio-temporal land cover change in Chamoli District, Uttarakhand, over the period 1990–2026, with emphasis on the interaction between land surface processes, climate variability, and human land use. Such analysis is important in Himalayan districts because land cover patterns regulate water availability, slope stability, biodiversity, carbon storage, and settlement safety, while also recording the cumulative effects of agricultural change, urban expansion, glacier retreat, and vegetation redistribution (Zhang et al., 2024; Taloor et al., 2020; Pu et al., 2025). The evidence is assembled from partly mismatched time windows and methods rather than one harmonized district-wide series. The previous studies on the LU/LC of Chamoli show strong vegetation redistribution and substantial changes in built-up and fallow land, while other studies related to Uttarakhand and the Garhwal region support the same direction of change and identified some of the drivers of LU/LC changes, especially temperature increase, infrastructural growth, and hazards caused due to the slope-constrained area are majorly contributing to the LU/LC conversion (Kumar et al., 2026; Nautiyal et al., 2022; Aves et al., 2026).

Beyond descriptive mapping, land cover change in Chamoli district is closely linked to hazard exposure, hydrology, and the ecosystem of the area. The concentration of glacial lakes is found at high altitude; the Dhauliganga catchment has lost glacier area over the last two decades, and the 2021 Chamoli disaster showed how cryosphere change, steep terrain, and infrastructure vulnerability can interact in a single landscape system (Deepti et al., 2025; Ali et al., 2022; Zhou et al., 2021). The district contains the highest concentration of glacier lakes in Uttarakhand, substantial glacierized catchments in the Dhauliganga–Rishiganga system, and strong recent evidence of upward vegetation expansion and snow decline, making it a sensitive indicator of broader central Himalayan landscape transition (Deepti et al., 2025; Ali et al., 2022; Kumar et al., 2026). Three progressive stages can be depicted as three clear stages of the study of the land cover changes of the Chamoli since 1990. The timeline points to a methodological shift from the comparison between temporal Landsat imagery toward a multisensor method, elevation awareness, and prediction-oriented analysis. The evidence base has become more sophisticated, but the district still lacks one consistent 1990–2026 classification series with common classes, validation, and transition accounting (Aves et al., 2026; Zhang et al., 2024; Yan et al., 2023).

1990–2010 Baseline

In early Himalayan LULC studies, the methods mostly involved **multi-temporal Landsat imagery**, a supervised classification method, and GIS-based change detection, which were adopted to compare yearly data of a certain gap, i.e., 1990 and 2010 (Rawat & Kumar, 2015; Rawat et al., 2013). ERDAS was the most commonly used platform for the maximum likelihood classification, usually in a few classes, 5–6 classes, such as vegetation/forest, agriculture, barren land, built-up land, and water (Rawat & Kumar, 2015; Rawat et al., 2013).

Comparable Uttarakhand studies reported declining agriculture and increasing built-up or vegetation, showing the kind of baseline pattern expected in mountain districts undergoing livelihood transition (Rawat & Kumar, 2015; Rawat et al., 2013). In Garhwal, cross-tabulation

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methods also showed long-run forest cover loss and fragmentation between 1976 and 2014, with scrub and barren land expansion contributing to non-forest accumulation (Batar et al., 2017).

2010–2020 Transition

In later studies, mostly **terrain and fragmentation analysis**, simple classification has been observed. Slope analysis from SRTM DEM data explains the major changes in the land cover found along the transitional zone on a nearly level to gentle surface of the Uttarakhand Himalayas (Taloor et al., 2020). Cross-tabulation transition matrices and fragmentation tools were also used to detect class-to-class conversion and loss of core forest area (Sur & Singh, 2020; Batar et al., 2017).

All the evidences of the Chamoli-specific studies indicates substantial changes in the physical landscape from 2000 to 2020, including a **541.57 km² increase in built-up area**, a **76.96 km² decline in dense forest**, and a **364.09 km² decline in fallow land** (Nautiyal et al., 2022). This study also linked these shifts to warming conditions, reporting a minimum temperature rise of **0.68°C per decade**, while identifying about **500 glacial lakes**, many at 5000–6000 m, underscoring the coupling of land cover and hazard dynamics (Nautiyal et al., 2022).

