Study of Ecosystem Services Provided by Mountain Watersheds

Thesis submitted for the award of the degree of
Doctor of Philosophy

In

WILDLIFE SCIENCE

By

Anindita Debnath

To

Saurashtra University
Rajkot -360005 (Gujarat)

Under the supervision of
Dr. Gautam Talukdar

भारतीय वन्यजीव संस्थान
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DECLARATION

I, hereby, declare that the work conducted under this thesis titled **“Study of Ecosystem Services Provided by Mountain Watersheds”** is a record of original and independent research work done by me and subsequently submitted for the award of the degree of **Doctor of Philosophy in Wildlife Science** to the **Saurashtra University, Rajkot (Gujarat)**. This research work has been carried out under the guidance and supervision of **Dr. Gautam Talukdar, Scientist** of Wildlife Institute of India, Dehradun.

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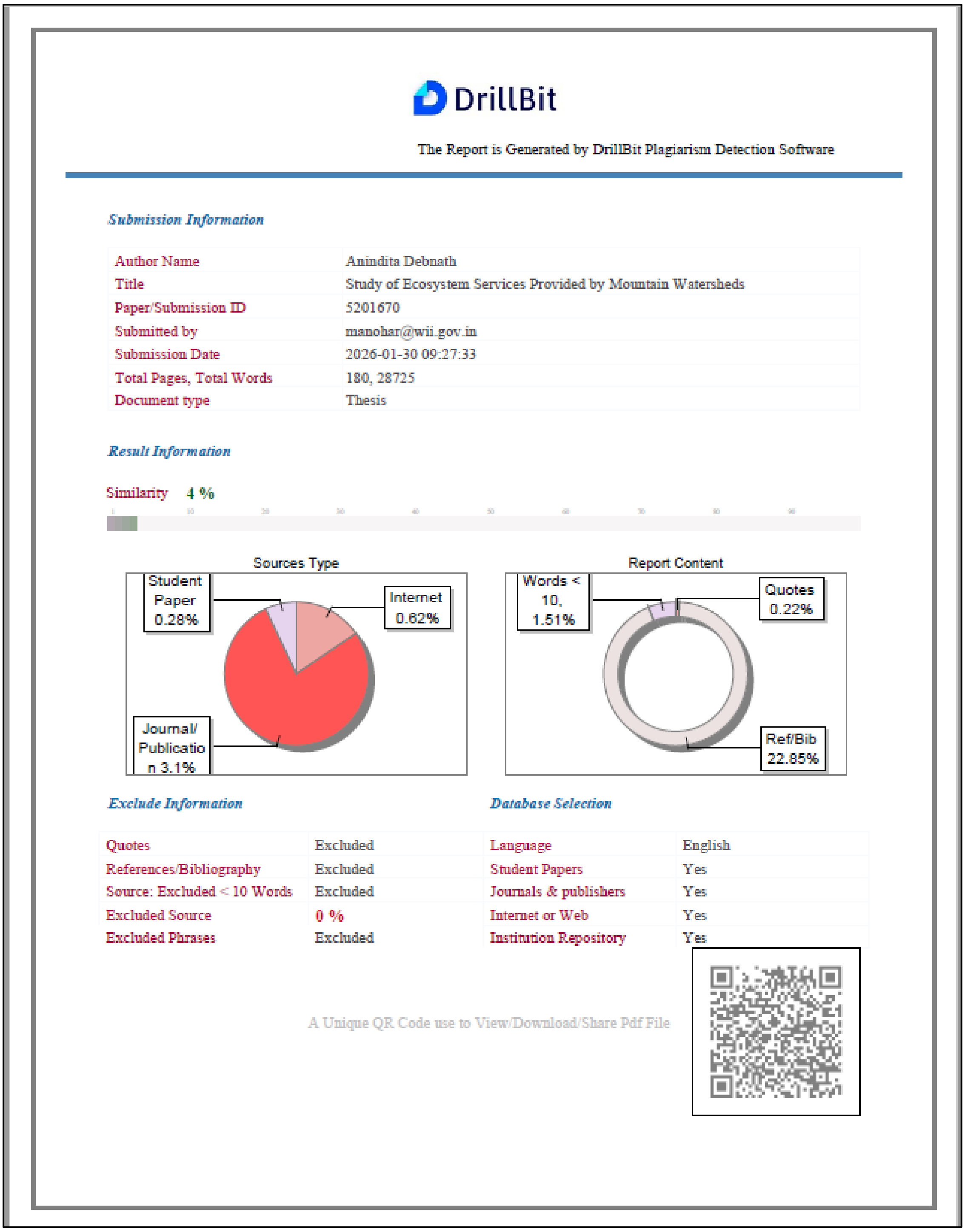

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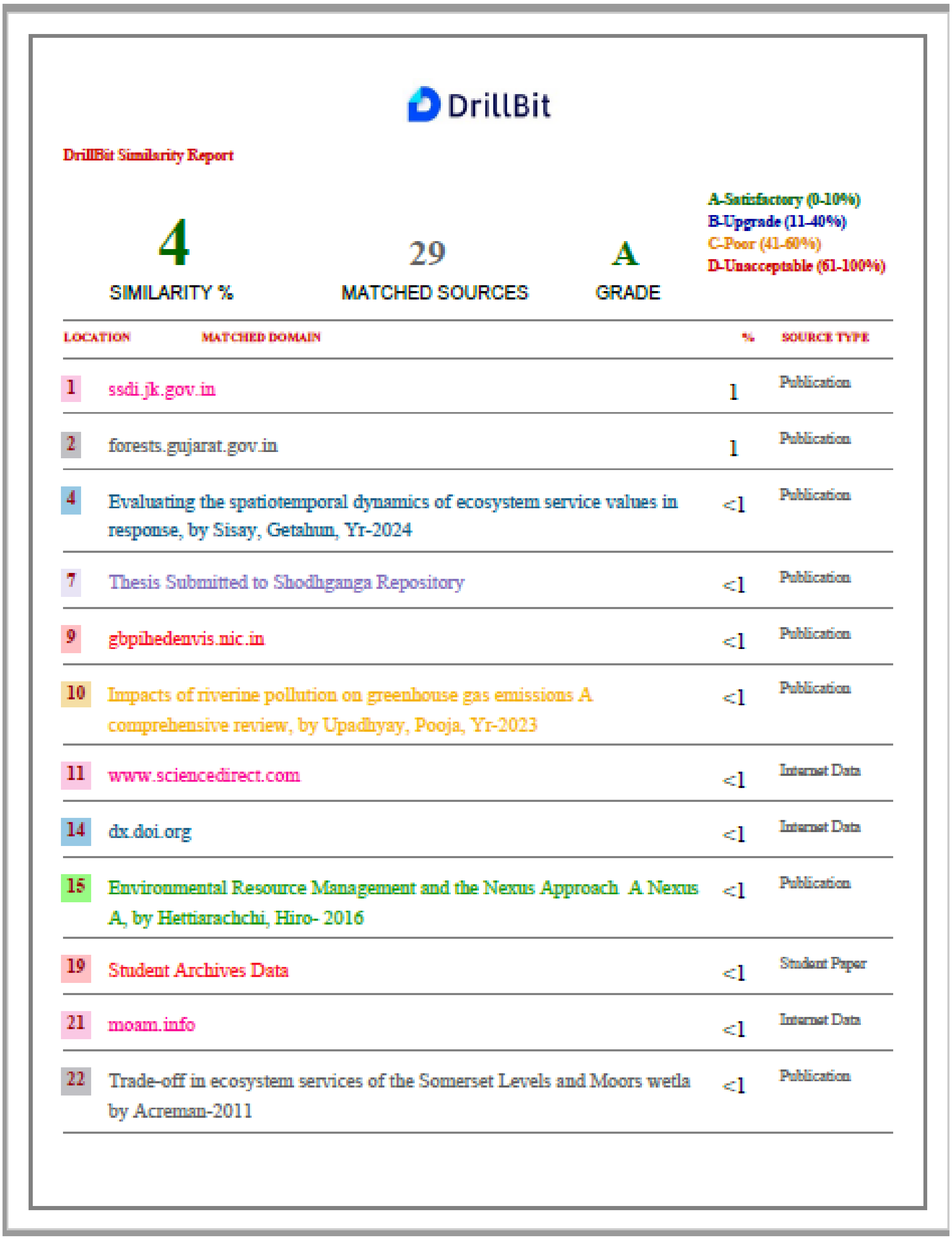

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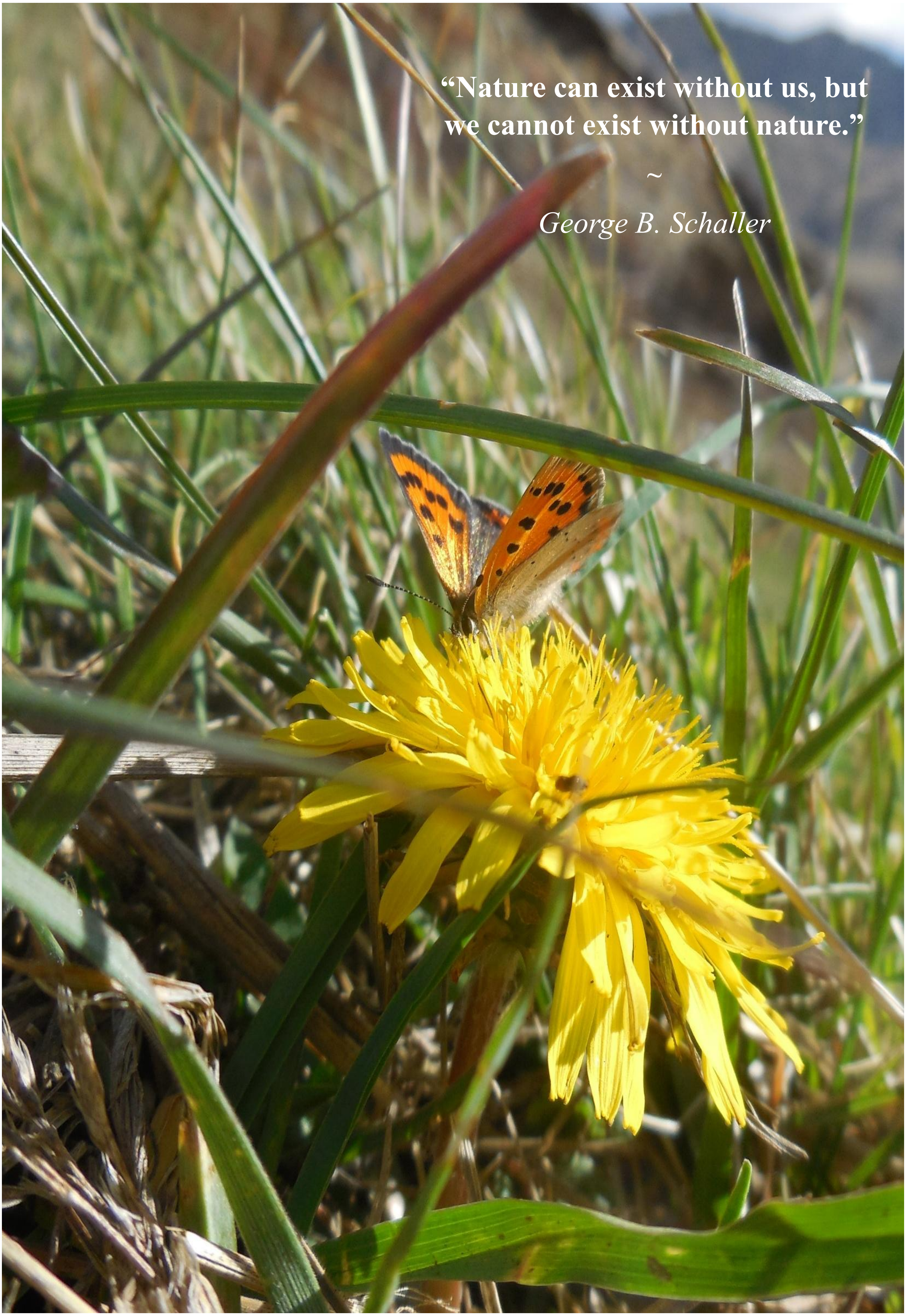

“Nature can exist without us, but
we cannot exist without nature.”

~

George B. Schaller

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Papers published

1. **Debnath, A.,** and Talukdar, G. (2025). Above-Ground Carbon dynamics of forest in Pithoragarh district, Uttarakhand. J. Botan. Soc. Bengal 79(2) : 1-7 (2025), ISSN 0971-2976

2. Sarkar, D., Jagannivsan, H., **Debnath, A.,** & Talukdar, G. (2024). A systematic review on the potential impact of future climate change on India's biodiversity using species distribution model (SDM) studies: trends, and data gaps. Biodiversity and Conservation, 1-17. 10.1007/s10531-024-02785-1

Conference presentations

1. Debnath, A., Ramachandran, A., and Talukdar, G. (2025). Spatiotemporal Dynamics and Prediction of Land Use Land Cover Change in a Himalayan Watershed Using Land Change Modeler. **ISG-ISRS National Symposium** 2025: Geomatics and space innovations towards Atmanirbhar Bharat: Insights and Frontiers, IIT Kharagpur Research Park, W.B. India, 25-27 November 2025

2. Debnath, A., Talukdar, G. (2024), Tracking Carbon Over Decades: Monitoring Ecosystem Services in the Askot Landscape, Indian Himalayas. **5th ESP Europe Conference**, Ecosystem Services: One Planet, One Health, Wageningen, The Netherlands, 18-22 November, 2024

3. Debnath, A., and Talukdar, G. (2024). Land Use and Land Cover Changes Over Three Decades (1990-2020) in the Western Himalaya: A Case Study of the Askot Landscape. **IEEE** India Geoscience and Remote Sensing Symposium **(InGARSS),** National Institute of Technology, Goa, India, 2-5 December, 2024.

4. Debnath, A., and Talukdar, G. (2023). Assessment of aboveground carbon stock in Askot Landscape: Implications for ecological restoration and climate change mitigation. First Indian Conservation Conference (**ICCON**), Mysuru, Karnataka, India, 9-11 April, 2023.

5. Debnath, A., Sarkar, D., and Talukdar, G. (2023). Modelling climatically vulnerable areas in Askot Landscape- A case study in the Indian Himalayan Region. 3rd International Workshop on 'Biodiversity and Climate Change – Sustainable Development Perspective (BDCC 2023), IIT Kharagpur, W.B. India,16-19 February, 2023

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Executive Summary

Ecosystem service (ES) mapping has emerged as a robust scientific approach to understanding landscape dynamics, conserving biodiversity, and sustaining nature's contributions to people amid land-use/land-cover change and accelerating climate change. In ecologically fragile mountain systems such as the Himalaya, ecosystem services are highly sensitive yet rarely quantified for decision making. The Askot landscape, situated in the western Himalayan landscape in Pithoragarh district of Uttarakhand, covers approx. 4496.49 sq.km. Despite providing vital regulating, provisioning, and supporting services, this region has received limited integrated assessment. Addressing this gap, the present study examined long-term land-use–land-cover (LULC) dynamics, associated carbon sequestration trends, and future climate vulnerability to support evidence-based decision making.

To achieve this, this study pursued three objectives:

(i) to analyse spatial and temporal LULC changes, (ii) to quantify trends in above-ground carbon storage across forest and vegetation types, and (iii) to identify climatically vulnerable areas under future climate scenarios.

The results reveal that nearly 10% of the Askot landscape experienced LULC change over the study period, with the most pronounced transformations occurring between 2011 and 2020, indicating an acceleration of recent landscape dynamics. Forests occupy only ~18% of the total landscape, yet they underpin a substantial share of ecosystem services. Dense forest area declined from 391.7 sq.km (1990) to 369.4 sq.km (2020), while moderate dense forest showed a sharper reduction (259.3 to 227.9 sq.km), accompanied by a marked increase in open forest (155.9 to 206.9 sq.km). This

pattern reflects widespread forest degradation rather than abrupt deforestation. Scrub ecosystems also declined, while landslides more than doubled (7.45 to 15.8 sq.km), signalling growing geomorphic instability. High-elevation systems exhibited strong climate sensitivity, with alpine meadows shrinking (842.2 to 790.4 sq.km) and snow cover declining by over 100 sq.km, alongside a substantial expansion of the Moraine class (473.3 to 714.5 sq.km), indicating snowline instability and water stress, affecting another vital ES.

Vegetation-type analysis further confirms degradation across major forest types. Oak-dominated systems (*Quercus leucotrichophora* (Banj Oak), *Quercus semecarpifolia* (Kharsu Oak), *Quercus floribunda* (Moru Oak), *Betula-Abies* (Birch–Fir), Deodar, Pine, and Mixed broadleaf forests all showed declines in dense and moderate canopy classes with a concurrent rise in open forest cover. Above-carbon carbon storage and sequestration show consistent declines across oak-dominated forests (Banj, Kharsu, Moru), Birch–Fir, Deodar, Pine, and mixed broadleaf systems, primarily through transitions from dense and moderate canopy classes to open forest. These structural changes directly influenced carbon dynamics. In 1990, the total AGC was estimated at 67,529.41 MgC, which declined to 66,597.79 MgC by 2020. Projections for 2050 indicate a further reduction in AGC to 66,062.30 MgC, corresponding to an additional loss of 535.49 MgC between 2020 and 2050. Total above-ground carbon stock declined from 67,529.41 MgC in 1990 to 66,062.30 MgC by 2050, representing a cumulative loss of 1,467.11 MgC over six decades. Meadows and scrub ecosystems showed the steepest proportional carbon losses, while forest carbon decline was driven largely by canopy thinning rather than loss of forest area. The relatively lower projected future carbon loss reflects the slow-changing nature of forest types, even as degradation continues.

Oak forests emerge as the primary climate mitigation asset in the Askot landscape, contributing ~61% of total above-ground carbon (AGC) by 2050 despite occupying less than 10% of the total area. When combined, all forest classes (oak, temperate, and mixed forests) account for 18% of total area and contributing to approximately 85% of total AGC, clearly establishing forests as the dominant carbon pool within the watershed.

This concentration of carbon within a limited forested area highlights the disproportionate importance of forests. Even marginal losses in forest cover translate into substantial carbon emissions; for instance, a 0.26% reduction in oak forest area corresponds to an estimated loss of ~105 MgC.

The scope of present study was to identify climatically vulnerable ecosystems in the Askot landscape by integrating Climate-Ecological Niche Factor Analysis (CENFA). To perform this analysis, two Shared-Socioeconomic Pathways (SSP) were considered, SSP245 (Middle of the road) and SSP585 (Worst-case scenario) for mid-century (2041-2060) and end-of century (2081-2100). Climate vulnerability assessment using CENFA highlights extensive areas of medium to high vulnerability, particularly under SSP585. High-vulnerability zones increase from 1266.7 sq.km (SSP245) to 1535.2 sq.km (SSP585) in the near future, and further expand to 1762.6 sq.km by end-century, disproportionately affecting alpine, sub-alpine, and degraded forest regions. These areas spatially correlated with zones of observed LULC change and carbon decline, underscoring climate–LULC risks.

Askot landscape is undergoing progressive ecological degradation driven by forest structural decline, high-elevation climate stress, and increasing disturbance. Integrating LULC dynamics, carbon assessment, and CENFA this research can support ecosystem-based adaptation leading to climate-adaptive land-use planning.

The study has been distributed in six chapters, outlined as follows:

Chapter 1

This chapter introduces concepts of ecosystem services, highlighting their ecological significance and set the context of the rest of the study. It offers a literature review from global to local context on ecosystem services, identifies research gaps and mentions the objectives/research questions of this study.

Chapter 2

Chapter 2 provides a comprehensive overview of the study area, offering an in-depth description of Askot landscape's geographical features, diverse habitat types, and ecological significance. It explores the region's topography, dominant vegetation, and key landscape elements that shape the local environment. And cultural significance. Additionally, the chapter delves into the human communities inhabiting the valley, their livelihoods, and their relationship with the land.

Chapter 3

Chapter 3 offers a comprehensive analysis of the landscape dynamics of Askot. The chapter also generates information on vegetation types, and changes in forest canopy cover density across vegetation types. It details the methodologies used for landuse landcover (LULC) mapping, and change analysis. It also discusses role of stressors/ drivers and implications in the landscape.

Chapter 4

Chapter 3 offers a comprehensive analysis of the spatio-temporal changes in above-ground carbon sequestration in the Askot landscape. It predicts future LULC for 2050, and quantifies above-ground carbon for past, present and future.

Chapter 5

This chapter looks into the future climate vulnerability of Askot landscape. A set of environmental variables, and spatial data used to quantify vulnerability scores. The Climate Niche Factor Analysis method was implemented using the (CENFA) package in R to analyse the climate sensitivity, exposure and vulnerability of Askot landscape.

Chapter 6

This chapter discusses the overall conclusions. It also highlights the relevance of current study. It tries to outline future research and management directions. It further mentions way forward and policy recommendation.

Chapter 1: Introduction

1.1 Evolution and Classification of Ecosystem Service Frameworks

Ecosystem Services (ES) represent the interface between ecosystem functioning and human well-being. While the recognition of nature's life-supporting role is ancient, modern ecosystem services framework has rapidly matured into a central tool for linking ecological health, human well-being, and economic decision-making over the last two decades (Wang et al., 2021). During the second half of the twentieth century, the degradation and loss of ecosystem services became increasingly evident as natural resources was rapidly depleted (Beddoe et al., 2009). This period also witnessed significant advances in ecological understanding—particularly at the scale of whole ecosystems—along with growing recognition of the non-market value associated with natural systems (Costanza et al., 2017).

The modern era of ES research began with the Millennium Ecosystem Assessment (MEA, 2005). The MEA defined '*Ecosystem services*' are the ecological characteristics, functions, or processes that directly or indirectly contribute to human wellbeing: that is, *the benefits that people derive from functioning ecosystems* (Costanza et al., 1997)). The MEA (2005) is the most widely recognized framework. It established the four-pillar classification: Provisioning, Regulating, Supporting and Cultural services. *Provisioning Services* include tangible products such as water, food, timber, and medicinal plants. *Regulating Services* encompasses benefits obtained from the regulation of ecosystem processes, such as climate regulation, flood control, and water purification. *Supporting Services* are necessary to produce all other services, such as soil formation, nutrient cycling, and primary production. *Cultural Services* includes non-material benefits like spiritual enrichment, recreation, aesthetic values, and religious heritage (e.g., sacred peaks and rivers). This framework was the first global assessments to highlight the importance of mountain ecosystems as natural "water towers," noting that the degradation of upstream regulating services creates profound downstream vulnerabilities (MEA, 2005).

Following the MEA, The Economics of Ecosystems and Biodiversity (TEEB, 2010) shifted the focus toward economic valuation. TEEB provided the language for "Natural Capital". It framed biodiversity loss not merely as an ecological concern but as a measurable economic cost arising from the degradation of ecosystem assets (Brouwer et al., 2013). In the Himalayan context, TEEB-informed approaches have played a key role in shaping '*Payment for Ecosystem Services*' (PES) mechanisms, wherein downstream beneficiaries—such as hydropower operators and urban water users—provide financial compensation to upstream mountain communities for conserving forest cover that enhances water quality, regulates flows, and reduces sedimentation.

To operationalize ecosystem services within policy frameworks, the Common International Classification of Ecosystem Services (CICES) was developed. CICES (v5.1) is a standardized tool designed for ecosystem accounting. CICES (Haines-Young & Potschin-Young, 2018) refined the categories to avoid "double counting" by focusing strictly on final services—those that directly interface with human well-being. It uses a 5-level hierarchy (Section, Division, Group, Class, and Class-type) for precise mapping and reporting (Czúcz et al., 2018). This is particularly useful for mountain watersheds when distinguishing between the ecological process (soil formation) and the service (reduced sediment in drinking water).

Conversely, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) introduced Nature's Contributions to People (NCP) in 2018, to broaden the conceptualization of human–nature relationships (Díaz et al., 2015). This framework acknowledges that the Western "utility" model of ES often overlooks Indigenous and local knowledge. NCP acknowledges that different cultures (including Indigenous and local communities) perceive their relationship with nature differently and explicitly recognizes cultural, spiritual, and relational values. NCP identifies *Material, Regulating, and Non-material* contributions (Díaz et al., 2018). For Himalayan cultures, where mountains are often personified as deities, NCP provides a more inclusive framework to capture 'relational values' that cannot be adequately represented through monetary valuation alone, thereby complementing accounting-focused approaches such as CICES.

The most recent conceptual milestone, The Dasgupta Review (2021), reframes ecosystem services as "dividends" derived from the global stock of natural assets, emphasizing the economic consequences of degrading natural capital. Dasgupta simplifies ecosystem service classification into three broad categories: *Material (provisioning) services, Regulating and Maintenance services,* and *Non-material (cultural) services* (Dasgupta, 2021). A central argument of the review is that regulating and maintenance services have been systematically undervalued in economic and policy decision-making. In the context of mountain watersheds, this imbalance is particularly evident: while economic benefits are often derived from material outputs such as timber extraction, the concurrent degradation of regulating functions—such as carbon sequestration, slope stabilization, and landslide prevention—remains largely unaccounted for, despite their critical role in safeguarding both upstream ecosystems and downstream communities (Dasgupta, 2021).

Following the Dasgupta Review (2021), global policy has moved toward institutionalizing natural capital through environmental accounting. In this context, the United Nations Statistical Commission (UNSC) adopted the *System of Environmental-Economic Accounting—Ecosystem Accounting (SEEA EA)* in March 2021 (United Nations, 2021). The SEEA EA represents an internationally agreed statistical framework developed under the auspices of the UNSC to systematically describe ecosystems, extent, their condition, and the ecosystem services they provide to society and the economy. Importantly, it aligns ecosystem accounting with the System of National Accounts (SNA) (United Nations, 2009; 2014), thereby enabling the incorporation of ecosystem services and natural capital into national economic reporting and policy frameworks. An editorial in Nature emphasized the critical role the SEEA could play in the context of the post-2020 global biodiversity framework, highlighting that the system "needs to become the global standard for environmental reporting" (Nature, 2020).

It is widely recognized that healthy ecosystems and biodiversity are essential for sustaining human well-being, supporting communities, and underpinning economic systems. Frameworks now explicitly connect ecosystem extent & condition to service capacity, flows, sustainability, and efficiency, showing that better ecological status generally enhances regulating and cultural services, while intensive provisioning can degrade ecosystems (Grizzetti et al., 2019; Hernández-Blanco et al., 2022). In mountain regions like the Himalayas, these frameworks are essential for translating the "invisible" benefits of upstream watersheds making them visible into actionable policy.

1.2 Effects of Land Use-Land Cover and Climate Change on Ecosystem Services in Mountain Watersheds

Land constitutes a fundamental natural resource that underpins ecological integrity and human well-being across both developed and developing regions (Sisay et al., 2021). Land use describes the ways in which humans utilize land—such as for agriculture, recreation, or settlement—whereas land cover refers to the physical and biological characteristics of the Earth’s surface, including vegetation, water bodies, and bare soil (Lambin et al., 2003). Although conceptually distinct, land use and land cover are tightly interlinked and evolve through prolonged interactions between human activities and natural processes (Liu et al., 2025). Changes in land use and land cover (LULC) have emerged as a major driver of ecosystem degradation worldwide (Admasu et al., 2023). Anthropogenic alterations to landscapes disrupt fundamental biophysical processes such as soil formation, as well as biogeochemical cycles including carbon storage and nutrient regulation (Riano Sanchez et al., 2024). While LULC transitions often deliver short-term economic benefits to societies, they simultaneously modify ecosystem structure and functioning, frequently leading to imbalances in critical services such as air and water quality, disaster regulation, and human health support systems (Admasu et al., 2023). These transformations highlight the trade-offs inherent in land-use decisions, where immediate gains are often offset by long-term ecological costs.

At the global scale, the combined influence of climate change and intensified land-use practices has substantially altered ecosystem functions and services (Hasan et al., 2020). Climate change acts as a pervasive, long-term stressor that modifies temperature regimes, precipitation patterns, and hydrological cycles, while LULC change tends to exert more immediate and localized impacts. Together, these drivers interact synergistically, amplifying ecological stress and accelerating biodiversity loss and ecosystem service decline (Brodie, 2016). The conversion of natural ecosystems into agricultural and urban landscapes, in particular, has been identified as a leading cause of ecosystem degradation (Elias et al., 2019).

Mountain watersheds are especially sensitive to these interacting pressures. Globally, and particularly in the Himalaya, LULC change and climate variability jointly reshape essential ecosystem services such as freshwater provision, soil stabilization, carbon sequestration, habitat quality, and disaster risk regulation. While LULC changes rapidly alter land-surface processes and ecosystem functions, climate change intensifies hydrological extremes, compounding risks such as floods, landslides, and water scarcity (Pepin et al., 2022). At the global scale, LULC change and land degradation now affect ecosystem health to such an extent that nearly half of humanity is directly impacted, resulting in annual losses of ecosystem service values estimated at approximately USD 40 trillion—nearly half of global GDP in 2021 (Z. Zhang et al., 2026).

In the geologically fragile and environmentally dynamic montane systems such as the Himalaya, where understanding the underlying ecological mechanisms driving ecosystem change is essential for effective monitoring and management (Xu et al., 2009). Continued LULC change threatens ecosystem functioning and resilience, undermining the capacity of mountain landscapes to sustain ecosystem services for present and future generations. This underscores the critical need to systematically quantify and evaluate the impacts of LULC dynamics on ecosystem services to support informed conservation and land-use planning strategies (Belay et al., 2022; Hasan et al., 2020).

1.3 Review of Ecosystem Service Studies in the Himalayan Region: Indian Context

Across the Himalayan region, ecosystem services (ES) research is strongly skewed toward provisioning services, followed by regulating services, while cultural and supporting services remain poorly represented. Within the Hindu Kush Himalaya, China and Nepal dominate the literature, with India ranking third; Indian studies largely emphasize biophysical assessments and provisioning-oriented services, with limited attention to socio-political dimensions of ES management (Kandel et al., 2020; Das et al., 2023). In the Far Eastern Himalaya, including Northeast India, nearly 77% of valuation studies focus on recreation, water regulation, forest products, and carbon sequestration, predominantly using economic valuation approaches, whereas socio-cultural and biophysical valuations are comparatively rare (Shrestha et al., 2023). Quantitative reviews further confirm this imbalance, with provisioning services accounting for ~48% of Himalayan ES studies, followed by regulating (28%), supporting (13%), and cultural services (11%), fuelwood and natural hazard regulation being the most frequently examined services (Mandal et al., 2023). Similar Himalaya-wide syntheses report consistent underrepresentation of cultural services and limited integration of regulating services such as carbon, highlighting persistent thematic and methodological gaps in the region's ES literature (Sharma et al., 2024; Bhatt et al., 2024).

Several persistent gaps characterize ecosystem services research in the Himalayan and Indian context. Regulating services beyond water and hazard mitigation, such as climate regulation (carbon sequestration) and soil fertility, along with cultural services, remain far less quantified and valued than provisioning services (Mengist et al., 2019;

Mandal et al., 2023; Sharma et al., 2024; Bhatt et al., 2024). Methodologically, many studies are limited to identification of ES, with comparatively fewer providing spatially explicit quantification (~40%) or economic valuation (~24%) (Sharma et al., 2024). Spatially, research is concentrated in the Central Himalaya, while the Western Himalaya districts remain under-represented (Mondal & Zhang, 2018; Mandal et al., 2023). Reviews further highlight a scarcity of landscape-scale, multi-service modelling that integrates LULC change with ecosystem service dynamics, particularly in the western Himalaya (Mondal & Zhang, 2018).

Recent Himalayan ES work increasingly uses spatial models and empirical–GIS approaches (production possibility frontiers, trade-off/synergy analysis, watershed-scale ES bundles) but still from few landscapes and mostly outside India (Aryal et al., 2023; Gupta et al., 2023). Reviews for western Himalaya explicitly recommend quantification and spatial mapping of ES as a major research need (Mondal & Zhang, 2018). Model-based tools such as InVEST fit this emerging direction, especially to move from site-level studies to landscape-scale ES assessment and scenario analysis (Aryal et al., 2023; Shakya et al., 2021).

The Uttarakhand Himalaya, situated in the central sector of the Indian Himalayan Region, represent a key component of this mountain system. The state is characterized by complex terrain, fragile geology, and pronounced altitudinal variation, giving rise to numerous mountain watersheds (ICIMOD, 2012). Despite their importance, watershed ecosystems in the Uttarakhand Himalayas are increasingly under stress. Rapid infrastructure development, expansion of road networks, hydropower projects, land-use change, and deforestation have altered natural watershed processes. These pressures, combined with climate-induced changes such as glacier retreat, shifting precipitation patterns, and an increase in extreme rainfall events, have heightened the vulnerability of mountain watersheds and the services they provide (FAO, 2011; ICIMOD, 2012). Given these challenges, a systematic understanding of ecosystem services provided by mountain watersheds in the Uttarakhand Himalayas is essential. Assessing the structure, functioning, and service provisioning of these watersheds can support informed decision-making and promote integrated management approaches.

Uttarakhand explicitly treats forest carbon stock and NPP as core regulating services, combining them with water retention and sediment control into a multiple ecosystem services indicator, and shows a strong inverse relationship between service supply and human activity (Gwal et al., 2020; Gupta et al., 2023).

A broader Himalayan review summarizes >135 carbon related studies, quantifying regional C stocks and sequestration (≈65 Mt C yr^{-1} for the Indian Himalayan Region) and emphasizing the role of above and below ground biomass in national mitigation commitments (Tolangay & Moktan, 2020).

1.4 Justification for selecting Above-ground Carbon

Mountain ecosystems deliver a wide range of ecosystem services to more than 15% of the global population residing in mountainous regions (Locatelli et al., 2017; Dragonetti et al., 2024). These services including food, freshwater, medicinal resources, and livelihood support are central to human well-being and socio-economic development (MEA, 2005). In addition, mountain systems play a critical role in regulating climate, air quality, and hydrological processes, thereby providing indispensable benefits far beyond their geographical boundaries (Grêt-Regamey et al., 2012; Schirpke et al., 2019; Viviroli et al., 2020). However, the sustained provision of these services is highly dependent on LULC patterns and their trajectories over time (Belay et al., 2022).

Among the various ecosystem services influenced by land-use change, *above-ground carbon storag*e represents a key regulating service that is particularly sensitive to shifts in forest cover, vegetation density, and land management practices.

Himalayan forests are highlighted as key carbon reservoirs whose sequestration and carbon-credit potential can directly support India's REDD+ and NDC goals (Joshi & Garkoti, 2025). Yet, reviews of LULC and ES in western Himalaya note that spatial mapping of carbon-related ES and LULC impacts is sparse and incomplete, and specifically call for regional/landscape-level ES maps to guide land-use decisions (Mondal & Zhang, 2018).

In mountain landscapes such as Askot, carbon stocks are unevenly distributed across elevation zones and land-use classes, making them highly responsive to both deforestation and forest regeneration. Moreover, above-ground carbon serves as a measurable indicator of ecosystem functioning and climate regulation, with implications for regional carbon budgets and climate mitigation strategies. Given its strong linkage with observed LULC transitions and its relevance to both ecological integrity and policy frameworks, above-ground carbon was selected for detailed present and future assessment in this study.

1.5 Rationale and Objectives

The Western Himalaya is widely recognized as an ecosystem service hotspot, yet it remains poorly represented in spatially explicit ecosystem service despite well-documented land-use/land-cover (LULC) change and ongoing forest restoration initiatives (Mondal & Zhang, 2018; Jha et al., 2022; Negi et al., 2022; Gupta et al., 2023; Dangwal et al., 2022). Addressing this gap is important as accelerating climate variability and LULC transitions in Himalayan Mountain watersheds are jointly reshaping ecosystem service dynamics, particularly carbon storage, habitat integrity, and regulating services. While climate change alters hydrological processes and hazard regimes, land-system changes such as forest loss, degradation, and recovery exert strong controls on ecosystem functioning. However, existing studies often assess individual drivers or ecosystem services in isolation, limiting their relevance.

This thesis attempts spatially explicit above-ground carbon modelling of the Askot region aligned with global calls for model-based, ecosystem service assessments in mountain systems (Mengist et al., 2019; Shakya et al., 2021; Aryal et al., 2023) and directly addressing recognized research gaps in the western Himalaya. This thesis therefore aims to assess ecosystem service provisioning in the Askot landscape, Uttarakhand, to support sustainable watershed management and enhance ecological resilience in the Himalayan region.

Objectives

The specific objectives and associated research questions of this study are as follows:

1. **To examine the landscape dynamics in Askot Landscape**
    1. How has LULC changed spatially and temporally in the study area?
    2. Which LULC classes show the highest rates of change?
    3. What are the key drivers shaping LULC dynamics?

2. **To quantify the trends in select ecosystem services in the study area**
    1. How do temporal changes in land-use/vegetation types influence above-ground carbon sequestration in the Askot landscape in past, present and future?

3. **To identify climatically vulnerable regions in Askot landscape under the future climate change scenarios**
    1. Where are the climatically vulnerable areas in Askot ?

Chapter 2: Study Area

2.1 Introduction

The Askot landscape lies between latitude $29^{0}05'$ to 30^{0}N, and longitude 80^{0} to $81^{0}05'$E, in Pithoragarh district of Uttarakhand. It encompasses an area of approximately 4500 km^{2} and shares an international border with the Tibetan Autonomous Region of the Peoples' Republic of China in the north (Fig 2.1). The Kali River forms the southeastern border of the landscape till Jauljibi, as well as an international border between India and Nepal (Government of India 2011). The Kali River has three tributaries on the Indian side namely Gori-Ganga, Dhauli and Kutti, which form the catchments of the Askot Landscape. The Western and North - Western boundary of the landscape runs along the right bank of the East Gori River. The total study area includes part of Munsyari and whole of Dharchula intermediate/ Khestra Panchayat. The landscape is a converging point of bio-geographic elements of the Western Himalaya, the Central Himalaya and the Tibetan Plateau.

Due to the significant compression of life-zones within a compact geographical area, this landscape showcases a remarkable diversity of landscapes and ecosystems. From about 590 metres above sea level at Jauljibi, at the confluence of the Gori with the Kali, to 7434 metres a.s.l at the summit of Nandadevi East, amongst a multitude of high, ice-bound mountain massifs, including some others over 7000 meters such as Hardeol and Trisuli. Among the notable peaks in the region are Suitilla, Chiringwe, Chikulawe, Bambhadhura, Rajrambha, Ngalaphu, Ngangling, and Adi Kailash, all towering at heights exceeding 6000 meters. These high mountain precipices slope down to progressively warmer valleys, yield altitudinal gradients and climatic conditions that range from frigid arctic conditions to the warm and humid sub-tropical.

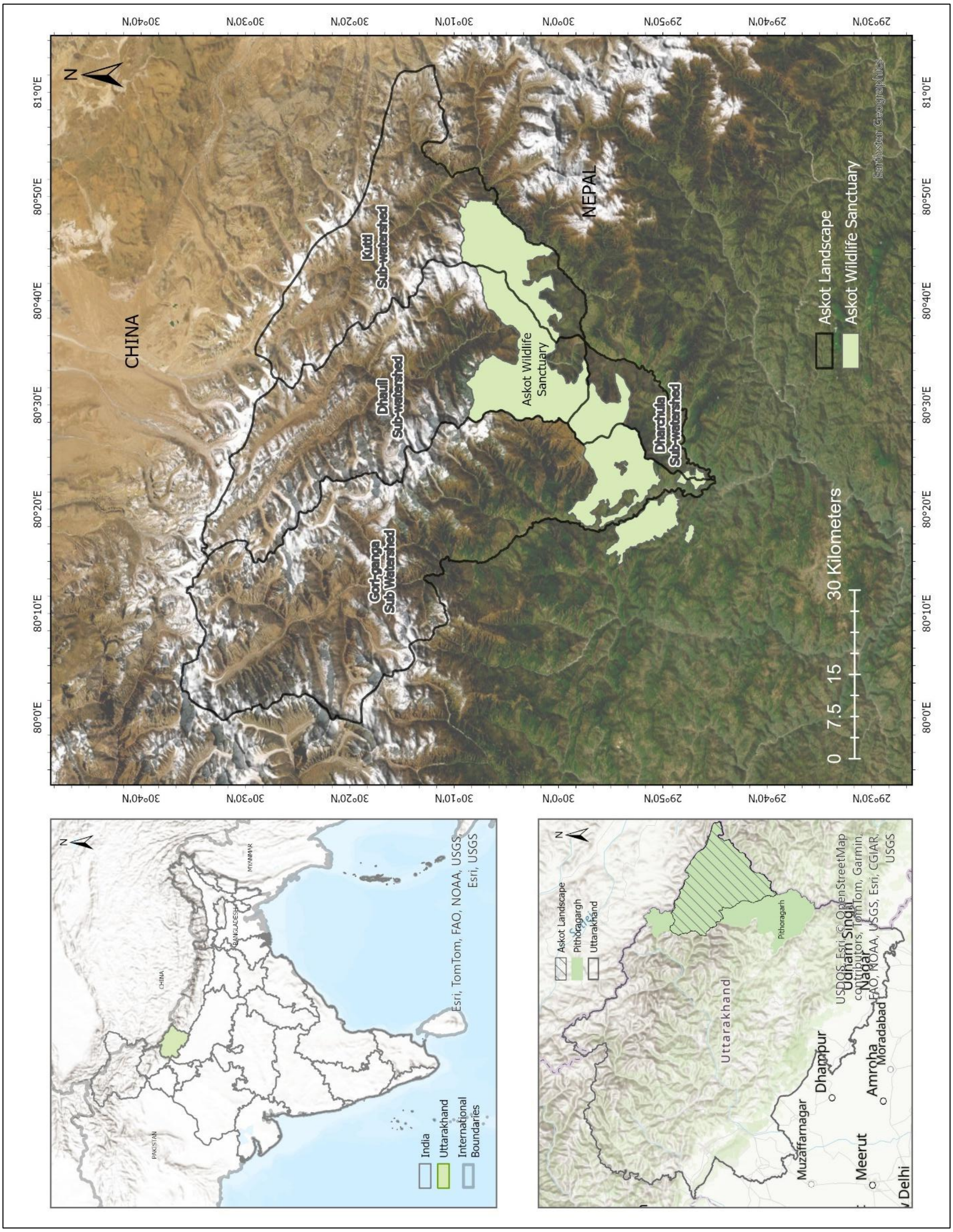


Fig 2.1: Study area map

2.2 Climate

The climate of Askot is highly varied and complex due to its wide range of elevations, stretching from subtropical valleys to high Himalayan peaks. The region is classified into several climatic zones: cool moist and dry zones (600–2500 m), cold snow-bound regions (2000–3500 m), perpetually snow-covered alpine areas above 3500 m, and dry trans-Himalayan valleys in the rain-shadow belt. The region experiences four distinct seasons—a cold winter from mid-December to mid-March, a hot summer from mid-March to mid-June, the south-west monsoon bringing the bulk of rainfall from mid-June to mid-September, and a retreating monsoon from mid-September to mid-November. In summer with the temperature varying from 15°C to 40°C and the very cold winter season with the temperature varying from 7°C to below 0°C. In the cold winter season the region is buried under snow with snow depth varying from 1.5 to 3m. The snow melts in the first week of June. The cold winter wind during the month of October in the latter half of the day forces people to abandon the outdoor activity. The summer season is called *Chaumas* and the cold winter season is called *Huin* (Negi, 2010).

Long-term temperature data for the Askot landscape were derived from gridded and station-based datasets provided by the India Meteorological Department (IMD), Pune, accessed through the IMD Climate Monitoring and Prediction Group (CMPG) portals and the ***imdlib*** Python library. Annual and seasonal temperature variables were extracted for the period ~1970–2024 from IMD's high-resolution gridded datasets, including maximum and minimum temperature records (fig 2.2, 2.3, 2.4). Seasonal means were computed for summer (March–June) and winter (November–February), while annual mean maximum and minimum temperatures were also calculated. Linear trend analysis was applied to each time series to quantify long-term warming signals, and the results were visualized to assess temporal variability and directional change in temperature regimes relevant to ecological and climatic vulnerability assessment in Askot.