2020–2026 Expansion

The recent focus has been shifted from the horizontal land conversion to the elevation-based vegetation cover change for the high altitude, i.e., Chamoli, Uttarakhand. It is evident that the forest cover that has been in Chamoli has increased from **224,027 ha in 1983 to 323,554 ha in 2023**, with especially strong expansion at high elevations, indicating an upward migration of forest cover (Kumar et al., 2026). Grassland also expanded from **93,647 ha to 118,330 ha**, while barren land increased and snow-covered land sharply declined (Kumar et al., 2026).

There is a clear indication of the upward shifting of the vegetation line by **7–28 m/year and** expansion of grassland in the deglaciated terrain across the border area of the Himalayas (Bandyopadhyay et al., 2022). The NDVI studies on the Garhwal region above the altitude of 3000 m using LISS-IV and AI/ML-based methods detected a sharp increase in NDVI value by 2025, especially above 4500 m (Shukla et al., 2025). Predictive modeling further suggests the highest amount of mean sequestered carbon in Chamoli was found in 2012 at **10.58 Mg/ha** before declining to **3.08 Mg/ha in the future,** implying future land-cover trajectories may reduce ecosystem carbon storage if present patterns continue (Khan et al., 2024).

Methodological Basis

In recent studies in the last five years, multi-temporal and multi-sensor approaches have improved the classification method and accuracy in uneven mountain landscapes. Landsat Sentinel-2 seasonal feature stacks substantially raise classification accuracy, mountain vegetation mapping performs better with growing-season multi-temporal imagery than with single-date images, and combined spectral, index, terrain, and SAR inputs can further improve long time-series mapping under complex topography (Arfa-Fathollahkhani & Minaei, 2024; Wakulinska & Marcinkowska-Ochtyra, 2020; Yan et al., 2023). Mountain studies also show why a simple two-date comparison is no longer enough. Continuous Landsat change detection can identify the timing of pixel-level change with high accuracy, though early pre-2000 imagery remains sparse and often needs wider temporal windows or sensor fusion to stabilize mapping (Zhu & Woodcock, 2014; Zhang et al., 2024).

Methods Used in Relevant Studies

Study Focus	Data	Method	Main Use
Chamoli vegetation dynamics	Multi-temporal satellite series, 1983–2023	Elevation-zone land cover analysis	Track tree, grassland, barren, snow shifts (Kumar et al., 2026)
Chamoli geoclimatic change	Climate trends, LST, landscape data	Geospatial hazard-landscape assessment	Relate LULC change to warming and glacial lakes (Nautiyal et al., 2022)
Garhwal fragmentation	MSS, TM, OLI Landsat	Cross-tabulation + LFT	Detect forest loss and fragmentation (Batar et al., 2017)
Uttarakhand carbon futures	RS/GIS time series, 2002–2032	Predictive CA-Markov modeling	Forecast ecosystem service implications (Shukla et al., 2025)
High-altitude Garhwal greening	LISS-IV, NDVI, 2013–2025	AI/ML altitudinal analysis	Measure vegetation gains above 3000 m (Shukla et al., 2025)

Table 1: Methods used in Chamoli-related land cover studies

Analyzing the existing literature on the LULC study of Chamoli District, the use of Landsat data, Sentinel-2 imageries, terrain analysis using DEM data, NDVI analysis, the use of transition and fragmentation metrics, and accuracy assessment methods are inevitable. Field or community validation should be included because the studies that add household surveys, field observations, or reference maps are more suitable to identify drivers and resolve ambiguous classes such as fallow land, seasonal settlement, and managed vegetation (Taloor et al., 2020; Phartiyal & Sharma, 2024; Wakulinska & Marcinkowska-Ochtyra, 2020).

Interpreting the Main Trends

Vegetation redistribution is one of the major indicators of the landcover change in the Chamoli district, which increased from 224,027 ha in 1983 to 323,554 ha in 2023, with especially large expansion in the 4149–5152 m elevation zone, while grassland also increased and snow cover declined sharply (Kumar et al., 2026). This pattern is consistent with the wider Himalayan region and also elevation-dependent. Vegetation lines across the Himalaya have shifted upward at rates of 7–28 m per year reported in glacier-influenced terrain, and expansion of forest cover on the south slope of the Himalayas is strongest across mid-to-high elevations where slight temperature increases support plant growth (Leng et al., 2026; Bandyopadhyay et al., 2022; Mukhtar et al., 2025).