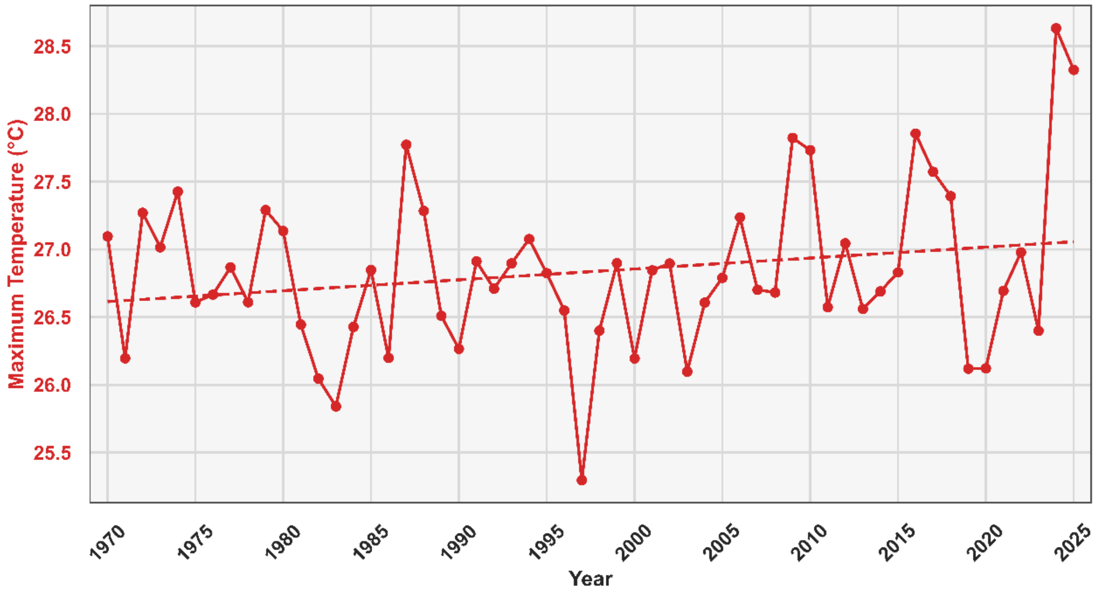


Fig 2.2: Annual mean maximum temperature for Askot (1970–2025)

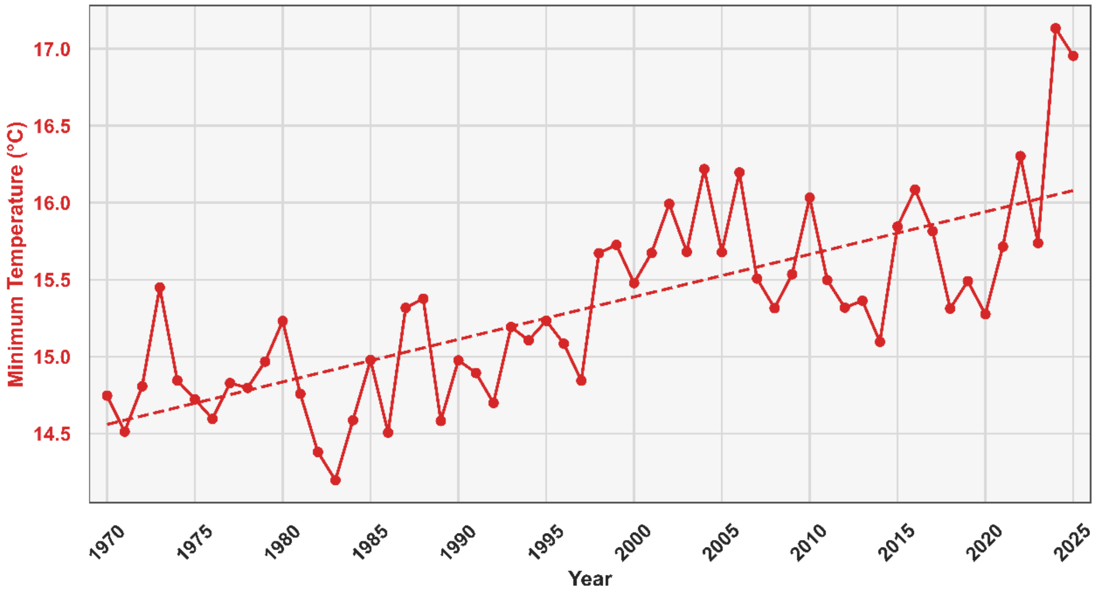


Fig 2.3: Annual mean minimum temperature trend for Askot (1970 - 2025)

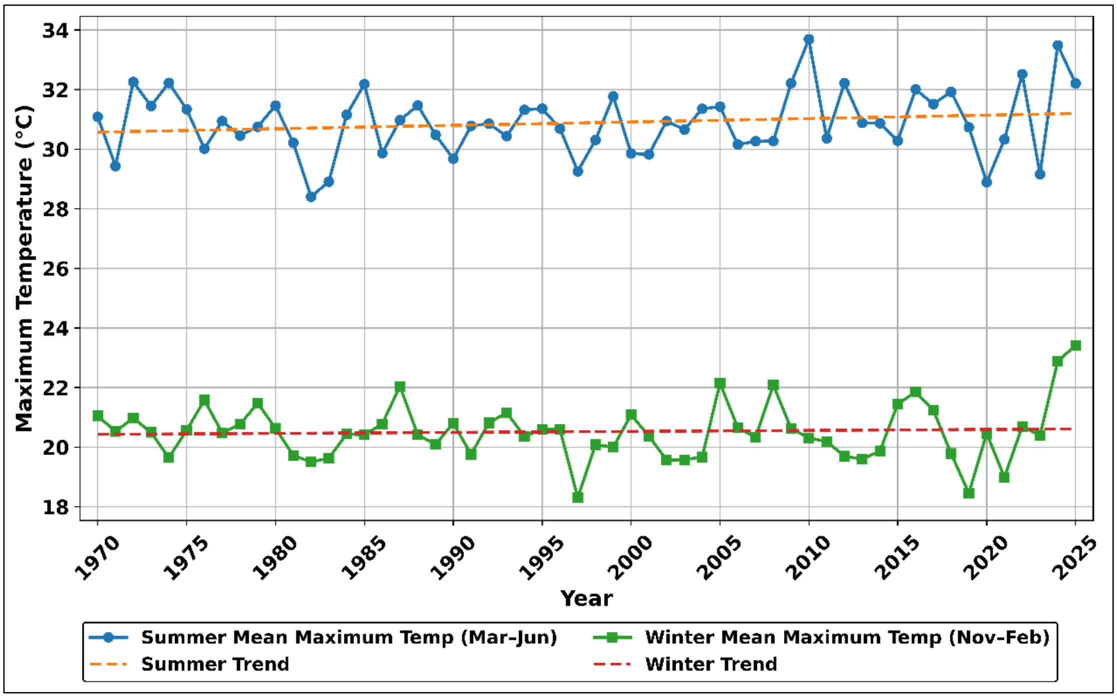


Fig 2.4: Annual Summer/Winter mean maximum temperature trend for Askot (1970 - 2025)

The graphs indicate a clear long-term warming trend in Askot across seasons. Summer mean maximum temperatures show a gradual but consistent increase over the past five decades, with higher interannual variability and pronounced peaks in recent years. Winter mean maximum temperatures also exhibit a positive trend, indicating reduced winter cooling. The annual minimum temperature series reveals a stronger and more persistent warming signal, suggesting a rise in night-time temperatures, which is ecologically significant for montane ecosystems. Similarly, annual maximum temperatures display an overall upward trend, with recent decades characterized by higher extremes. Together, these patterns reflect ongoing climatic warming in the Askot region, with implications for vegetation dynamics, ecosystem services, and climate-sensitive species.

2.3 Precipitation

The significant fluctuations in altitudes across the region play a crucial role in influencing climatic conditions within the landscape. Coupled with the terrain, these variations contribute to the development of unique microclimatic characteristics in various locations. Consequently, the weather shows extreme variations in temperature and precipitation. Rainfall is quite variable in this area (fig 2.4). Averaging below 200 cm annually in the lower reaches of these valleys, the areas in the Greater Himalaya zone here, for example the Panchachuli basin on the western flanks receives as much as 300 cm of torrential rain. The upper Trans-Himalaya reaches of these valleys, on the other hand, are in the rain-shadow, and comprise an arid cold-desert area that receives less than 15 cm of rain annually. This is excluding the precipitation in the form of snow in winter. Avalanches are a regular phenomenon, as witnessed by the huge, impacted cones of avalanche debris along many gorges, forming snow bridges across the rivers at many points that can sometimes remain un-melted till the following winter.

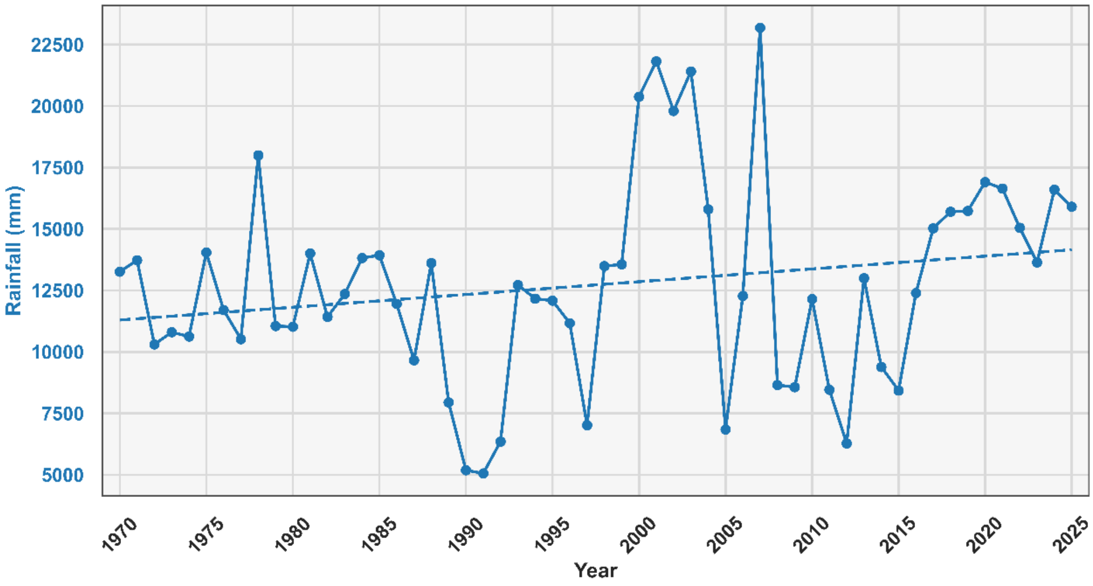


Fig 2.5: Annual mean daily rainfall trend (1970-2025)

The mean annual rainfall series for the Askot region shows pronounced inter-annual variability over the past five decades, characteristic of Himalayan monsoon-dominated systems. While individual years exhibit sharp extremes—ranging from notably dry years to episodes of exceptionally high rainfall—the fitted linear trend indicates a modest long-term increase in mean annual rainfall. This upward tendency suggests a gradual intensification of annual precipitation totals, likely driven by changes in monsoon dynamics. Importantly, the increasing variability, rather than the mean alone, points to a higher frequency of rainfall extremes, which has direct implications for slope stability, soil erosion, hydrological regimes, and ecosystem processes in the Askot landscape.

Sources (footnote)

https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html

https://imdlib.readthedocs.io/en/latest/

https://www.imdpune.gov.in/cmpg/Realtimedata/min/Min_Download.html

https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html

2.4 Drainage and Watershed

Askot landscape has perennial snow and glaciers, which forms a part of upper Ganga basin and Ghagara sub - basin, where many important rivers originate. The major rivers flowing in the landscape are Kali and Gori. River Kali forms the northern border of the landscape and has a length of 96.14 km. Originating from Trans - Himalayan zone it forms a continuous border with Nepal from Kalapani to Tanakpur. It runs in the South-Eastern direction forming a serpentine hilly course and meets river Gori at Jauljibi. Kutti - Yangti river originates from Parvati Tal near Adi Kailash and meets river Kali at Gunji. It is placed in the extreme North-Eastern region of the landscape and forms the main river in Kutti basin. Dhauli-ganga River is formed at the confluence of Lissar Yangti and Darma Ganga rivers. It forms the Dhauli drainage basin which joins Kali River at Tawaghat. Gori Ganga forms the largest drainage basin in the landscape.

There are four sub - watersheds in the study area. Gori-ganga is the largest, constituting 1920.21 km² area, Dhauli - 1363.33 km², Kutti 988.96 km² and Dharchula spread across 223.65 km².

2.5 Habitat, flora & fauna biodiversity

The climate, soil diversity, and unique topography of the region comprise lush vegetation, diverse species, and habitats (Samant et al., 2006). Reserve Forests and Van Panchayats (VP) constitute 46.42% of the landscape and are some of the most pristine areas of high biodiversity values. The study area is mainly dominated by a wide variety of flora, including many unique subtropical, temperate, and alpine plants (Kala et al. 2022). The landscape contains 2607 species of vascular plants, 265 species of birds, 37 of mammals, many of which are endemic, rare or endangered (Consortium, 2007). According to a study (Samant, Dhar, & Rawal, 1998) total of 1262 species of vascular plants belonging to 707 genera and 173 families were recorded in Askot Wildlife Sanctuary, Pithoragarh province of Uttarakhand. Maximum diversity was observed in the family *Orchidaceae* in 120 taxa. 44 species were identified as major source of fuel and fodder out of which 36 were trees, 6 shrubs and 2 woody. The Askot Wildlife Sanctuary alone represents over 60% of its native flora as endemic to the Himalayas. In the area 196 taxa were identified in the threatened category. Out of which 10 has already been recorded in the Red Data Book of Indian Plants (Samant, Dhar, & Rawal, 1998).

2.6 Socio-Economy

Traditionally the Bhotias have been traders with Tibet and this engagement was the predominant reason for the establishment of the high altitude villages, then thriving with people and prosperity. The Bhotiyas traded jaggery, millets and woolen products with the residents of the Tibetan highlands for salt, borax, and products lie yak tales, furs, hides, and livestock such as goats, sheep and ponies. The India China war of 1962, however, led to a termination of the border trade and proved to be a turning point for the trans-Himalayan traders. This event led to the first wave of outmigration from the highlands of Kumaon by erstwhile traders who could afford to settle in the plains. Those who did not out-migrate settled in the hills and were dependent on agriculture and pastoralism predominantly. The Bhotiyas of the Johar valley are known as Shaukas. One of the defining characteristic of the Bhotiya community is the practice of transhumance, or migration between summer and winter villages to use grazing land and grow crops. The main pastoralist community using the alpine meadows include Shaukas and Anuwals who migrate seasonally to these pastures with their animals (Sharma, Rollefson & Morton 2003).

Economy is agriculture based with small and fragmented land holdings. The crops grown are wheat, lentil, mustard, spinach, onion, garlic, peas in winter and paddy, maize, soyabean, potato, rajma in summer. Livestock play a significant role including means of goods transportation and employment through wool production with strong livestock-farming-forest linkage. The people had a strong barter trade relationship with the Tibetans and were masters of the trans-Himalayan trade. Extraction and cultivation of medicinal and aromatic plants could provide an opportunity to enhance the incomes of the people. The now declining cottage industry of wool and woollen products had as major products: Dan (carpet), Chutaka (shawl), Pankhi (shawl), Thulma (blanket), Asan (prayer rugs), Karboze (saddle bags for sheep and goats). 211 different local varieties of food crops are grown out of which 105 are cereals or pseudo-cereals, 21 pulse crops, 10 oil-yielding plants, 10 spices, 41 varieties of paddy (31 upland varieties not needing flooding), 20 varieties of wheat and barley, 14 varieties of finger millet, 5 other millets. Villages above 1800 m cultivate only 7-8 varieties of vegetables and use 10-12 different wild plants as vegetables. A wide range of NWFP is also harvested in the landscape such as herbs, honey, fruits and food plants, lichens and a larva (*Cordyceps sinensis*) that gets infected by a fungus and thereby acquires as a high value Chinese medicinal value.

2.7 Cultural Importance of Askot Landscape

Dotted with sacred sites, high-altitude lakes, rivers, snow peaks, this ecologically diverse and multicultural landscape has a history that goes back to thousands of years. This landscape is part of Kailash Sacred landscape. The district Pithoragarh finds its mention in many ancient scriptures like Mahabharat, Skand Purana, and others as the holy mountain Kailash and the divine lake *Maansarovar* in Tibet are located close to its northern boundary (Srichandan et al. 2021). From a strategic geopolitical perspective, the landscape is situated at the tri-junction of India, China, and Nepal. It is home to ancient transhumance routes used for pilgrimage (*Kailash–Maansarovar Yatra*), trade, and seasonal migration. The Askot-Adi-Kailash region is of great reverence and brings together people of different faiths such as Hindus, Buddhists, Jains, and The landscape’s elevation ranges from 500m to 6000m, while the majestic heights of Panchachuli (6,904 m), Adi Kailash (6,191 m), and Om Parvat (5,590 m) fascinates people of all faiths. The main languages include Kumaoni (high variability), Rung Low (comprising of Darma Low, Bangba Low and Byankhupa Low where Low means language), Hindi, and Nepali. Indigenous ethnic groups in this area include Van Rawats and Rung communities. The Rang, Byasi, Johari and Chaudasi live permanently/migrate in upper Himalayas. Their traditional occupations are woollen craft business, agriculture, and medicinal plant collection. Now there is also a shift towards government jobs. The Anwal community is mainly occupied in the goat and sheep business. They partially do farm nowadays. Van Rajis are a tribal community, mainly occupied with wooden work. Other communities are engaged in private and government jobs.

Chapter 3: Landscape Dynamics of Askot Landscape

3.1 Introduction

Human-induced land conversions—particularly the transformation of natural ecosystems into agricultural and urban areas—remain a dominant cause of ecosystem degradation worldwide, with cascading impacts on climate patterns, biodiversity, and socio-economic systems (Corlett, 2015; Sala et al., 2000; Flynn et al., 2009; Admasu et al., 2023). These pressures, compounded by rapid anthropogenic climate change, intensify risks of biodiversity loss, hydrological extremes, and climate-related hazards such as floods and droughts (Radchuk et al., 2019; Turvey & Crees, 2019).

Scenario-based studies from major mountain systems worldwide highlight that the relative influence of climate change and land use–land cover (LULC) on ecosystem services is service-specific. Research from China's Changbai, Hengduan, karst, and Altay Mountain regions consistently indicates that climate change is the dominant driver of water-related ecosystem services, particularly through its effects on precipitation regimes, snowmelt, and runoff dynamics. In contrast, LULC change exerts a stronger control over carbon storage and habitat quality by directly modifying vegetation structure, biomass accumulation, and landscape connectivity (Wang et al., 2022; Liu et al., 2025; Li & Xu, 2023; Wang & Dai, 2020).

Comparable patterns have been reported across the Himalayan region, although with pronounced spatial heterogeneity. Reviews focusing on Nepal and the Western and Central Himalaya's basin-scale LULC assessments in the Gandaki, Koshi, Karnali, and Phewa demonstrate that gains in forest and grassland cover can increase total ecosystem service value (ESV). However, these benefits are frequently offset by concurrent losses of glaciers and seasonal snow, which weaken water regulation and climate-regulating services (Rimal et al., 2019; Rai et al., 2023; Rai et al., 2018; Shrestha et al., 2022; Shrestha et al., 2019). Studies also show that community-managed and restored forests substantially improve sediment retention, carbon sequestration, and habitat quality, though in some cases this occurs at the expense of reduced dry-season water discharge (Rai et al., 2018; Paudyal et al., 2019).

Land use and land cover (LULC) change is one of the most important drivers of ecosystem service alteration in mountain systems, particularly in the Himalaya, where steep environmental gradients and human dependence on natural resources amplify landscape sensitivity. Evidence from the Western and Central Himalaya consistently shows that LULC transitions affect bundles of ecosystem services, including provisioning, regulating, supporting, and cultural services, rather than individual services in isolation (Mondal & Zhang, 2018). Across Uttarakhand and adjoining Himalayan regions, forest loss and fragmentation coupled with expansion of agriculture, built-up areas, and barren land have resulted in declining ecosystem service potential, especially regulating services such as carbon sequestration, water regulation, soil conservation, and habitat support (Mondal & Zhang, 2018; Gu et al., 2021; Pokhariya et al., 2024). District-scale assessments in Uttarakhand further demonstrate that LULC transitions—particularly forest conversion and urban expansion—significantly alter carbon storage and sequestration patterns, with strong spatial heterogeneity (Khan et al., 2024). Similar patterns are observed across the broader Himalayan region, where forest degradation leads to disproportionate losses in ecosystem service value, while restoration and community forestry enhance regulating and supporting services, often with trade-offs in agricultural provisioning (Rai et al., 2023; Das et al., 2023). Despite this growing body of work, most studies remain LULC-centric, rely on aggregated ecosystem service valuation, and rarely examine spatially explicit carbon dynamics alongside landscape transitions (Mondal & Zhang, 2018; Rai et al., 2023). Against this backdrop, the present study focuses on Askot, a climatically sensitive and ecologically diverse Himalayan landscape, to examine how multi-decadal LULC changes have influenced carbon storage patterns, thereby addressing a critical gap in fine-scale, ecosystem-based assessments for mountain decision-making.

3.2 Methodology

3.2.1 Analysis of LULC Spatial extent

Land use–land cover (LULC) change in the Askot landscape was assessed using multi-temporal satellite imagery from Landsat 4 TM (1990), Landsat 7 ETM+ (1999), IRS LISS III (2011), and Sentinel-2A (2020) (table 3.1). All images were radiometrically corrected to ensure consistency across sensors and time periods. LULC classification was carried out through on-screen visual interpretation (Fig 3.1) for identifying vegetation type (table 3.2), supported by ground truth data and Forest Survey of India (FSI) forest type and density maps from the India State of Forest Report (ISFR). Forests were further classified into dense, moderate, and open categories. On-screen visual interpretation method (was employed using Google Earth and ArcGIS desktop (v10.8.0) software to map the changes in spatial extents. The resulting LULC maps were subjected to accuracy assessment using independent reference data, and post-classification comparison was employed to detect temporal changes, enabling the identification of forest degradation and transitions among forest density classes over time. The resulting change layer is stored in both raster and vector formats for subsequent analysis (Fig 3.2).

Table 3.1:Details of geospatial data used for analysis

S.No.	Satellite/Sensor	Source	Date of acquisition	Path & Rows	Resolution	Columns & Rows	Bands
1.	LANDSAT 5 Thematic Mapper	USGS Earth Explorer	23.10.1990 15.11-1990	144/39	30 m	145/39	Standard False Colour Composite (NIR, R, G)
2.	LANDSAT 7 Enhanced Thematic Mapper	USGS Earth Explorer	09.11.1999 15.10.1999	144/39	30 m	145/39	Standard False Colour Composite (NIR, R, G)
3.	IRS P6 Linear Imaging Self-Scanning System (LISS) III	Bhuvan	18.10.2011	098/049	23.5 m	099/050	Standard False Colour Composite (NIR, R, G)
4.	SENTINEL-2A	Copernicus	22.11.2020 14.11.2020	0500/062	10m	0500/019	Standard False Colour Composite (NIR, R, G)

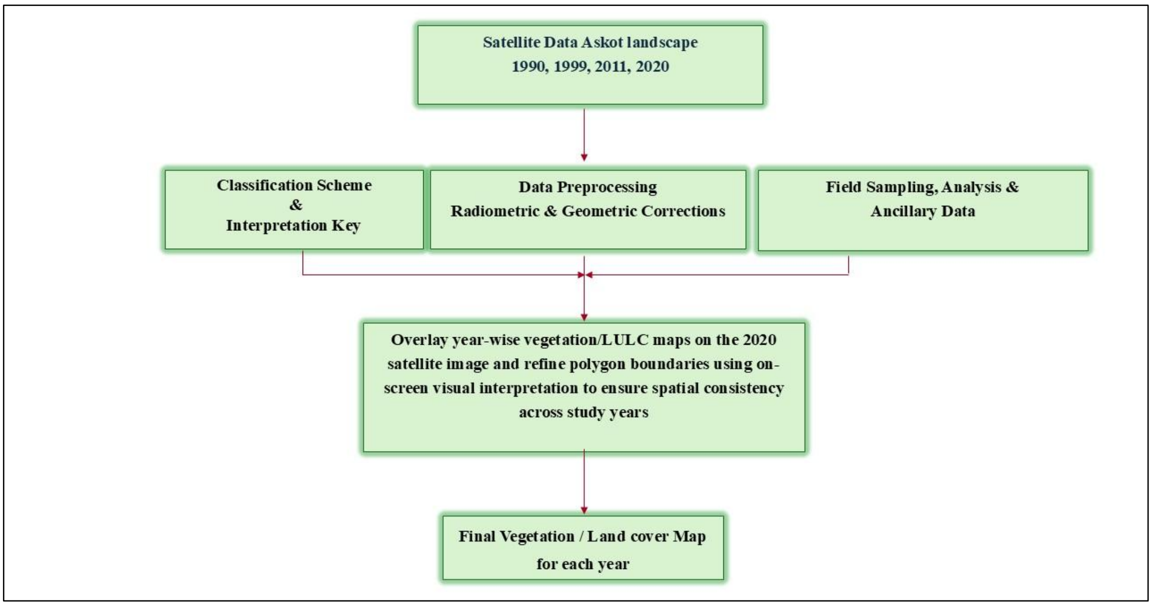


Fig 3.1:Methodology for data preparation & visual interpretation

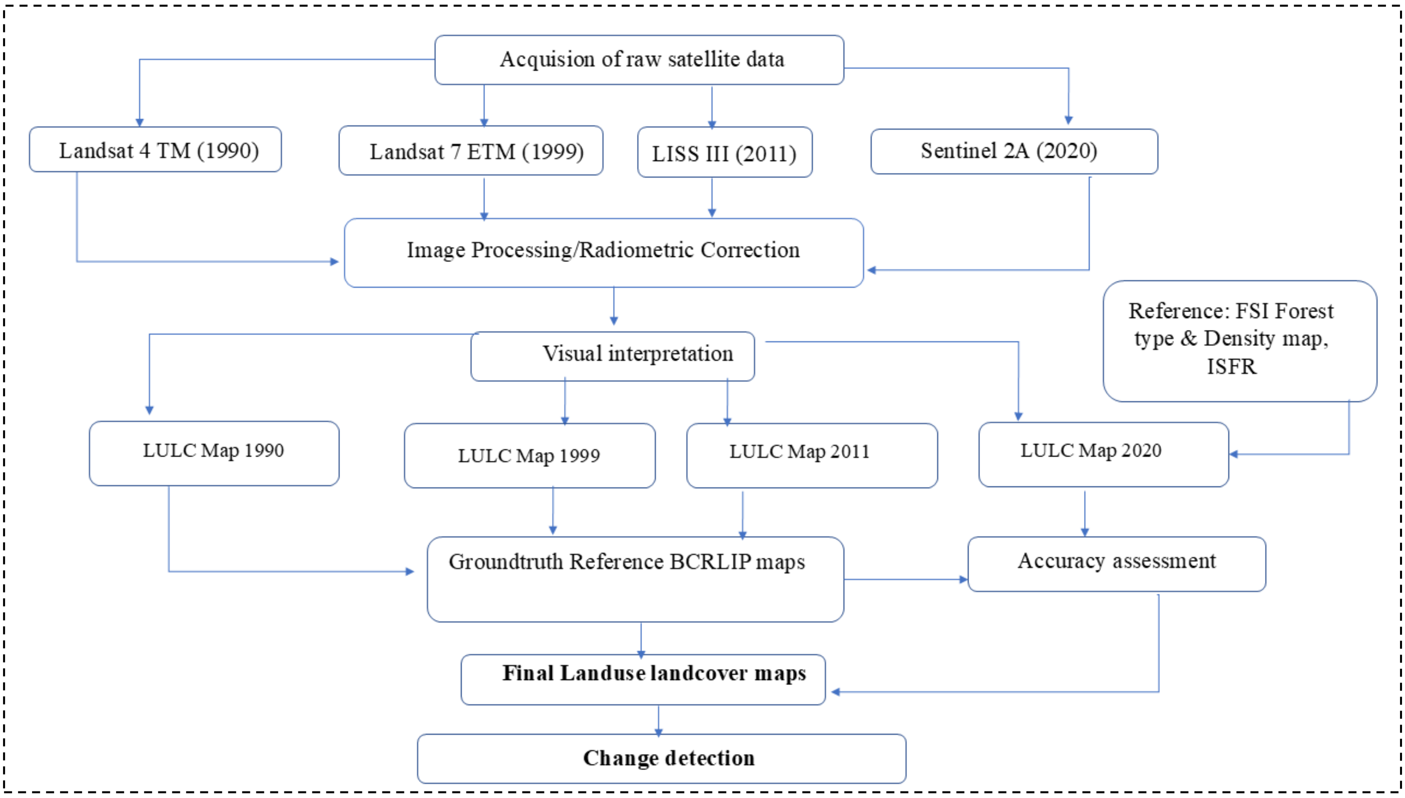


Fig 3.2:Methodology for change detection

3.2.2 Definition of different Land Use Land Cover and vegetation type Category

1. Settlement (Built – up)

It is an area of human habitation developed due to non-agricultural use and that has a cover of buildings, transport and communication, utilities in association with water, vegetation and vacant lands. In the satellite imagery it appears in cyan to grey in colour (Fig 3.3)

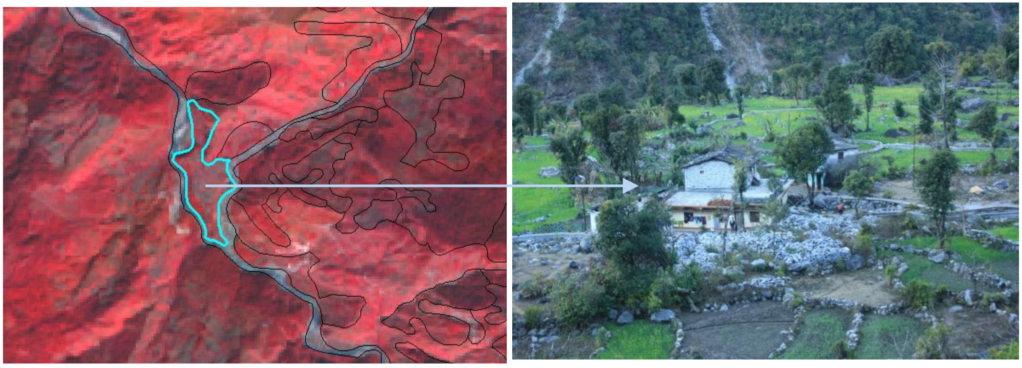


Fig 3.3: Depiction of settlement on satellite data and ground

2. Agriculture

These are the lands used for farming and for production of food, fiber and other commercial and horticulture crops. It includes lands under crops (irrigated and unirrigated, fallow, plantation etc.). They appear in bright red (fig 3.4) to red grey in colour

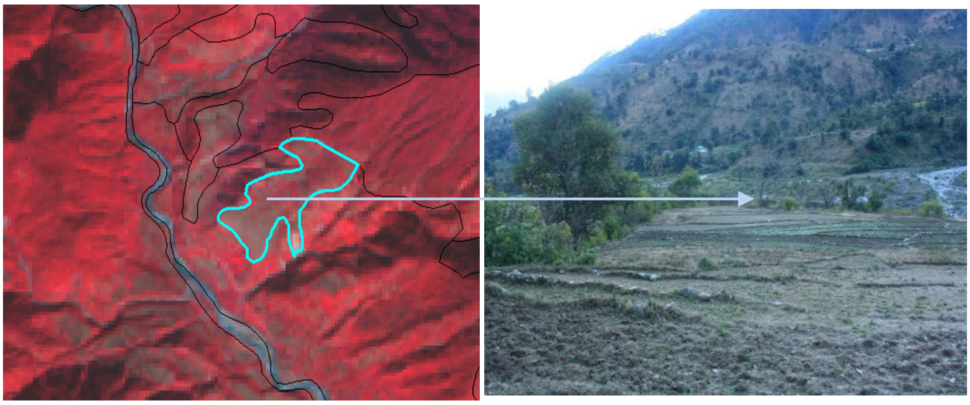


Fig 3.4: Depiction of agriculture on satellite data and ground

with varying shape and size in a contiguous to non-contiguous pattern. In the hilly terrain they are scattered and are closely associated with houses.

3. Landslide

Landslide is defined as a downward movement of rock, earth or debris material. Landslides in the mountainous terrains are natural degradation processes, and one of the most important landscape building factors. In the satellite data (fig 3.5) it appears cyan to white in colour and was seen frequently in the area.

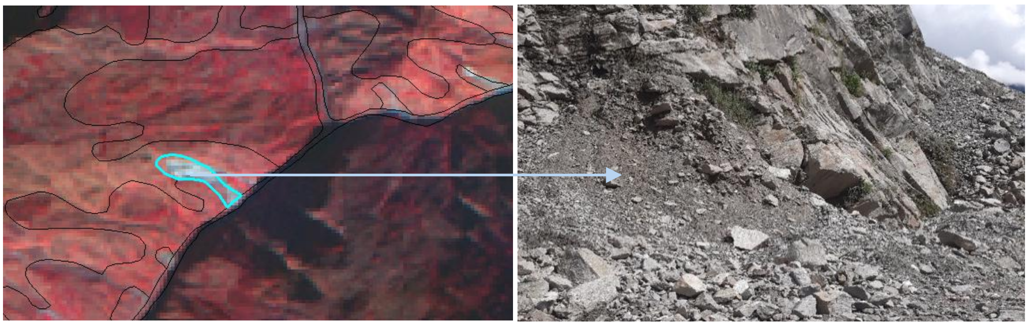


Fig 3.5: Depiction of landslide on satellite data and ground

4. River/Waterbody

This category comprises areas with surface water, either impounded in the form of ponds, lakes and reservoirs or flowing as streams, rivers, canals etc. These are seen clearly on the satellite image in blue to dark blue or cyan color (fig 3.6) depending on the depth of water. River appears as long narrow to wide pattern associated with drainage pattern on hill slopes, flood plains or uplands, at times with vegetation along the banks.

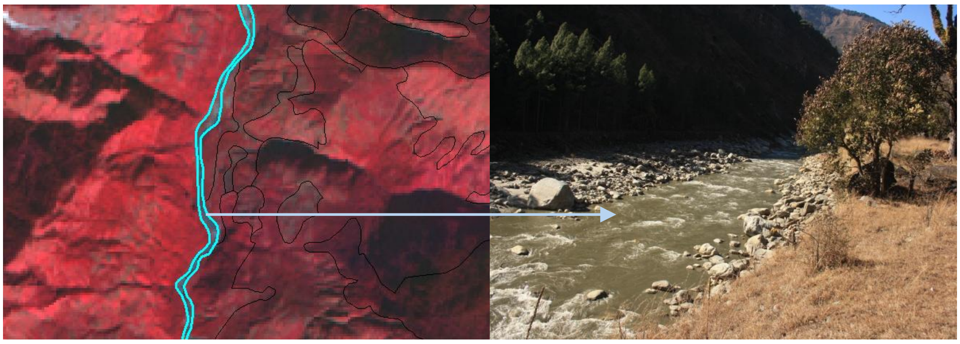


Fig 3.6: Depiction of waterbody on satellite data and ground

5. Alpine Meadow

These are the lands that are exclusively formed of grasses and are also called as alpine meadows and pastures. They are generally placed between coniferous forest and permanent snow covered areas (fig 3.7). An alpine zone begins where the tree zone ends at the limit of the timberline. Altitude at which the alpine zone commences is variable and lies between 3300-5000m.

Fig *3.7: Depiction of alpine meadow on satellite data and ground*

6. Snow

These are the areas under perpetual snow cover confined to the Himalayan region. They appear bright white in color (fig 3.8) depending on the moisture and thickness of the snow spread in large areas. They possess irregular shape with a contiguous pattern, located in mountain peaks and slopes and high relief areas.

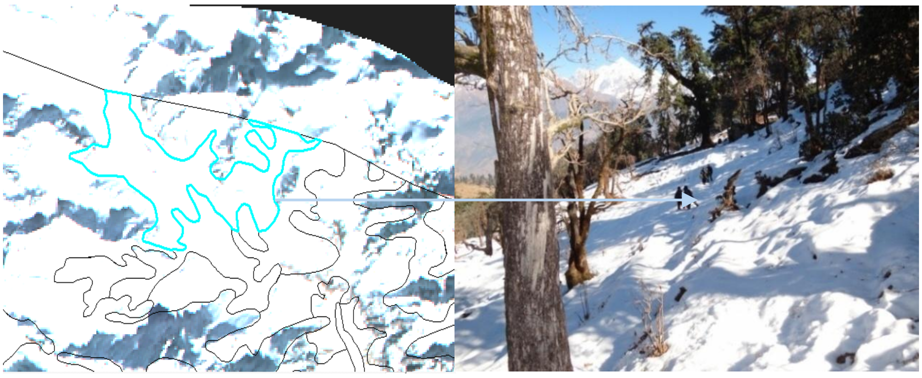


Fig 3.8: Depiction of snow on satellite data and ground

7. Moraine

These are glacially derived debris-covered surfaces composed of unsorted material such as boulders, gravel, and sand. They appear as light grey to brownish, rough-textured patches, (fig 3.9) often forming ridges or irregular mounds. In the study area, moraine occurs mainly adjacent to retreating glaciers and permanent snow zones, with little to no vegetation cover.

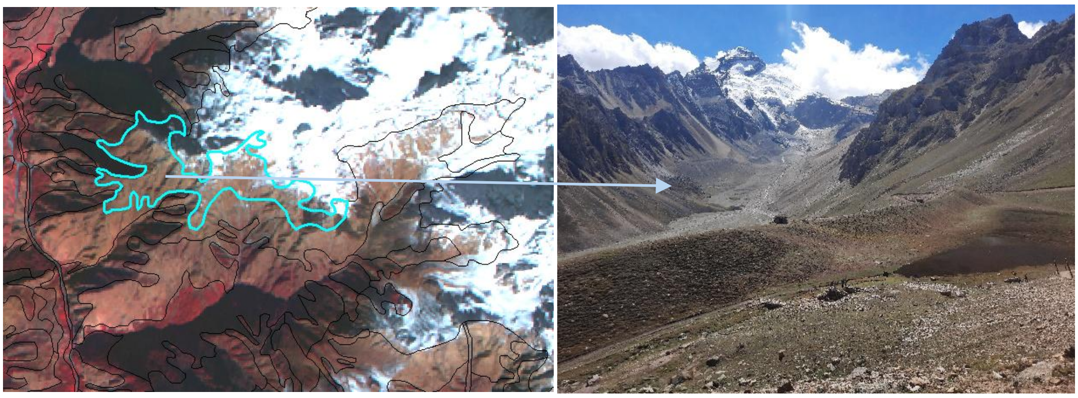


Fig 3.9: Depiction of moraine area on satellite data and ground

8. Barren

These are rock exposures of varying lithology often barren and devoid of soil and vegetation cover. They appear in greenish blue to yellow to brownish (fig 3.10) in color depending on the rock type. In the study area it mainly constitutes the areas in proximity to permanent snow and vegetation does not occur at all.

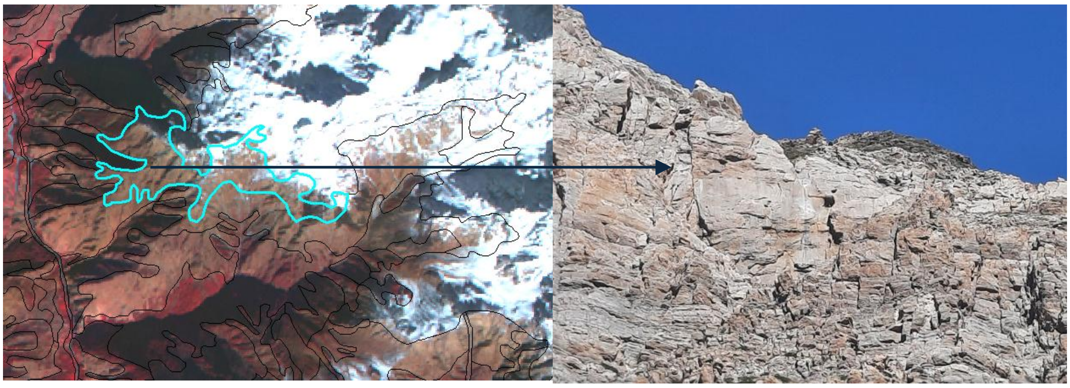


Fig 3.10: Depiction of barren area on satellite data and ground

9. Scrub

This type is found on the fringes of dense forest of the settlement. They appear in light red to dark brown in color depending on the canopy cover and soil background. Their size will vary from small to big, irregular to discontinuous in shape, (fig 3.11) contiguous to non-contiguous in appearance.

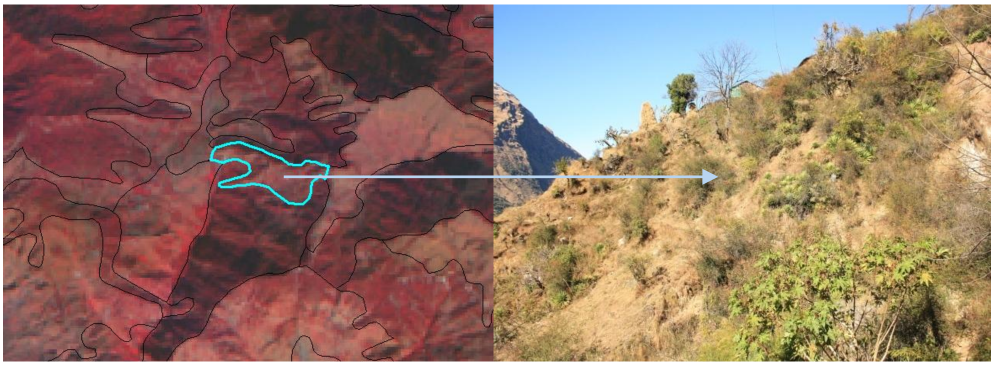


Fig 3.11: Depiction of scrub on satellite data and ground

10. Pine *(Pinus roxburghii)*

This type of forest is generally found at the elevation of 1000-2000 m. They can occur in almost all the geological formations which occur within its range. Also found in dry southern slopes where xerophytic conditions exist and forest fires are prevalent. In the northern aspect it is found in association with banj and other species (fig 3.12). In all the chir forests the pine is sole dominant and usually found to be the only tree species present with practically no underwood. They seldom form very dense forests appearing as bright to dull pink in colour. Towards its lower limit chir passes into the forest of miscellaneous species and at times directly into sal.

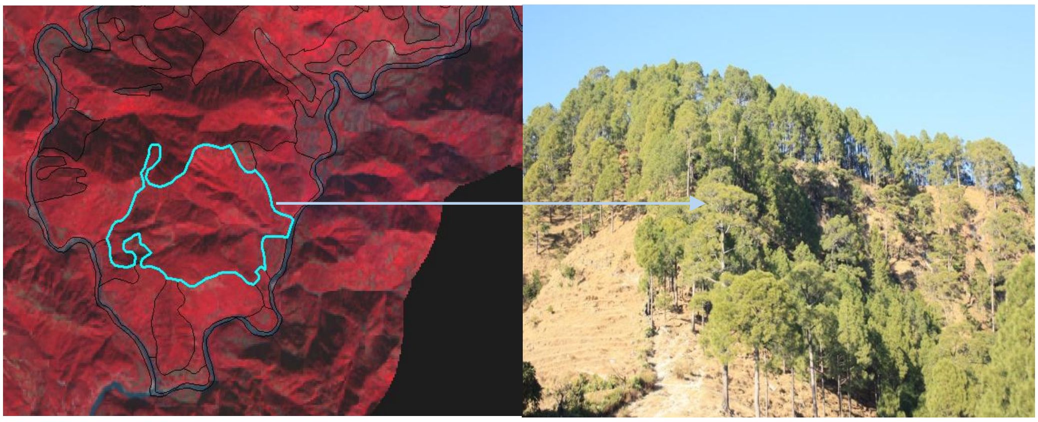


Fig 3.12: Depiction of pine on satellite data and ground

11. Banj Mix (*Quercus leucotrichophora)*

At an elevation of 1300-2000m banj is found in the damp ravines and other favorable sites with the appreciable mixture of other deciduous trees contributing to the main canopy. They are found on the south aspect but in the north aspect they form dense forests. They form dense understorey of other deciduous trees. *Rhododendron arboretum* and *Lyonia ovalifolia* are the very comman associates of banj sited in the field. Mixing with pine was also observed in some of the places. Others associates were *Castanopsis tribuloides, Quercus glauca, Pyrus Pashia, Persea odoratissima, Myrica esculenta, Cinnamon tamala, Pgostemon plactranthoides, Berberis sp.* The reflectance of banj mix forest (fig 3.13) varied between dark red to pink in colour depending on the aspect.