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The hazard analysis-based studies of Chamoli district identified about 500 glacial lakes, with 40.92% located between 5000 and 6000 m, while the glaciers of Dhauliganga catchment lost 58.95 km² of debris-free glacier area between 2001 and 2020, and in Uttarakhand overall glacier lake area rose by 8.1% from 2013 to 2023 (Nautiyal et al., 2022; Ali et al., 2022; Deepti et al., 2025).

Key Observed Landscape Trends

Trend	Chamoli-Specific Evidence	Broader Regional Support
High-elevation greening	Tree cover expanded strongly at upper elevations (Kumar et al., 2026)	Upward vegetation-line shifts are widespread in Himalaya (Leng et al., 2026)
Snow/ice decline	Snow cover decreased markedly in Chamoli (Kumar et al., 2026)	Glacier area and snow-linked cover are declining regionally (Ali et al., 2022)
Agricultural contraction	Fallow land decreased sharply in Chamoli (Nautiyal et al., 2022)	Cultivation declines in Pithoragarh, Tehri, Kumaon, and Dehradun analogues (Phartiyal & Sharma, 2024; Singh et al., 2025; Lohani, 2024)
Built-up growth	Built-up increased by 541.57 km² from 2000–2020 (Nautiyal et al., 2022)	Mountain districts repeatedly show settlement expansion (Jaiswal et al., 2025; Rawat & Puri, 2017)
Fragmentation risk	Dense forest declined in Chamoli (Nautiyal et al., 2022)	Core forest loss documented across Garhwal (Batar et al., 2017)

Table 2: Observed land cover trends in Chamoli and analogues

Agricultural land gradually contracted, and it declined by 364.09 km² between 2000 and 2020, while multiple similar reports also confirmed the same for Uttarakhand, declining cultivation or cropland alongside increases in vegetation or built-up area, a pattern consistent with agricultural abandonment, livelihood transition, and selective concentration of activity in accessible terrain (Nautiyal et al., 2022; Phartiyal & Sharma, 2024; Rawat & Puri, 2017).

Built-up areas growth is inevitable but spatially uneven. The district-level analysis of Chamoli has reported a 541.57 km² increase in built-up area over 2000–2020, and sub-basin evidence from Dhauliganga villages shows rapid settlement expansion in selected locations tied to development and transport corridors rather than uniform district-wide urbanization (Nautiyal et al., 2022; Patayari et al., 2022).

Instead, different elevational belts are changing in different directions: lower and middle valleys show settlement growth and agricultural restructuring, mid-elevation forests show pressure of fragmentation and land-use conversion, and upper elevations show vegetation encroachment into former snow- and barren-dominated terrain (Kumar et al., 2019; Batar et al., 2017; Shukla et al., 2025). The evidence also supports linking land-cover change to climate-sensitive hazard regimes. Rising minimum temperature, glacier retreat, expanding or vulnerable glacial lakes, shrinking local ice cover, and slope-instability signals before the 2021 Chamoli event together indicate that land-cover analysis in this district should be interpreted alongside geomorphic and cryospheric risk rather than as a standalone land accounting exercise (Nautiyal et al., 2022; Ali et al., 2022; Mao et al., 2021).

Hazard-Linked Landscape Evidence

Hazard Dimension	Evidence
Glacial lakes	Chamoli contains the largest glacier-lake concentration in Uttarakhand (Deepti et al., 2025)
Glacier retreat	Dhauliganga debris-free glacier area fell 12.35% from 2001–2020 (Ali et al., 2022)
Slope instability	Rock-ice body movement at Chamoli began around 2017 with climatic anomalies implicated (Zhou et al., 2021)
Development exposure	Hydropower and settlement growth increase vulnerability in narrow valleys (Dash et al., 2023; Nautiyal et al., 2022)