Fig 3.13: Depiction of banj on satellite data and ground

12. Moru Mix (*Quercus floribunda)*

Moru forest is found at the altitudinal range of 2000 -2500m. It forms the intermediate zone between the Banj and Kharsu (fig 3.14). Found in the damp climate it forms luxuriant forest and finest moist temperate broadleaved forests the canopy is generally thick and form a dense second storey composed of small trees and shrubs of varying sizes. The evergreen second storey is of *Rhododendron arboreum*, *Ilex dipyrena*, *Aesculus indica, Castanopsis tribuloides,* Acer spp., and shrubby undergrowth of Rubus, Spireae and Viburnum.

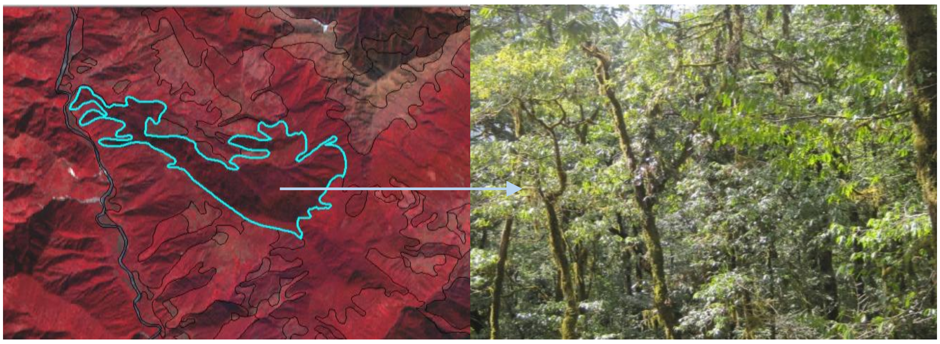


Fig 3.14 : Depiction of moru-mix on satellite date and ground

13. Kharsu (*Quercus semicarpifolia)*

Khasru forest is found at an elevation of 2400 – 3300m in south and north aspect. The trees are hung with dark green-brown moss. It forms the dense thicket and do not have second storey. The lower limit is formed by moru and the upper limit (fig 3.15) is formed by rhododendron, fir and birch. They often form association with Rhododendron in the form of *Krummholz* and *Abies pindrow*. Often it passes directly into the alpine pastures forming the tree line.

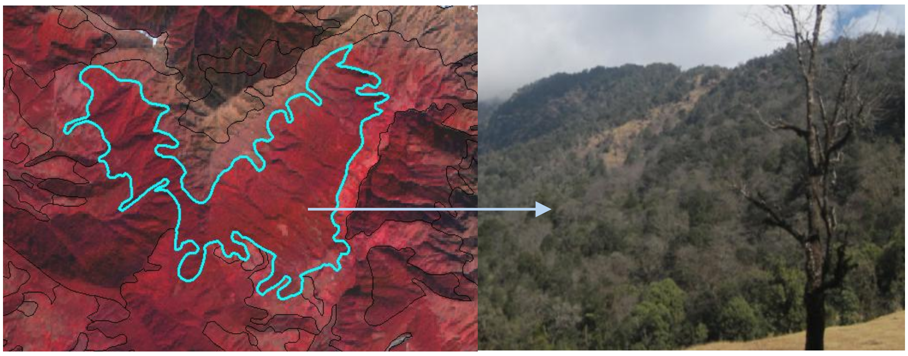


Fig 3.15: Depiction of kharsu on satellite date and ground

14. Birch Fir (Betula – Abies)

It forms the sub-alpine forest at elevation of 3200-4100m. Generally found on the ridges and slopes where snow slides are not of frequent occurrence. It forms an irregular forest consisting of fir, birch and dense undergrowth of rhododendron. Kharsu may occur in association. They are generally found on the northern aspect and on the image it gives greenish grey colour (fig 3.16).

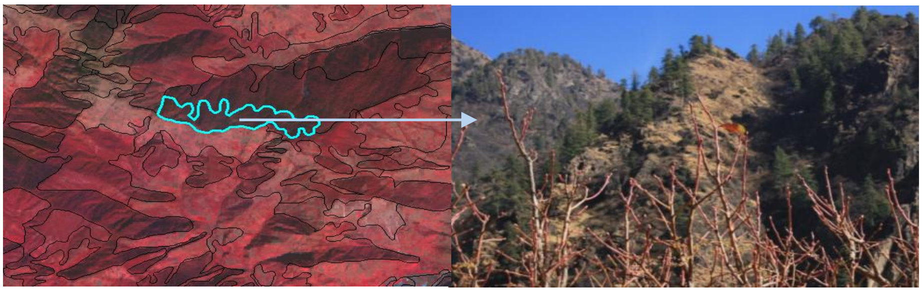


Fig 3.16: Depiction of birch -fir on satellite data and ground

15. Uties *(Alnus nepalensis)*

The altitudinal range is from 600-2000m. It is found near the permanent water supply as the strip of varying length near the stream. They are also found in newly formed shingle beds along the streams and landslide areas that are not too dry. It appears bright red in colour with wooly texture (fig 3.17).

Fig 3.17: Depiction of uties on satellite data and ground

16. Riyanj *(Quercus lanuginosa)*

Found at 1800 – 2300m elevation. There are pure patches of riyanj forest and it occurs at times in association with *Quercus leucotrichophora*, *Quercus floribunda, Lyonia ovalifolia*, *Myrica esculenta,* and rhododendron species. The leaves have high nutrient value thus heavily lopped (fig 3.18).

Fig 3.18: Depiction of riyanj on satellite data and ground

17. Rhododendron

It is found at an elevation of 3300 - 4500 m. It is found in moist dry and arid zones in association with birch and fir. They form large patches in the alpine areas. Different species of rhododendron is found in different altitudinal zones. They form bright red distinct patches near the alpine region (fig 3.19).

Fig 3.19: Depiction of rhododendron on satellite data and ground

18. Deodar *(Cedrus deodara)*

It is found at an altitude of 1700 -2000 m on the cooler aspects. They can also be seen as high as 3000m. In the image they are seen as the dark red or bright red in colour (fig 3.20).

Fig 3.20: Depiction of deodar on satellite data and ground

19. Sal mix *(Shorea robusta)*

The sal pine mix was found at around 1000m. They are confined in the lower areas close to the river. There are pure patches of sal near the lower valleys of Gori and Kali River. It frequently shows the mixing with other species as mixed patches of various size and shape. They appear as bright red in colour on the image (fig 3.21). Mixing with Pinus roxburghii and *Diploknema butyraceae* were observed in some areas. Species like *Malotus phillipienesis, Sapuim insigne, Ficus semichordata etc.* were also found in mixing with sal.

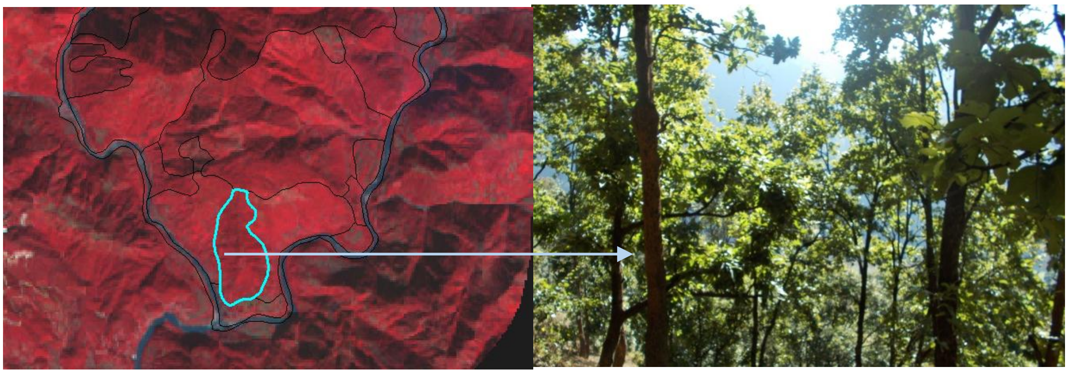


Fig 3.21: Depiction of sal mix on satellite data and ground

20. Mixed Broad Leaf

Mixed broad leaf consist of group of many species that are seen both in lower and higher altitudes. The species found are *Malotus phillipienesis, Sapuim insigne, Bauhinia purpurea, Bauhinia vahlii, Colibrookia oppositifolia, Boehmeria rugulosa, Quercus leucotrichophora, Quercus glauca, Castanopsis tribuloides, Fucus semichordata, Lyonia ovalifilia, Myrica esculenta, Toona ciliate, Macaranaga pustulata, Syzygium cumini, Cinnamon tamala, Phyllanthus emblica etc.* There are some of the weed species *like Urtica ardens, Pgostemon plactranthoides, Osyris quadripartia, Boehmeria macrophylla.* In the higher altitudes there are broad leaf mix forests with Acer species. They are found in proximity to oak forests in North facing slopes. It forms regular patches with red tone (fig 3.22).

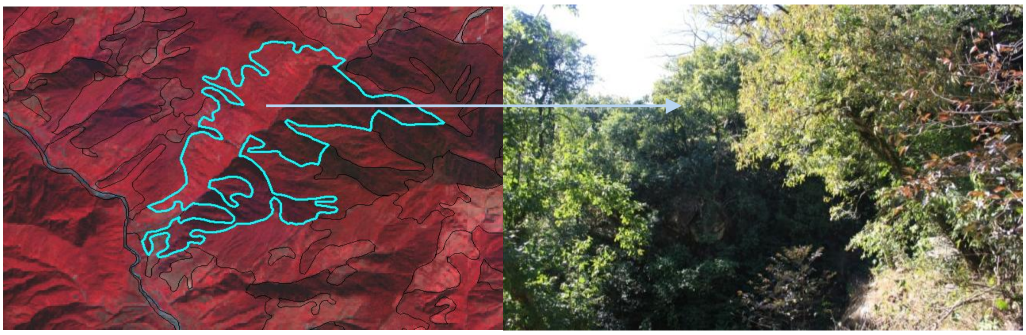


Fig 3.22: *Depiction of mix broad leaf on satellite data and ground*

21. Upper and Lower Temperate Grassy Slopes

The grassy slopes have been divided into two categories – Upper and Lower Temperate at an altitudinal range of 2200-2700m, 1200-2200m respectively. They give dull red to greyish red tone (fig 3.23) and are generally present in the south facing slopes in the drier areas. It is quite prevalent above Dharchula along Kali river and along Gori river they are seen near Madkot area.

Fig 3.23: Depiction of grassy slopes on satellite date and ground

Table 3.2: Visual interpretation key used for analysis

S.No.	Type	Tone	Texture	Aspect	Elevation	Association	Corresponding Forest type by Champion & Seth (1968)
1.	***Alnus nepalensis (Uties)***	bright red in colour	Wooly	-	600 - 2000m	Found near the streams, old landslide areas & screes.	12/1S1: *Alnus nepalensis* Forests
2.	***Shorea robusta (Sal Mix)***	Bright red	Smooth	-	Below and 1000m	Lower areas close to the river.	5B/C1a: Dry Sal Bearing Forests
3.	***Pinus roxburghii (Pine)***	bright to dull pink	Smooth	South	1000-2000 m	Dry areas and steep slopes	9/C1b: Himalayan Chir Pine Forest
4.	***Quercus leucotrichophora (Banj Mix)***	Dark red to pink	Medium	North - South	1300-2000m	In the damp ravines.	12/C1a: Banj oak forest
5.	***Quercus lanuginosa (Riyanj)***	Bright red to dark pink	Smooth to rough	North	1800 – 2300m	High lopping areas	-
6.	***Cedrus deodara (Deodar)***	Dark red or bright red	Coarse	North	1700 - 2000 m	Cooler areas	12/C1c:Moist Deodar Forest
7.	***Quercus floribunda (Moru Mix)***	Dark red	Woolly to smooth		2000 - 2500m	Found in the damp climate	2/C1b: Moru oak forest
8.	***Quercus semecarpifolia (Kharsu)***	Red to bright red	Smooth to medium	North - South	2400 - 3300m	Prefers south aspect and scrap slopes.	12/C2a: Kharsu oak forest
9.	***Mixed Broad Leaf***	Bright red	Smooth to medium	North	1000 – 2500 m	-	-
10.	***Betula-Abies (Birch Fir)***	Greenish grey colour	Coarse to rough	NW-N-NE	3200-4100m	Found on the ridges and slopes where snow slides are not of frequent.	12/C1b: West Himalayan Birch Fir Forest
11.	***Rhododendron (Rhododendron sp.)***	Brown to dull red	Rough	North	3300 - 4500 m	Found in moist dry and arid zones of alpines areas.	15/E1:Dwarf rhododendron scrub

3.2.3 Accuracy Assessment

The accuracy of the land use/land cover (LULC) classification was assessed using a stratified random sampling approach, following standard remote sensing accuracy assessment protocols. The study employed a LULC classification scheme, and validation samples were distributed evenly across all classes to ensure balanced representation of both dominant and less abundant categories.

Approximately 40 reference points per class were generated, resulting in a total of 560 validation points, which falls within the recommended range of 30–50 points per class for multi-class LULC assessments. Reference points were interpreted using high-resolution satellite imagery and supported by field observations wherever available. To reduce uncertainty, samples located near class boundaries or within mixed pixels were avoided.

Each reference point was compared with the corresponding classified LULC map and labelled as TRUE (correct classification) when the reference and classified classes matched, or FALSE (misclassification) when they differed. These TRUE/FALSE outcomes were compiled into a confusion (error) matrix, which formed the basis for computing overall and class-wise accuracy metrics.

Accuracy Metrics and Formulae

Overall Accuracy (OA), representing the proportion of correctly classified samples, was calculated as:

$$\mathbf{OA} = \frac{\sum \boldsymbol{x_{ii}}}{\boldsymbol{N}}$$

where x_{ii} denotes the number of correctly classified samples and N is the total number of validation points.

To account for agreement occurring by chance, Cohen's Kappa coefficient (κ) was calculated using:

$$\boldsymbol{\kappa = \frac{P_o - P_e}{1 - P_e}}$$

where P_o is the observed agreement (Overall Accuracy) and P_e is the expected agreement by chance.

Kappa values were interpreted using the standard scale:

κ value	**Interpretation**
< 0.20	Poor
0.21–0.40	Fair
0.41–0.60	Moderate
0.61–0.80	Substantial
> 0.80	Almost Perfect

3.3 Results

3.3.2 Vegetation type analysis across decades

The vegetation type analysis of the Askot landscape over four decades (1990–2020) revealing both relative stability and emerging transformations across ecological zones. (Table 3.3).

Table 3.3: The vegetation type analysis of the Askot landscape over four decades

Vegetation Type	**Area (sq.km)**			
	1990	**1999**	**2011**	**2020**
Quercus leucotrichophora (Banj Oak)	120.88	120.83	120.75	120.17
Quercus semecarpifolia (Kharsu Oak)	204.52	204.52	204.52	204.17
Quercus floribunda (Moru Mix)	102.57	102.57	102.57	102.43
Quercus lanuginosa (Riyanj)	20.44	20.44	20.44	20.43
Betula-Abies (Birch Fir)	157.93	157.93	157.93	157.37
Cedrus deodara (Deodar)	47.30	47.30	47.30	47.23
Pinus roxburghii (Pine)	55.92	55.92	55.92	55.51
Rhododendron	66.70	67.31	67.31	66.94
Myrica esculenta & Lyonia ovalifolia (Mixed Broad Leaf)	71.59	71.59	71.59	71.17
Shorea robusta (Sal Mix)	8.84	8.84	8.83	8.83
Alnus nepalensis (Uties)	6.01	6.01	6.01	5.96
Scrub	38.73	37.79	29.24	28.66
Upper Temperate Grassy Slope	92.84	92.67	92.84	92.35
Lower Temperate Grassy Slope	86.14	86.30	86.06	85.15
Alpine Meadow	786.41	770.37	813.36	734.42
Agriculture	52.93	53.15	56.92	56.18
River	60.43	60.43	60.43	60.43
Waterbody	0.80	0.93	0.93	0.93
Snow	1013.43	1046.80	968.74	909.64
Barren	1020.34	981.64	978.71	935.57
Moraine	473.27	492.84	534.05	714.49
Landslide	7.45	9.15	10.70	15.80
Settlement	1.02	1.16	1.35	2.66

Oak-dominated forests—including *Quercus leucotrichophora*, *Q. semecarpifolia*, *Q. floribunda*, and *Q. lanuginosa*—remain largely stable over the three decades, with only marginal declines by 2020. This stability suggests persistence of mature temperate forest systems, although small reductions may indicate localized degradation or conversion at forest edges. Similarly, coniferous and mixed forest types such as *Betula–Abies*, *Cedrus deodara*, *Pinus roxburghii*, and mixed broad-leaf forests show minimal area loss, pointing to relatively intact mid- to high-elevation forest cover.

In contrast, scrubland exhibits a pronounced decline, reducing from 38.73 sq. km in 1990 to 28.66 sq. km in 2020, possibly reflecting either succession into forest or conversion to other land uses. Temperate grassy slopes show slight reductions, indicating gradual pressure on open grazing landscapes. Alpine meadows, despite remaining extensive, display substantial fluctuations, with a net decline by 2020, suggesting sensitivity to climatic variability, grazing pressure, and cryospheric changes.

Among non-vegetated classes, snow and barren areas show consistent declines, particularly snow cover, which decreases sharply after 1999. This pattern aligns with warming trends and glacier retreat in high-altitude Himalayan regions. Conversely, moraine area increases dramatically, reflecting enhanced glacial retreat and exposure of unconsolidated substrates. Landslide extent more than doubles, indicating increasing geomorphic instability, likely driven by intense precipitation events and permafrost degradation.

Human land-use classes show gradual expansion, with agriculture and settlements increasing steadily, highlighting growing anthropogenic pressure even in mountainous terrain. Overall, the results underscore a landscape that appears structurally stable in forest cover but increasingly vulnerable in alpine, cryospheric, and geomorphically sensitive zones, reflecting early signals of climate-driven and human-induced change.

The major forest area is formed of the kharsu forest followed by birch – fir followed by Moru mix and Banj mix as major vegetation classes. The major patches of banj was mostly observed near low altitude villages of gori valley followed by other oak species as we go higher in altitude. Banj and riyanj was observed to be heavily lopped for fodder to the cattles in the villages. Birch – Fir are mostly associated to the alpine areas where in the cooler aspect they form association with Kharsu forests. The kharsu mostly forms the tree line. In the alpine areas the rhododendron frequently forms the scrubby vegetation forming khrummoltz due to cold and harsh climatic conditions. Mixed broad leaf forest was observed near the Gosi gad area forming the major patch. Pine and Sal were found to be confined in the low atlitude areas closer to the Gor rivers. Sal was frequently observed from Jauljibi till Baram along Gori river. Sal mixed with Chura was seen near the dudhi village. Patches of Sal mixed with pine was found as moved higher the dudhi village. Large patches of pine forest were observed in lumti – choribagarh – bangapni area.

3.3.3 Land-Use Land-Cover Change Analysis

The land-use and land-cover (LULC) analysis of the Askot landscape over three decades (1990–2020) reveals pronounced changes across forest, cryospheric, and anthropogenic land-use classes (Table 3.4).

Table 3.4: Spatial extent of Askot across three decades

Sl. no	**Class**	**Area (sq.km)**			
		1990	**1999**	**2011**	**2020**
1	**Dense Forest**	391.70	391.70	391.62	369.44
2	**Moderate Dense Forest**	259.25	257.96	252.88	227.86
3	**Open Forest**	155.98	157.22	162.28	206.90
4	**Scrub**	38.73	37.79	29.24	28.66
5	**Temperate Grassland**	178.97	178.97	178.89	177.50
6	**Alpine**	842.18	826.76	869.75	790.44
7	**Agriculture**	52.93	53.15	56.92	56.18
8	**River**	60.43	60.43	60.43	60.43
9	**Waterbody**	0.80	0.93	0.93	0.93
10	**Snow**	1013.43	1046.80	968.74	909.64
11	**Barren**	1020.34	981.64	978.71	935.57
12	**Moraine**	473.27	492.84	534.05	714.49
13	**Landslide**	7.45	9.15	10.70	15.80
14	**Settlement & built up**	1.02	1.16	1.35	2.66

Dense Forest area declined from 391.70 km² in 1990 to 369.44 km² in 2020, representing a 5.7% reduction, while Moderate Dense Forest showed a sharper decline of 12.1%, decreasing from 259.25 km² to 227.86 km². In contrast, Open Forest expanded substantially from 155.98 km² to 206.90 km², an increase of 32.6%, indicating a marked shift from closed-canopy to more degraded forest conditions. Scrub cover declined by 26.0%, whereas grassy slopes remained largely stable, showing less than 1% change over the study period.

High-altitude and cryospheric classes exhibited significant transformations. Snow cover decreased from 1,013.43 km² to 909.64 km², corresponding to a 10.2% reduction, while the Moraine mixed class expanded dramatically by 51.0%, increasing from 473.27 km² to 714.49 km². Alpine areas declined by 6.1%, and barren land decreased by 8.3%, reflecting redistribution among high-elevation land-cover classes rather than absolute stability. River and waterbody extents remained largely unchanged throughout the period.

Anthropogenic and disturbance-related classes showed consistent and pronounced increases. Agricultural land expanded modestly by 6.1%, while Settlement and Built-up areas increased from 1.02 km² to 2.66 km², representing a 161% increase. Landslide-affected areas more than doubled, increasing by 112% from 7.45 km² to 15.80 km², marking the highest proportional change among all classes. Overall, the LULC results between 1990 (fig 3.24) and 2020 (fig 3.25) indicate a clear trend of forest degradation, cryospheric retreat, and increasing human and geomorphic disturbances shaping the evolving landscape dynamics of the Askot region. This is further explained in the transition matrix (Table 3.5).