Table 3: Hazard-linked landscape change evidence for Chamoli

The observed changes include tree-cover increase, dense-forest decline, fallow-land reduction, glacier retreat, and built-up expansion, whereas inferred processes include agricultural abandonment, climate-driven upslope migration, and future carbon decline, which are plausible and supported but not yet harmonized in one district-wide causal model (Nautiyal et al., 2022; Kumar et al., 2026; Shukla et al., 2025). The major research gap identified is in the sense of the absence of a uniform method, consistent class definitions, annual or near-annual change tracking, and explicit uncertainty reporting of LULC analysis of the Chamoli district from 1990 to 2026. Recent long-time-series methods can do this in principle through dense Landsat archives, GEE workflows, continuous change detection, and multi-source fusion, but that integration has not yet been carried through for Chamoli (Zhang et al., 2024; Amini et al., 2022; Yan et al., 2023).

Ground validation is the second major gap. Comparable Himalayan studies increasingly integrate household surveys, field observations, reference maps, or botanical/landscape field data, yet it is rarely found in the literature taken for the Chamoli-centered change studies that can validate the ground-level data, which weakens the classification of some of the classes, such as fallow land, rangeland, sparse vegetation, and seasonal settlements (Phartiyal & Sharma, 2024; Kumar et al., 2019; Nautiyal et al., 2017). CA-Markov and AI/ML studies show that forecasting is feasible, and recent Chamoli-related work already points to future declines in snow cover and ecosystem carbon under continuing change, but district-specific predictive LULC scenarios

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remain sparse and are not yet tightly coupled to hazard exposure or adaptation planning (Shukla et al., 2025; Aves et al., 2026).

Results and Discussion

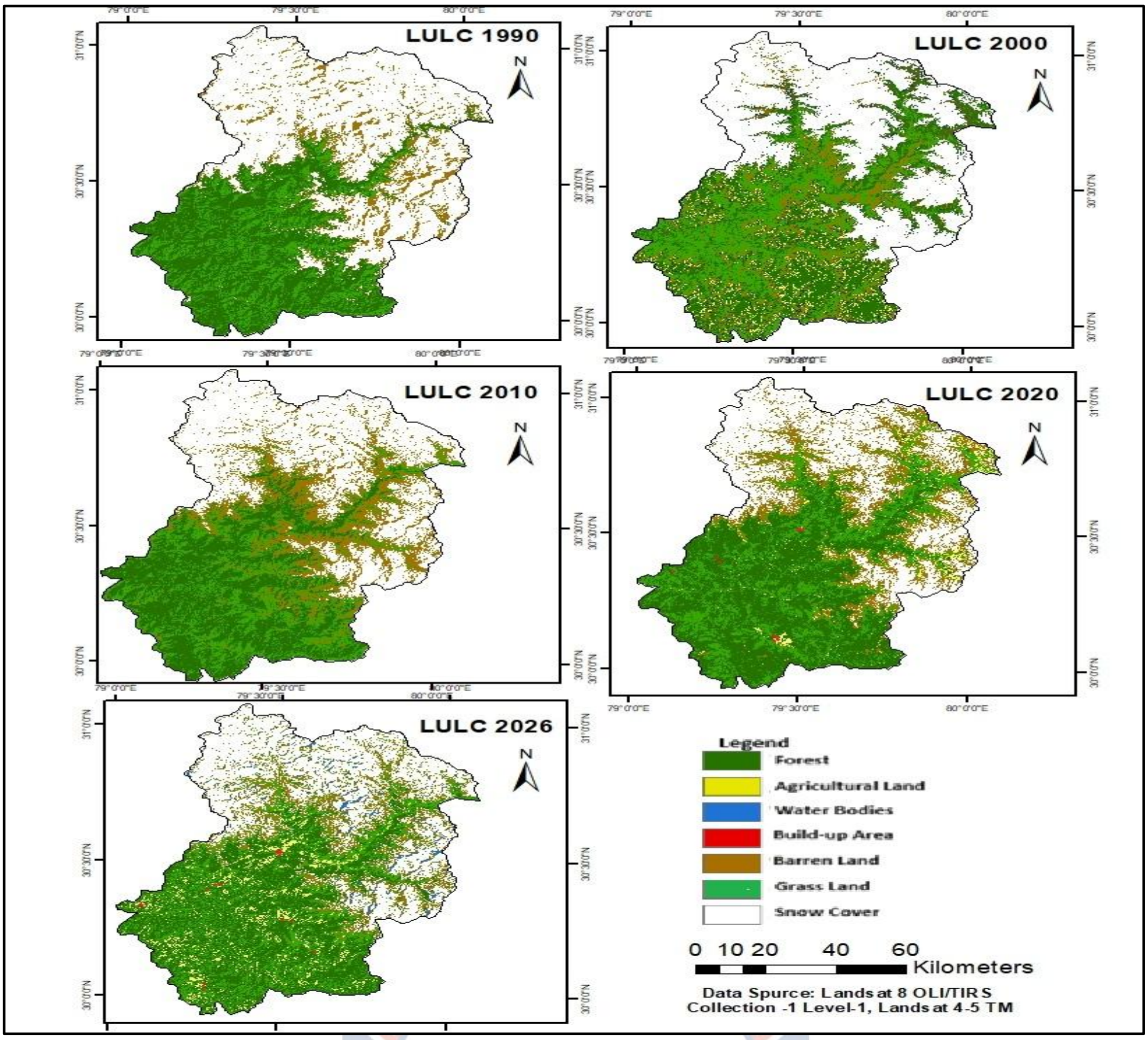

Figure 1: LULC Map of Chamoli District from 1990 to 2026

LULC Classes and their respective areas

LULC Change (Percentage)

LULC Classes	Percentage change (1990-2000)	Percentage change (2000-2010)	Percentage change (2010-2020)	Percentage change (2020-2026)	Percentage change (1990-2026)
Snow Cover	-18.85	-3.95	-4.47	-8.29	-31.71
Forest	7.89	3.30	-4.41	1.73	8.38
Grassland	18.46	-11.41	2.61	10.58	19.09
Barren Land	6.52	7.64	14.26	0.43	31.56
Agricultural Land	31.39	10.03	2.71	-1.46	46.31
Water bodies	0.77	1.86	-10.49	6.39	-2.25
Built-up Areas	123.61	1.45	1061.43	63.75	4214.35

Table 5: LULC classes and their percentage change in area from 1990 to 2026

Between 1990 and 2026, **snow cover** declined from 3071.54 to 2097.62 km², a net reduction of 31.71%, while forest cover increased from 2664.21 to 2887.37 km², a net increase of 8.38%. Over the same period, grassland increased by 19.09%, barren land by 31.56%, and built-up area from 2.16 to 93.19 km², equivalent to a 4214.35% rise. Agricultural land increased from 428 to 635.47 km² by 2020 and then declined slightly to 626.21 km² by 2026, suggesting that net agricultural expansion in the aggregate record does not rule out local abandonment, redistribution, or conversion among smaller, fragmented mountain parcels. The most abrupt transition was in **built-up land** after 2010, increasing from 4.90 km² in 2010 to 56.91 km² in 2020 and 93.19 km² in 2026. Comparable Himalayan studies show that built-up growth often occurs at the expense of agricultural land and concentrates near roads and urban nodes rather than uniformly across mountain districts (Ishtiaque et al., 2017; Jia et al., 2022; Mondal & Zhang, 2018).

The combined increase in grassland and barren land alongside declining forest and snow cover is consistent with **vegetation redistribution** rather than simple ecological improvement. Western Himalayan reviews report decreases in scrub forest and alpine meadows together with increases in open forest, cropland, fallow land, built-up land, and barren land, while hill districts elsewhere in Nepal show active conversion from farmland to forest or grassland under fragmented mountain conditions (Mondal & Zhang, 2018; Jia et al., 2022).

The main finding is not only that land-cover classes changed, but that the **interpretation of change** must now be elevation-sensitive and linked to climate. Earlier Himalayan LULC studies largely emphasized horizontal class conversion from multi-date Landsat imagery using supervised classification, which remains useful for identifying where agriculture, vegetation, settlements, barren land, and water changed (Rawat & Kumar, 2015; Mishra & Jabin, 2020). Newer work shows that DEM, land-surface temperature, and harmonized time-series inputs substantially improve classification and interpretation, and that snow-cover response varies sharply by elevation zone (Amini et al., 2022; Banerjee et al., 2021).

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