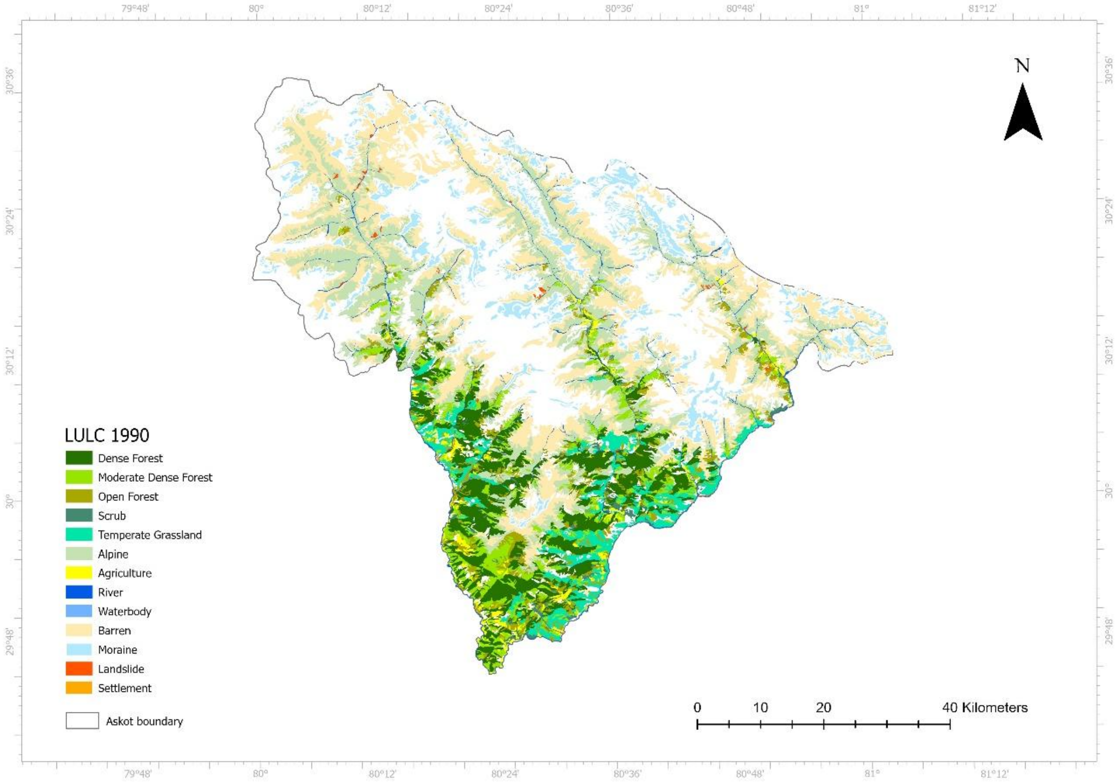


Fig 3.24: Landuse Landcover map of 1990

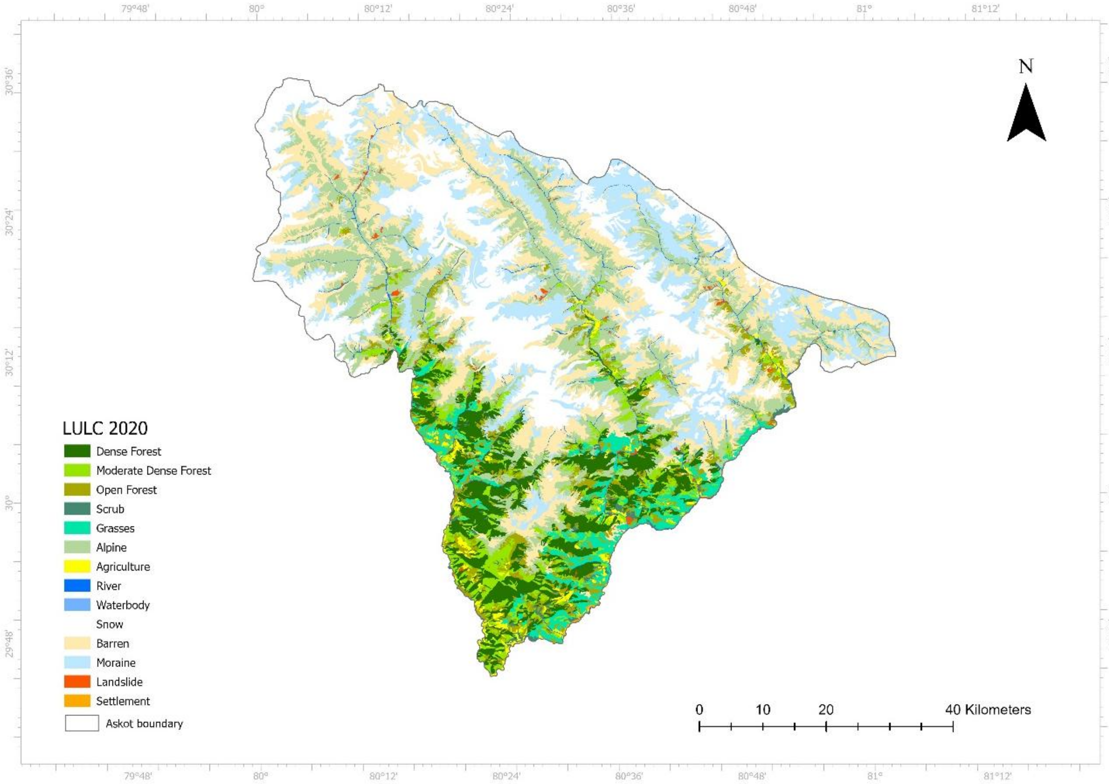


Fig 3.25: Landuse Landcover map of 2020

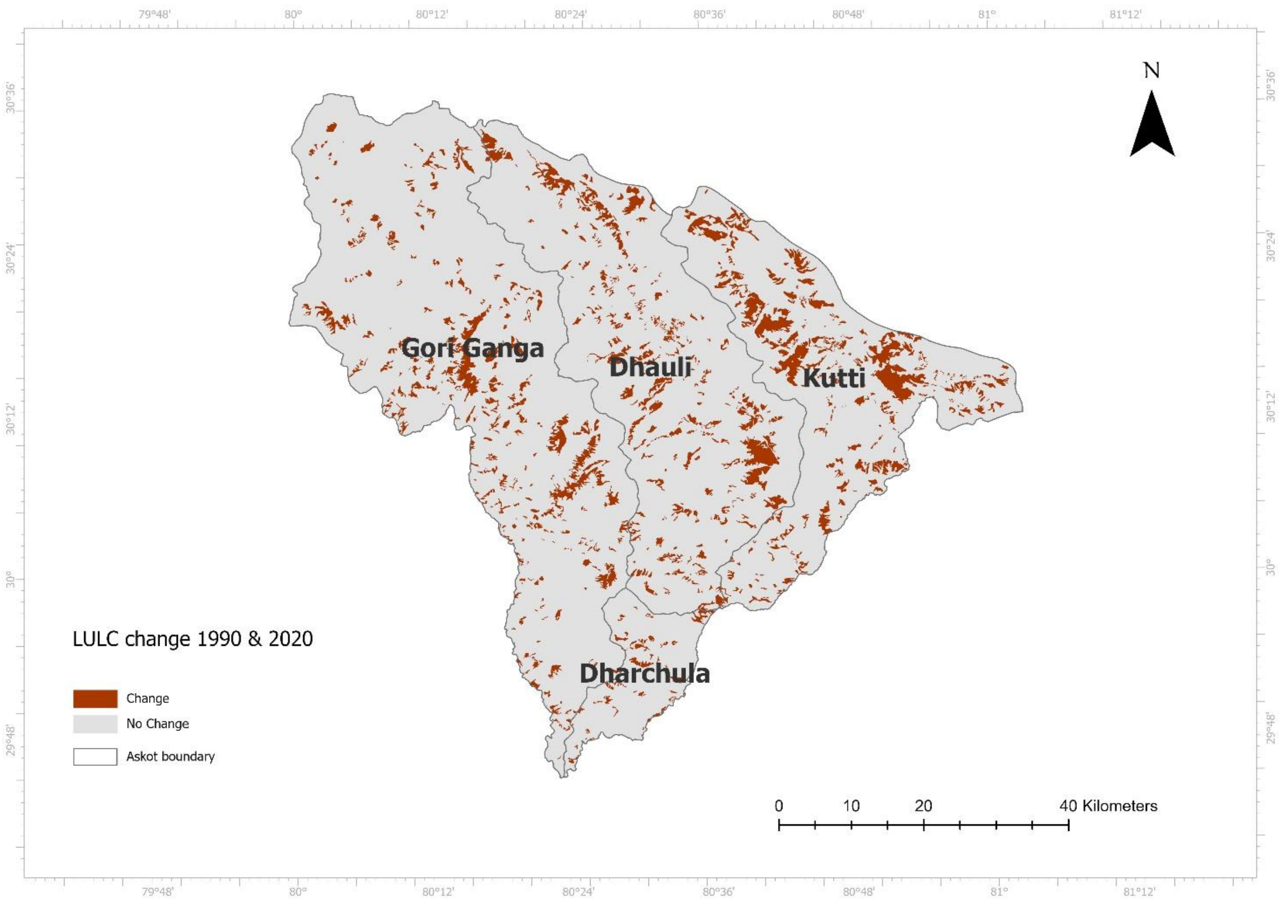


Fig 3.26: Change map between 1990 and 2020

The LULC change detection analysis between 1990 and 2020 indicates (fig 3.26) that approximately 443.48 sq.km of the Askot landscape experienced land-use/land-cover transitions, while 4053.01 sq.km remained unchanged. This corresponds to nearly 10% of the total landscape undergoing change with the majority of this transformation occurring during 2011–2020. This accelerated phase of change reflects a period of heightened landscape reorganization, likely driven by the influence of increasing anthropogenic pressures in the region.

Although the proportion of changed area appears modest, these changes are concentrated in ecologically sensitive zones, including forest degradation (dense to open forest), alpine and snow-covered regions, scrub expansion/contraction, and increasing landslide and settlement areas. Such targeted changes exert a disproportionate impact on ecosystem services, particularly carbon storage and climate regulation, underscoring that even limited spatial change can translate into substantial ecological consequences in fragile Himalayan watershed systems like Askot.

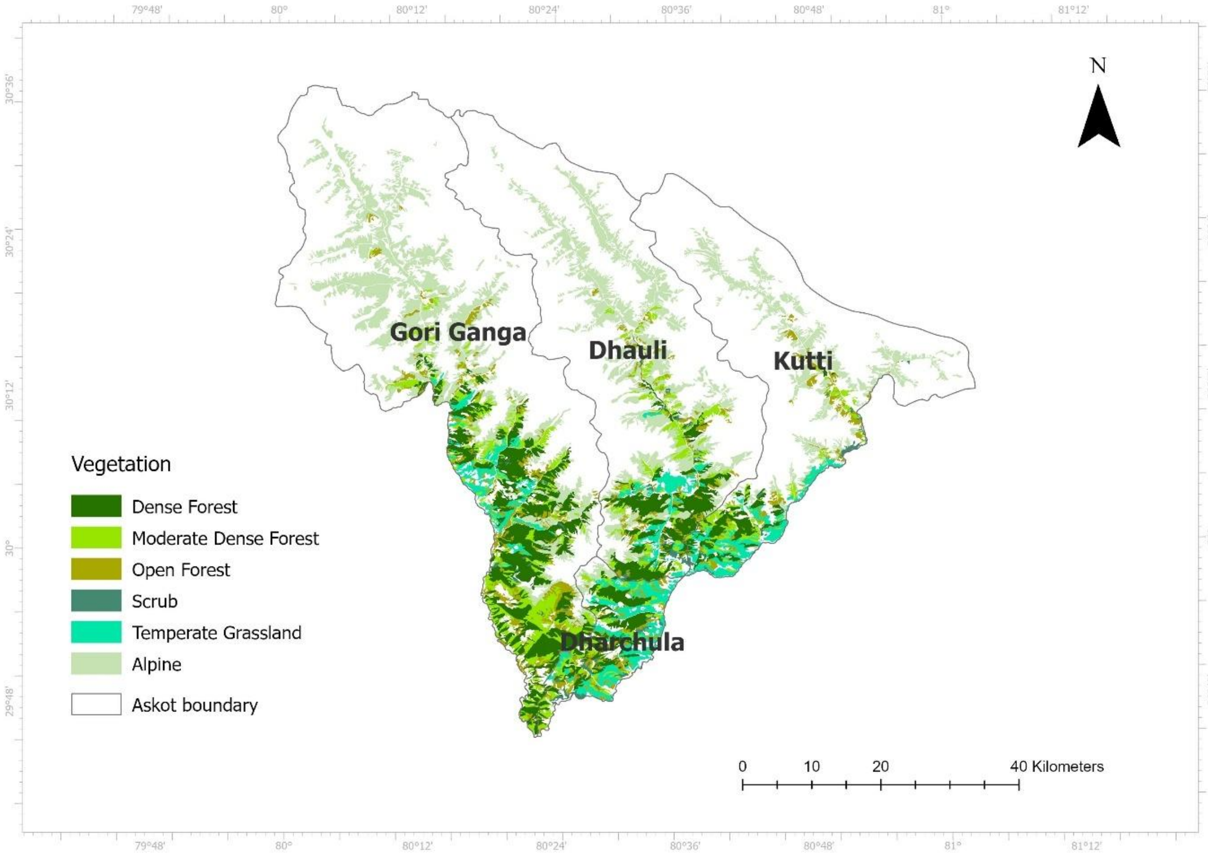


Fig 3.27: Forested area of Askot

With forests occupying only 18% of the total area (fig 3.27), the Askot landscape exhibits a constrained forest base, making these ecosystems particularly critical for maintaining carbon storage, biodiversity, and regulating ecosystem services.

Table 3.5: LULC Transition matrix between 1990 & 2020

1990 \ 2020	Dense Forest	Mod. Dense Forest	Open Forest	Scrub	Temperate Grassland	Alpine	Agriculture	River	Waterbody	Snow	Barren	Moraine	Landslide	Settlement & built up	Grand Total
Dense Forest	369.44	19.86	1.68	-	-	-	-	-	-	-	-	-	0.72	-	**391.7**
Mod. Dense Forest	-	207.66	50.3	-	-	-	-	-	-	-	-	-	1.3	-	**259.25**
Open Forest	-	0.34	154.92	-	-	-	-	-	-	-	-	-	0.71	0.02	**155.98**
Scrub	-	-	-	28.6	-	-	4.6	-	-	-	3.41	-	1.81	0.31	**38.73**
Temperate Grassland	-	-	-	-	177.5	-	-	-	-	-	-	-	1.47	-	**178.97**
Alpine	-	-	-	-	-	708.75	-	-	-	-	-	132.39	1.04	-	**842.18**
Agriculture	-	-	-	-	-	-	51.58	-	-	-	-	-	0.04	1.31	**52.93**
River	-	-	-	-	-	-	-	60.43	-	-	-	-	-	-	**60.43**
Waterbody	-	-	-	-	-	-	-	-	0.8	-	-	-	-	-	**0.8**
Snow	-	-	-	-	-	23.14	-	-	-	909.64	-	80.65	-	-	**1013.43**
Barren	-	-	-	-	-	-	-	-	-	-	932.15	41.64	0.12	-	**1020.34**
Moraine	-	-	-	-	-	58.54	-	-	0.14	-	-	459.81	1.21	-	**473.27**
Landslide	-	-	-	0.07	-	-	-	-	-	-	-	-	7.39	0.07	**7.45**
Settlement & built up	-	-	-	-	-	-	-	-	-	-	-	-	-	1.02	**1.02**
Grand Total	**369.44**	**227.86**	**206.9**	**28.67**	**177.5**	**790.43**	**56.18**	**60.43**	**0.94**	**909.64**	**935.56**	**714.49**	**15.81**	**2.73**	**4496.5**

Key Interpretations from the Transition Matrix

Alpine and Snow Zone Vulnerability: Despite high persistence, both Alpine and Snow classes show net losses when assessed against column totals. Alpine declines by 133.43 sq.km (842.18 to 708.75 sq.km), primarily transitioning to Barren (46.42 sq.km) and Moraine (132.39 sq.km), indicating upslope ecosystem retreat under reduced moisture availability. Snow similarly contracts by 103.79 sq.km (1,013.43 to 909.64 sq.km), with 80.65 sq.km shifting to Moraine, reflecting instability along seasonal snow boundaries consistent with precipitation deficits identified in the (Thakur et al., 2026) analysis.

Forest Degradation Gradient: Dense Forest remains largely stable (94.3% retention), but its transition to Moderate Dense Forest (19.86 sq.km) signals canopy thinning rather than abrupt loss. Moderate Dense Forest is more vulnerable (80.1%

retention), with 50.30 sq.km converting to Open Forest—the dominant off-diagonal forest transition. This sequential degradation (Dense → Moderate Dense → Open) suggests progressive moisture stress across mid-elevation zones rather than widespread deforestation.

Moraine Expansion as a Climate Signal: The Moraine class expands markedly by +241.22 sq.km (473.27 to 714.49 sq.km), driven by transitions from Alpine (132.39 sq.km), Snow (80.65 sq.km), and Barren (41.64 sq.km). This expansion captures the increasing instability of high-elevation snow–barren interfaces under warming and reduced precipitation, effectively acting as a spatial indicator of climate sensitivity.

Emerging Disturbance Patterns: Landslide area more than doubles (7.45 to 15.80 sq.km), with contributions spread across Scrub, Moderate Dense Forest, and Temperate Grassland. This diffuse origin points to landscape-wide destabilization linked to vegetation stress rather than localized slope failures. Settlement expansion (1.02 → 2.66 sq.km) occurs mainly through conversion from Agriculture, suggesting climate-mediated pressure on agrarian livelihoods in the lower watershed.

3.3.4 Changes in forest canopy cover density and vegetation type (1990–2020)

The analysis of vegetation structure between 1990 and 2020 reveals a consistent shift from dense forest classes towards more open forest conditions across most vegetation types (fig 3.28) in the Askot landscape (table 3.6). This pattern indicates widespread forest degradation rather than complete deforestation, characterized by canopy thinning, reduced basal area, and increasing fragmentation.

Table 3.6: Canopy cover density across different vegetation types between 1990 & 2020

Vegetation Type	**Dense canopy**		**Moderate canopy**		**Open canopy**	
	1990	**2020**	**1990**	**2020**	**1990**	**2020**
Quercus leucotrichophora (Banj Oak)	31.53	30.35	43.74	29.57	45.61	60.25
Quercus semecarpifolia (Kharsu Oak)	102.28	95.32	76.51	67.76	25.74	41.09
Quercus floribunda (Moru Oak Mix)	93.56	92.12	7.46	8.39	1.56	1.92
Quercus lanuginosa (Riyanj Oak)	10.55	9.22	7.42	8.19	2.47	3.02
Betula-Abies (Birch Fir)	38.52	32.35	68.86	61.26	50.55	63.76
Cedrus deodara (Deodar)	30.54	29.80	11.91	10.97	4.85	6.46
Pinus roxburghii (Pine)	30.66	28.99	18.61	17.99	6.66	8.52
Myrica esculenta & Lyonia ovalifolia (Mixed Broad Leaf)	48.25	45.80	17.17	17.19	6.17	8.17
Shorea robusta (Sal Mix)	5.04	4.71	2.41	1.94	1.39	2.17
Alnus nepalensis (Uties)	0.77	0.77	3.45	2.85	1.79	2.33

Across all major oak-dominated forest types, a decline in dense forest area is evident. *Quercus leucotrichophora* (Banj oak) shows a reduction in dense forest extent alongside a pronounced increase in open forest area, suggesting progressive canopy opening and structural simplification. A similar trend is observed for *Quercus* *semecarpifolia* (Kharsu oak), where dense forest area decreases markedly, while open forest nearly doubles over the study period. These changes are particularly significant because oak forests form the ecological backbone of mid- to high-elevation Himalayan ecosystems and are highly sensitive to both climatic stress and anthropogenic disturbance.

High-elevation forests such as *Betula–Abies* (birch–fir) also exhibit notable declines in dense forest cover, accompanied by substantial increases in open forest area. This shift is indicative of increasing vulnerability in cold-adapted forest systems, potentially driven by a combination of climate warming, reduced regeneration, and human pressures such as grazing and fuelwood extraction. The observed structural opening in these forests is consistent with regional evidence of declining forest integrity in the western Himalaya.

Coniferous forests, including *Cedrus deodara* (deodar) and *Pinus roxburghii* (chir pine), show more moderate but still consistent reductions in dense forest area, coupled with increases in open forest extent. In the case of pine, the expansion of open forest may also reflect its colonization of degraded sites, often at the expense of closed-canopy broadleaf forests, further reinforcing landscape-level degradation dynamics.

Mixed broadleaf forests (*Myrica esculenta–Lyonia ovalifolia*) and low-elevation *Shorea robusta* (sal) forests follow the same overall trend, with declines in dense and moderate classes and increasing representation of open forest. Although the absolute areas involved are smaller, these changes are ecologically significant as they point to declining canopy continuity even in forest types traditionally considered more resilient.

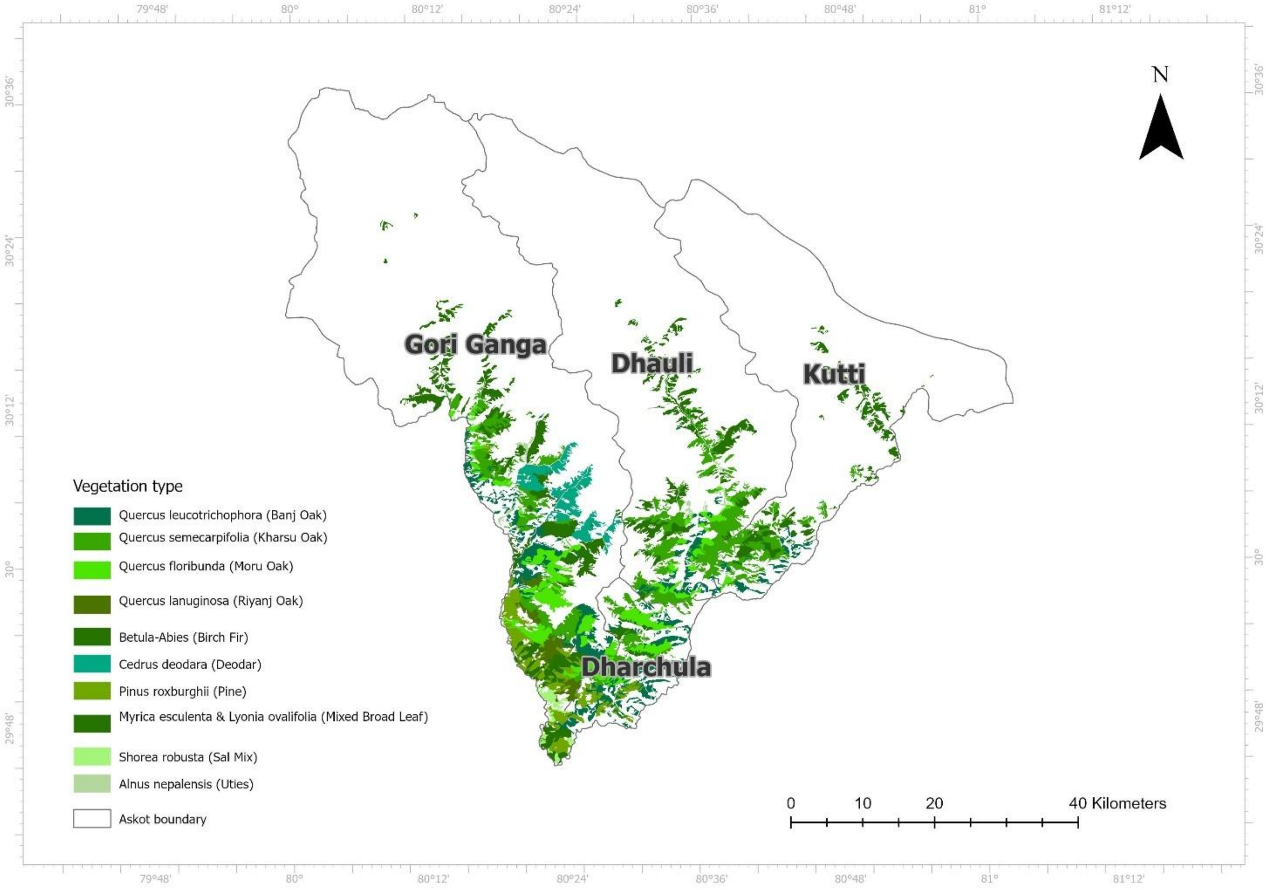


Fig 3.28: Major Vegetation types

Overall, the increase in open forest across nearly all vegetation types, combined with the systematic decline in dense forest cover, provides strong evidence of progressive forest degradation in the Askot region between 1990 and 2020. Such structural degradation reduces habitat quality, weakens carbon storage potential, and limits the capacity of forest ecosystems to buffer climatic stress.

3.3.1 Accuracy Assessment Results

Out of the 560 validation points, 487 samples were correctly classified, resulting in an overall classification accuracy of 86.9%, which exceeds the commonly accepted threshold of 80% for reliable thematic mapping. The corresponding Kappa coefficient was 0.86, indicating an almost perfect agreement between the classified LULC map and reference data (Table 3.7).

Table 3.7: Summary of Accuracy Assessment Results

Metric	Value	Interpretation
Total validation points	560	Stratified random sampling
Correctly classified (TRUE)	487	—
Misclassified (FALSE)	73	—
Overall Accuracy (%)	86.9	High accuracy
Kappa Coefficient (κ)	0.86	Almost perfect agreement
Minimum acceptable OA	≥ 80%	Achieved
Minimum acceptable κ	≥ 0.70	Achieved

Class-wise accuracy analysis showed high reliability for spectrally distinct classes such as Snow and Temperate Grassland, while forest classes achieved accuracies exceeding the target threshold of 85%, confirming effective discrimination of vegetation structure. Moderate accuracies observed for Alpine, Barren, and Moraine classes are attributed to spectral similarity, mixed surface conditions, and seasonal variability at high elevations. The Landslide class achieved acceptable accuracy despite its limited spatial extent, while River, Waterbody, and Settlement & Built-up classes exhibited strong classification performance due to their distinct spectral signatures.

Overall, the accuracy assessment demonstrates that the LULC classification is robust and suitable for subsequent spatial analysis and change detection.

3.4 Discussion

This study quantifies decadal changes in LULC and vegetation type within the Askot landscape. The LULC change clearly indicates degradation of forests in the Askot landscape between 1990 and 2020. Dense forest cover has decreased for nearly all forest types, particularly in ecologically significant Oak and Conifer-dominated systems. This decline is accompanied by reduction in moderate forest classes, while open forest areas have consistently increased. High-altitude ecosystems are undergoing major transformations. Snow cover reduced significantly while exposes Moraine transitional areas expanded strongly, reflecting snowline retreat and climate-driven shifts in alpine zones.

Himalayan winters show reduced snowfall amid climate change. Studies highlight a significant decline in winter snowfall across the Himalayas, resulting in bare, rocky landscapes during what should be peak snow season. This trend links to accelerating ice melt and broader climate shifts affecting the region's vital water sources for millions downstream. Observations from various parts confirm less snow accumulation, raising concerns for water security and ecosystems. (Muhammad, 2025). Satellites show alarming precipitation anomalies in winter 2025–26: In November 2025, rainfall was just 2-3 mm, compared to the average 12-15 mm (60-70% shortfall). In December 2025, precipitation was nearly absent, with only 2-3 mm compared to the normal 20 mm (−85% deficit The 2024–2025 winter saw a 23-year low in snow persistence (about 24% below normal), while snowfall in the northwestern Himalayas has dropped 25% over the past five years compared to the

1980–2020 average. In November–December 2025, satellite snow-cover data for Uttarakhand showed 45–75% snow deficits, indicating delayed or below-normal snow accumulation and the loss of essential early-winter precipitation to form stable snowpack (Thakur et al., 2026)

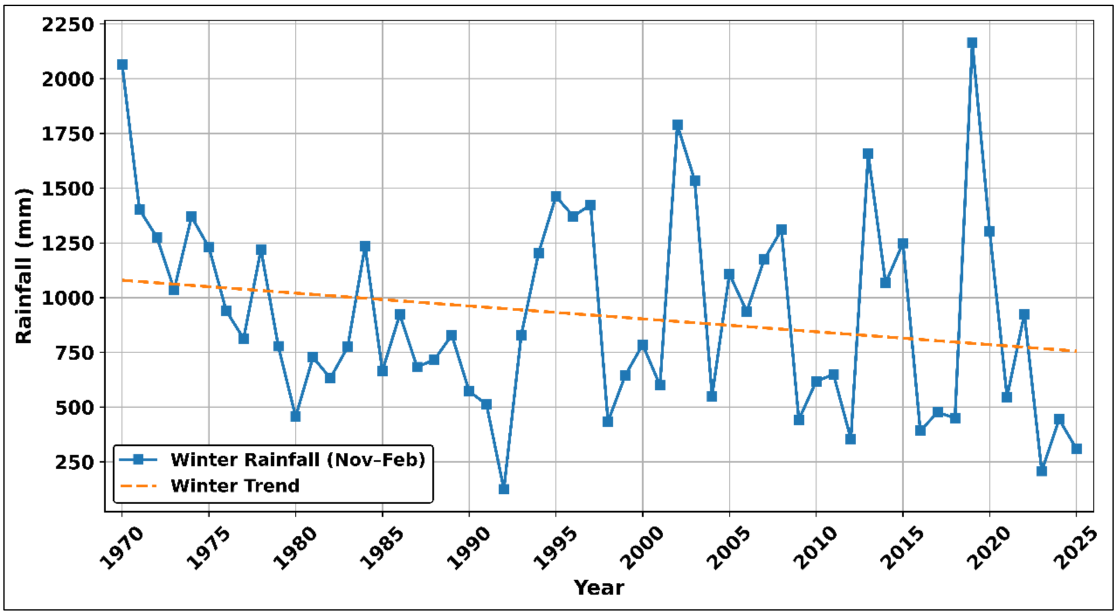


Fig 3.28: Reduced winter rainfall trend

Severe hydrological consequences immediately with record precipitation shortages, this observation is consistent with the research finding of the current study. The IMD rainfall data also shows this trend (fig 3.28). Central Water Commission data show a gradual and consistent decrease in Upper Ganga river flow, while snowmelt provides 25% of annual runoff for 12 major Himalayan river basins that supply drinking water and irrigation to nearly 2 billion South Asians. Weakening Western Disturbances low-pressure systems from the Mediterranean that historically brought heavy winter precipitation—and rising temperatures accelerate snowmelt and reduce snow cover.

Declining snowfall and glacier retreat affect mountain hydrology and ecosystem function (Khadka, 2024).

The 30-year LULC trajectory of Askot landscape (1990-2020) reveals landscape reorganization directly coupled to this precipitation decline. Snow-covered areas contracted by 103.79 sq.km (-10.2%), from 1,013.43 to 909.64 sq.km precisely the persistent snow loss documented in satellite records for 2025-26, while the expanding Moraine mixed class (rising 241.22 sq.km, +51%) reflects the destabilization of high-elevation boundaries where barren area increasingly dominates previously snow-persistent zones. Alpine vegetation zones simultaneously contracted by 51.74 sq.km (-6.1%), indicating upslope ecosystem migration pressure and reduced viability of alpine species under moisture-limited conditions consistent with contemporary "snow drought" phenomena.

Reduced water availability causes cascading stress in forests indicating moisture-stressed systems' degradation and canopy thinning. Reduced canopy interception and transpiration increase surface drying, prolonging the fire-susceptibility window. Satellite fire detections from October-December 2025 show concentrated clustering in mid-elevation pine and mixed broadleaf forests, where Askot's open forests dominate, indicating the landscape's emerging vulnerability to early-winter fire disturbance caused by precipitation lack and sustained drier fuel conditions.

This trajectory has significant consequences for Askot. The landscape's elevation gradient (600-7000 metres) shows the full range of precipitation-sensitive zones, from monsoon-dependent temperate forests to alpine meadows supported by residual snow and spring discharge to glacial zones with documented snow-accumulation failures.

The watershed's water provisioning capacity, carbon storage, and biodiversity conservation value are threatened by the contraction of persistent snow and alpine zones, forest degradation, and emerging fire vulnerability as downstream demand increases due to regional population growth and irrigation expansion. This increasing baseline degradation emphasizes the need for landscape-level action to preserve ecosystem services under changing LULC, precipitation-reduction and warming pressures.

Chapter 4: Spatio-temporal Trends of Above-ground Carbon-Ecosystem Services

4.1 Introduction

Forests play a crucial role in global carbon dynamics and aid in climate change mitigation. It is estimated that around one-third of current anthropogenic CO_2 emissions are removed by terrestrial ecosystems, mainly forests (Wang et al. 2021). Above-ground carbon (AGC) is a direct indicator of a forest's carbon sequestration capacity and is vital for understanding the carbon cycle (Tian et al. 2023). AGC varies significantly across vegetation types, driven by structure, species composition, and environmental factors. Dense, undisturbed forests typically store the most AGC, while degraded or secondary forests hold much less.

Forests remain the dominant land cover, and they are under intense pressure from deforestation, fragmentation and land-use conversion (Batar et al., 2017; Singh et al., 2016; Rashid et al., 2015). They play a major role in global carbon uptake and storage, with their carbon source-sink dynamics strongly shaped by human land use, climate change, and natural or anthropogenic disturbances. Changes in land-use patterns therefore contribute to both local and regional climate variability (Chase et al., 2000).

Quantifying above-ground carbon in diverse vegetation types is fundamental for effective forest management, climate modeling, and policy.

Several studies have been carried out to analyze forest carbon stock/biomass using different approaches, such as estimates based on forest inventories (Salunkhe et al. 2018) or allometric equations (Nyamari and Cabral, 2021), remote sensing (Fu et al. 2023) or integrated models (Dang et al. 2019). Field-based assessment of aboveground biomass (AGB) is widely recognized as the most accurate method for quantifying forest and vegetation biomass, but it is time-consuming, labor-intensive, and difficult to scale to large areas (Ma et al. 2024). In recent advances, carbon mapping and valuation model, i.e., InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), have emerged as reliable techniques providing promising results for stakeholders and decision-makers.

It has been applied in forests, watersheds, agricultural landscapes, urban areas, coastal wetlands and hilly regions across Asia, Europe, Africa, and South America (Babbar et al., 2021; Piyathilake et al., 2021; García-Ontiyuelo et al., 2024; Kohestani et al., 2023; Alaoui et al., 2023; Nel et al., 2022; Dida et al., 2021; Sharma et al.,2024; Kafy et al., 2023; Guo et al., 2024). Many studies couple InVEST with LULC change models (e.g., Markov/CA, PLUS, TerrSet/LCM, MOLUSCE) to predict future carbon under policy or climate scenarios (Babbar et al., 2021; Bacani et al., 2024; Kohestani et al.,2023; Alaoui et al., 2023; Shi et al., 2025; Sharma et al., 2024

Recent studies have extensively examined land-use and land-cover (LULC) dynamics across diverse global landscapes using cellular automata–Markov (CA-Markov) models and machine-learning approaches to reconstruct historical trends and project future trajectories. In East Asia, analyses of the Guanting Reservoir Basin, a critical water source for Beijing, revealed sustained conversion of grassland and cropland into built-up areas between 1980 and 2010, with scenario-based projections indicating continued urban expansion through 2090 under business-as-usual conditions, moderated under governance-oriented scenarios (Ruben et al., 2020). Large-scale assessments in the Congo Basin employed Random Forest algorithms to track forest cover change from 1990 to 2020 and projected substantial deforestation by 2050 under multiple IPCC climate scenarios (Yuh et al., 2024). In African highland watersheds supplying major urban centers, such as the Dire and Legedadi watersheds in Ethiopia, LULC changes between 1985 and 2022 were associated with pronounced declines in natural vegetation and ecosystem service values (ESVs) (Admasu et al., 2023), while studies in the Afro-alpine Guna Mountain region documented significant losses in food production and erosion control services between 1995 and 2020 (Belay et al., 2022). Site-level analyses across the eastern Brazilian Amazon quantified the ecological consequences of multiple LULC transitions, demonstrating substantial impacts on biodiversity, carbon stocks, and soil properties (Nunes et al., 2022). Collectively, these studies underscore the effectiveness of integrated CA-Markov and machine-learning frameworks for capturing complex LULC dynamics and highlight the pervasive ecological and ecosystem service implications of land transformation across contrasting environmental and socio-economic contexts.

Earlier carbon quantification studies are available at a coarse-scale (Sharma et al. 2010), for a relatively smaller geographical area (Verma et al 2024). The current study aims to quantify the spatio-temporal trends in AGC in Askot landscape.

4.2 Methodology

4.2.1 Reclassification of new LULC Classes for CA–Markov Analysis

The original vegetation and land use–land cover (LULC) classes were reclassified and merged into broader categories to perform the CA–Markov analysis, to ensure conceptual clarity, computational efficiency, and ecological relevance. The initial LULC dataset contained several detailed vegetation types that, while ecologically distinct, exhibited similar spatial behavior, and transition probabilities at the landscape scale. Retaining a large number of highly disaggregated classes can introduce uncertainty in transition matrices, reduce model stability, and complicate interpretation of future projections. Therefore, related vegetation types and land-use categories were clubbed into functionally meaningful classes based on dominant species composition, structural characteristics, and land-use function (Table 4.1).

By consolidating classes with similar ecological and land-use attributes, the revised classification (Fig 4.1) improves the robustness of transition probability estimation and facilitates a more interpretable assessment of landscape dynamics. This revised classification scheme formed the basis for the CA–Markov modeling, enabling consistent estimation of transition probabilities and spatial allocation of future LULC changes while preserving the dominant ecological gradients of the Askot landscape.

4.2.2 Prediction of future landuse landcover using CA-MARKOV in TerrSet LiberaGIS software

A hybrid Cellular Automata–Markov (CA-Markov) model was employed to simulate and predict future land use–land cover (LULC) scenarios. This approach integrates the Markov Chain’s capacity to quantify temporal change with the Cellular Automata’s ability to represent spatial patterns driven by neighborhood interactions. Markov Chain analysis was first used to estimate transition probabilities between LULC classes based on two historical time periods (T_1 and T_2), generating a transition probability matrix that describes the likelihood of class conversion and a transition area matrix that quantifies the expected area of change for a future time step (T_3).

To spatially allocate these transitions, transition potential (suitability) maps were developed using multi-criteria evaluation or logistic regression, incorporating key driving factors such as proximity to roads and settlements, topographic constraints (slope and elevation), and environmental or policy restrictions. The Cellular Automata component then governed the spatial distribution of change by applying neighbourhood rules through contiguity and spatial interaction filters (typically using a 3 × 3 or 5 × 5 moving window), ensuring realistic, clustered landscape evolution rather than random pixel transitions. TerrSet LiberaGIS software Version 10.2 was used to run the analysis.

Table 4.1 Reclassified new LULC

Sl.No.	Original LULC Category	Reclassified/Merged Category
1.	*Quercus leucotrichophora (Banj Oak Mix)*	**Oak Forest**
	Quercus semecarpifolia (Kharsu Oak)	
	Quercus floribunda (Moru Oak Mix)	
	Quercus lanuginosa (Riyanj)	
2.	*Betula-Abies (Birch Fir)*	**Temperate Forest**
	Cedrus deodara (Deodar)	
	Pinus roxburghii (Pine)	
	Rhododendron	
3.	*Myrica esculenta & Lyonia ovalifolia (Mixed Broad Leaf)*	**Mixed Broad leaf**
	Shorea robusta (Sal Mix)	
	Alnus nepalensis (Uties)	
4.	Upper Temperate Grassy Slope	**Meadows**
	Lower Temperate Grassy Slope	
	Alpine Meadow	
5.	Scrub	**Scrub**
6.	Agriculture	**Non-forest**
	River	
	Waterbody	
	Snow	
	Barren	
	Moraine	
	Landslide	
	Settlement	

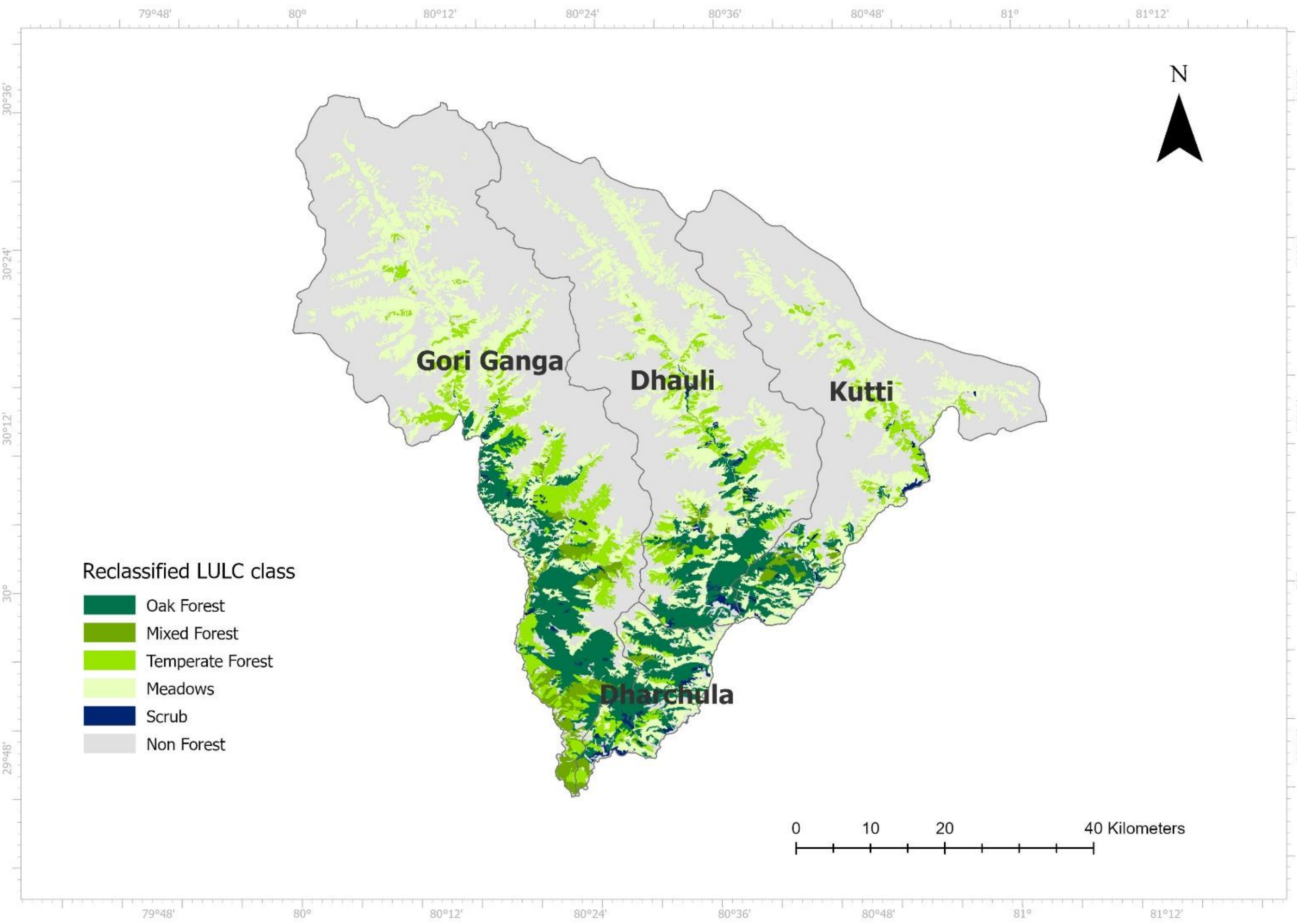


Fig 4.1: Reclassified LULC class

4.2.2 Above-ground carbon analysis using InVEST software

The Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model is an open-source, spatially explicit suite developed by the Natural Capital Project (NatCap), Stanford University, for mapping and quantifying ecosystem services (Natural Capital Project, 2022; Bera et al., 2022; Hoque et al., 2021). In this study, the InVEST Carbon Storage and Sequestration (CS & S) model (v3.12.0) was applied to estimate above-ground carbon (AGC) stocks across the Askot landscape for past

(1990), present (2020), and projected future (2050) periods. Future AGC dynamics were assessed by integrating LULC maps projected for 2050 using the CA–Markov model.

Carbon sequestration was quantified as the difference in static carbon stocks between time periods (Eq. 1),where C_{1990} and C_{2020} represent carbon stocks for the respective years.

$$C_{sequestration} = C_{1990} - C_{2020} \text{ ………………….} (1)$$

The model inputs included LULC maps for each time step and a biophysical table in .CSV format containing land-use codes and above-ground carbon density values (C_{above}). Other carbon pools (below-ground, soil, and dead matter) were assigned a value of zero, as the analysis focused exclusively on AGC. Carbon density values were compiled through a meta-analysis of published literature and reports relevant to vegetation types (annexure table 1) in the Indian Himalayan Region (Verma et al., 2023) and aggregated for new LULC class using a weighted average approach (table 4.2). Carbon stock was estimated as 50% of the dry biomass of each vegetation type (Nandal et al., 2022). Land-use classes with negligible biomass—such as snow, barren land, landslides, rivers, and water bodies—were assigned zero carbon values (Momo & Devi, 2022).

All LULC raster layers and biophysical inputs were integrated into the InVEST framework to generate spatially explicit AGC maps (Megagram/pixel) for the entire study area (methodology flowchart in fig 4.2). Carbon storage was quantified for major vegetation classes, including oak forest, temperate forest, mixed broadleaf forest, meadows, and scrub. Pixels retaining the same LULC class over time exhibited no net carbon gain or loss. The model outputs were produced as raster layers in

GeoTIFF format. The same workflow was repeated for 2050 using projected LULC maps derived from the CA–Markov analysis to assess future AGC dynamics.

Model limitations

- The model assumes static carbon storage for each LULC type, with changes in carbon occurring only when LULC transitions take place. Pixels with unchanged LULC therefore show zero sequestration, although in reality many areas experience recovery or succession. This limitation can be partly addressed by incorporating age classes within LULC categories.

- Model accuracy depends on the quality of LULC classification and carbon pool values. While carbon stocks vary across LULC types, substantial heterogeneity also exists within individual classes, which the model does not explicitly capture.

- The model does not account for carbon transfers among pools. Carbon from tree mortality or harvesting is assumed to be instantly released to the atmosphere, ignoring temporary storage in dead organic matter or wood products.

- Carbon sequestration is assumed to occur linearly over time, whereas in reality sequestration rates are nonlinear and higher in early years. This assumption, combined with discounting, may lead to underestimation of the true value of sequestered carbon

Table 4.2: Carbon pool values (Mg/ha) for each LULC class

LU_Code	**Class**	**AGC**
1	Oak Forest	90.60
2	Temperate Forest	39.80
3	Mixed Forest	40.92
4	Meadows	9.67
5	Scrub	26.00
6	Non-forest	0.00

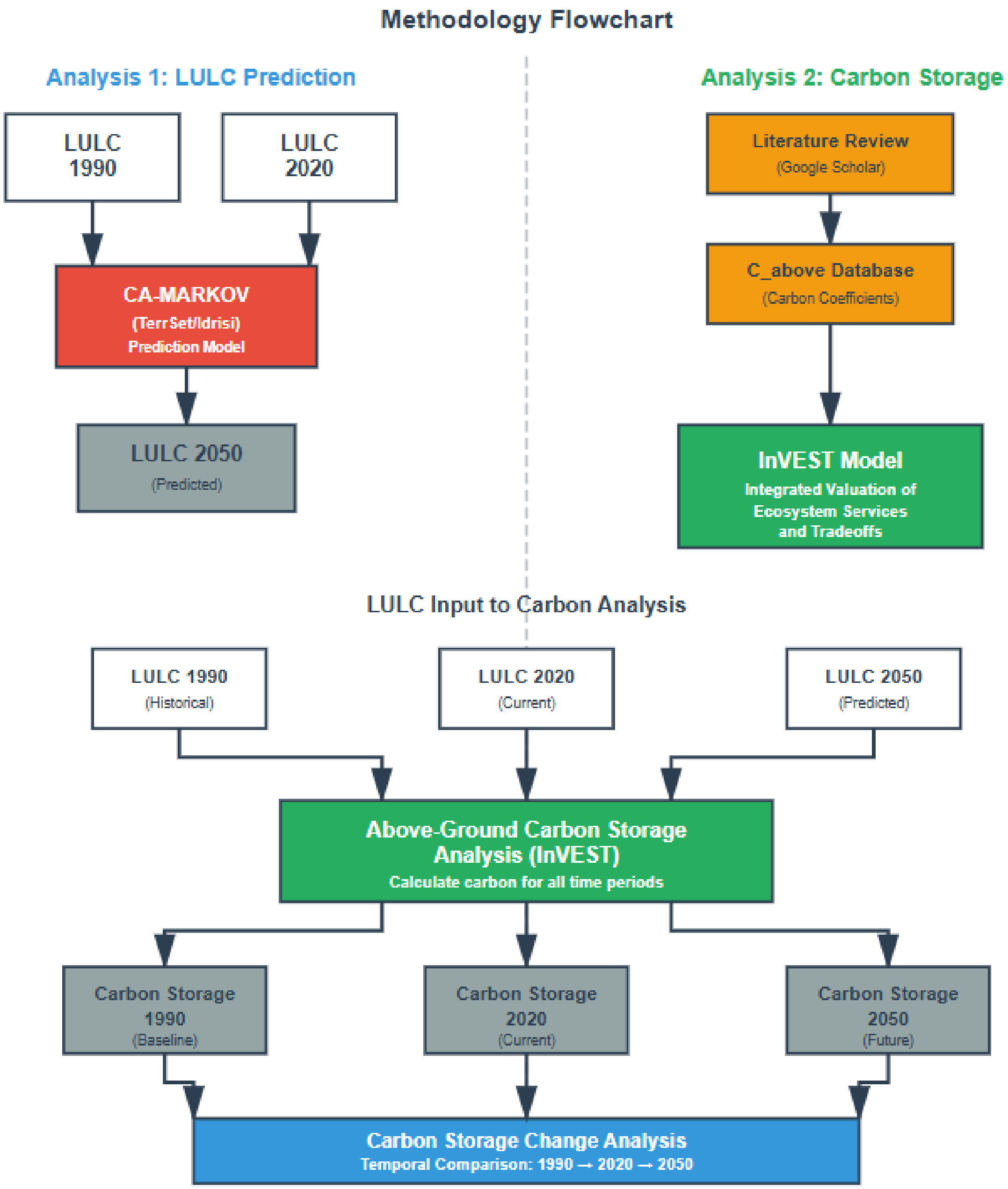


Fig 4.2: Methodology flowchart for spatio-temporal analysis of AGC

4.3 Results

Spatio-Temporal Dynamics of Above-Ground Carbon across LULC Categories

The spatio-temporal analysis of above-ground carbon stocks for 1990, 2020, and the projected year 2050 across LULC is depicted in (Table 4.3).

Table 4.3: Present and Projected Trends in Above-Ground Carbon Stocks Across LULC

Sl. No	Class	Area (sq.km)			Above-ground Carbon (MgC)		
		1990	**2020**	**2050**	**1990**	**2020**	**2050**
1.	Oak Forest	448.15	446.99	446.99	40600.4411	40495.3501	40495.3501
2.	Temperate Forest	327.62	326.78	326.78	13040.9132	13007.477	13007.477
3.	Mixed Forest	86.46	85.96	85.91	3537.9318	3517.47187	3515.42587
4.	Meadows	966.09	913.04	875.31	9344.9602	8831.80911	8466.84793
5.	Scrub	38.66	28.68	22.2	1005.16	745.68	577.2
6.	Non-forest	2629.64	2695.17	2739.43	-	-	-
	Total				67,529.41	66,597.79	66,062.30

In 1990, the total AGC was estimated at 67,529.41 MgC, which declined to 66,597.79 MgC by 2020. Projections for 2050 indicate a further reduction in AGC to 66,062.30 MgC, corresponding to an additional loss of 535.49 MgC between 2020 and 2050. Forested classes—Oak Forest, Temperate Forest, and Mixed Forest—dominate the above-ground carbon pool throughout the study period. Oak Forest remains the largest contributor to carbon storage, with an area of 448.15 km² in 1990, marginally declining to 446.99 km² in 2020 and remaining stable through 2050. Correspondingly, above-ground carbon stock in Oak Forest shows a slight reduction from 40,600.44 MgC in 1990 to 40,495.35 MgC in both 2020 and 2050 (fig 4.3). A similar trend is observed in Temperate Forest, where area decreases marginally from 327.62 km² in 1990 to 326.78 km² in 2020 and 2050, accompanied by a small decline in carbon stock from 13,040.91 MgC to 13,007.48 MgC. Mixed Forest exhibits a gradual reduction in area from 86.46 km² in 1990 to 85.91 km² by 2050, with a corresponding decline in carbon stock from 3,537.93 MgC to 3,515.43 MgC. In contrast, non-forest areas show a consistent expansion over time, increasing from 2,629.64 km² in 1990 to 2,695.17 km² in 2020 and further to 2,739.43 km² by 2050. Meadows and scrublands display pronounced declines in both area and carbon storage across the study period. Meadow area decreases from 966.09 km² in 1990 to 875.31 km² by 2050, with carbon stocks reducing from 9,344.96 MgC to 8,466.85 MgC. Scrublands show the steepest proportional decline, with area reducing from 38.66 km² in 1990 to 22.20 km² in 2050 and carbon stocks declining from 1,005.16 MgC to 577.20 MgC. Overall, the results indicate relative stability in forest carbon stocks, contrasted by continued expansion of non-forest land uses and substantial losses in meadow and scrub ecosystems. Overall, the landscape is projected to lose 1,467.11 MgC of above-ground carbon between 1990 and 2050. These results suggest that the most pronounced carbon reductions occurred during the earlier phase while the rate of carbon loss is projected to moderate in the future period.

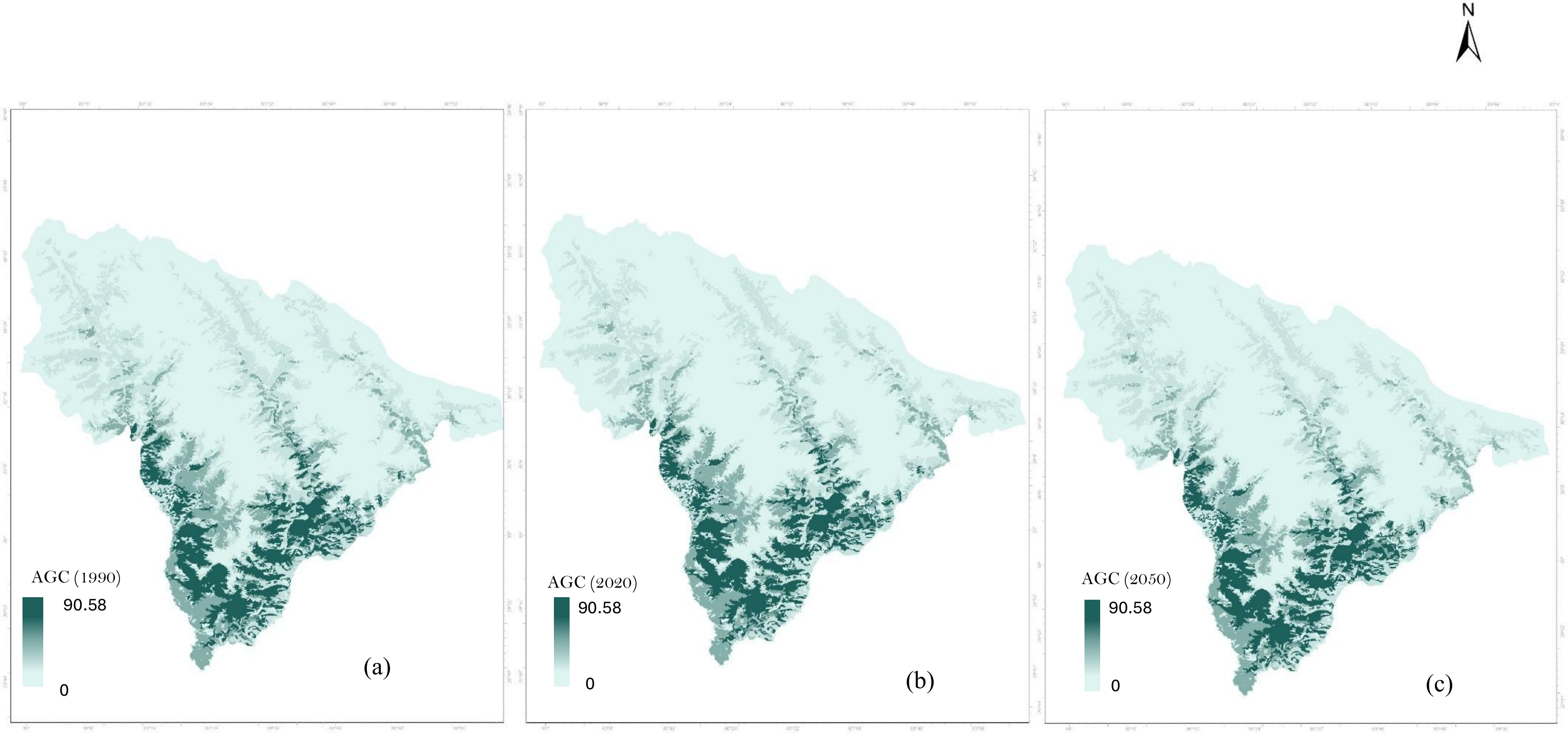


Fig 4.3: Above-ground carbon in Askot landscape in (a) 1990, (b) 2020 and (c) 2050

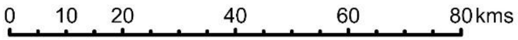


Table 4.4: Carbon Percent Contribution (1990–2050) with respect to area

Class	% Area_1990	%AGC_1990	% Area_2020	%AGC_2020	% Area_2050	%AGC_2050
Oak Forest	9.97	60.09%	9.94	60.79%	9.94	61.28%
Temperate Forest	7.29	19.32%	7.27	19.52%	7.27	19.68%
Mixed Forest	1.92	5.24%	1.91	5.28%	1.91	5.32%
Meadows	21.48	13.84%	20.31	13.25%	19.47	12.81%
Scrub	0.86	1.49%	0.64	1.12%	0.49	0.87%
Non-Forest	58.48	0.00%	59.94	0.00%	60.92	0.00%

The proportional comparison between areal extent and above-ground carbon (AGC) contribution reveals a pronounced asymmetry (table 4.4.) between land area and carbon storage in the Askot landscape. Although oak forests occupy only ~10% of the total landscape, they consistently contribute ~60–61% of total above-ground carbon across 1990, 2020, and 2050. This highlights oak-dominated systems as the primary carbon reservoirs of the watershed and underscores their disproportionate ecological value relative to spatial extent.

Temperate forests, covering ~7.3% of the area, account for nearly 19–20% of AGC, while mixed forests contribute ~5% carbon from less than 2% area. In contrast, non-forest areas expand beyond 58–61% of the landscape and hardly contribute to above-ground carbon. Despite occupying a substantial proportion of the landscape (∼19–21%), meadows contribute disproportionately less to above-ground carbon stocks (∼13%), while scrub ecosystems exhibit declining trends in both area and AGC over time. Importantly, these systems retain significant below-ground carbon reserves, highlighting their ecological value beyond above-ground biomass estimates. The persistence of high carbon shares within shrinking or stagnant forest areas indicates that carbon loss is driven primarily by forest degradation and canopy thinning rather than outright forest area loss. Future projections further show a relative increase in carbon dependence on oak forests, intensifying vulnerability if these systems are disturbed.

4.4 Discussion

Assessing carbon storage and sequestration (CS & S) are important as key indicators of ecosystem health (Tewari et al., 2017). The contrast in carbon storage between 1990, 2020 and 2050 reflects losses of forest and vegetation cover over the study period. Notably, Verma et al. (2023) assessed carbon storage within the Askot Wildlife Sanctuary—a subset of the broader landscape—and similarly reported declining carbon trends, reinforcing the patterns observed in the present analysis. The carbon loss is observed in the Dhauli sub-watershed (Darma valley) and Kutti sub-watershed (Vyas valley). This region is a major tourist attraction due to Adi-Kailash and Om Parvat. Road expansion has been observed in this region, particularly around these two major sites of spiritual importance.

The observed pattern of greater forest area and above-ground carbon loss during 1990-2020 relative to the projected losses for 2020-2050 reflects well-established ecological and LULC modelling trends documented across regions. This outcome is driven by a combination of intrinsic limitations of the CA-Markov modelling framework and genuine changes in landscape dynamics as forest depletion progresses. Central to this pattern is the stationarity assumption of the CA-Markov model, which presumes that transition probabilities derived from historical land-use change remain constant into the future—an assumption that is mathematically convenient but ecologically unrealistic over long time horizons (Asif et al., 2023). Markov models assume that future land states depend solely on current conditions, without accounting for historical trajectories or evolving socio-ecological drivers; consequently, as transition matrices are iteratively applied over multiple time steps, conversion probabilities decline as the available forest pool shrinks (Yuh et al., 2024).

This behavior is consistent with *Forest Transition Theory*, which describes an S-shaped trajectory of forest cover change wherein early transition phases are characterized by rapid deforestation, followed by a late-transition phase marked by declining rates of loss as landscapes approach stabilization (Behera et al., 2025; Singh et al., 2025).

The 1990-2020 period in the present study corresponds to this early transition phase, while the projected 2020-2050 period reflects a late-transition regime, similar to patterns reported for the Western Himalaya, where rapid urban expansion was accompanied by slowing rates of forest loss as remaining forests became increasingly fragmented, inaccessible, or protected (Mondal et al., 2020). As forest cover declines, conversion becomes constrained by saturation effects, fragmentation thresholds, and economic viability limits, particularly once forest cover falls below critical connectivity thresholds (Duan et al., 2025; Tahir et al., 2025). Comparable trends have been documented in the Congo Basin, where historical forest loss substantially exceeded projected future losses over equivalent time periods, reflecting landscape saturation rather than modelling pessimism (Yuh et al., 2024). Forest fragmentation directly reduces future conversion rates. Current study area has likely transitioned from large contiguous forest patches to a highly fragmented landscape by 2020. In the present study area, pressures from urbanization, and infrastructure development, during 1990–2020 likely exhausted the most accessible and economically valuable forests, leaving behind higher-elevation, fragmented, and often protected/reserved forest patches by 2020. While the CA-Markov model does not explicitly capture non-stationarity, policy interventions, or economic thresholds, these real-world processes further contribute to declining deforestation rates in the projected period (Mani, 2021; Taloor et al., 2024). The Indian Himalayan Region (IHR) represents a major carbon sink and biodiversity reservoir, making its conservation critical for achieving India's nationally determined contributions (NDCs) (Ahirwal et al., 2021). However, ongoing land-use and climatic transformations threaten to reverse this role, potentially converting the region from a net carbon sink into a carbon source.

Chapter 5: Climate Ecological Niche Factor Analysis (CENFA)

5.1 Introduction

Climate change is affecting global natural ecosystems in unprecedented ways, with mountain regions exhibiting extreme vulnerability. The Himalayas, a critical global biodiversity hotspot often termed the "Third Pole," are among the most severely impacted areas (Shrestha et al., 2012). With faster warming rates at high elevations, altered precipitation, glacier retreat, and upslope shifts of treeline and vegetation, this global biodiversity hotspot becoming especially fragile (Wani et al., 2022; Kattel, 2022; Ghimire et al., 2025; Matta et al., 2025). Despite its ecological richness, the region's warming threatens unique narrow-niche species (Kattel, 2022) and increasing extinction risk (Ghimire et al., 2025).

Most work in the Himalaya uses species distribution / ecological niche models (SDMs/ENMs) combined with climate scenarios Representative Concentration Pathway (RCPs)/ Shared Socio-economic Pathways (SSPs) rather than explicitly using Climate/Climatic Niche Factor Analysis (CNFA/CENFA).

MaxEnt and BIOMOD ensemble models have been widely applied to treeline trees, medicinal plants, orchids and invasive species to project range shifts and habitat loss (Wani et al., 2022; Chandra et al., 2023; Hamid et al., 2018; Lamsal et al., 2018; Chowdhary et al., 2025). High elevation, endemic or narrowly distributed plants (e.g., *Dactylorhiza hatagirea, Rheum webbianum, Valeriana wallichii, Taxus wallichiana*) are projected to lose 50–90% of suitable habitat under high emission scenarios, often with only moderate niche overlap between current and future climates, indicating strong niche shifts (Tiwary et al., 2024; Wani et al., 2022; Kumari et al., 2022).

Similar SDM based approaches show severe contractions or spatial shifts of suitable habitat for threatened orchids, treeline birch, and key mammals such as snow leopard and red panda, with alpine and temperate species more vulnerable than lowland taxa (Chandra et al., 2023; Thapa et al., 2025; Hamid et al., 2018). Invasive alien plants and expanding *Pinus roxburghii* also show climate driven suitability changes, implying additional biotic pressure on native communities (Lamsal et al., 2018; Chowdhary et al., 2025). These studies generally quantify exposure (change in climatic suitability and range size) and sometimes infer sensitivity (life history traits, endemism, elevation) but rarely decompose vulnerability into standardized niche components as CNFA/CENFA do. The Climate Ecological Niche Factor Analysis (CENFA) framework offers a robust solution to this gap.

Rinnan and Lawler (2019) proposed the Climate-Niche Factor Analysis (CNFA), a significant advancement over previous ecological niche factor analyses. This method is particularly suited for the Himalayas because it operates on presence-only data and provides a spatially explicit measure of vulnerability.

According to the Rinnan and Lawler framework, vulnerability is a product of two distinct ecological components:

- ***Sensitivity (Marginality):*** The degree to which a species' climate niche differs from the average climate of the study area.
- ***Exposure:*** The degree to which the available climate in the study area will shift away from the species' required niche in the future.

This methodology, helps identify "climatic traps"—areas where high sensitivity meets high exposure—and "climatic refugia," which are stable zones that may preserve Himalayan biodiversity despite global warming trends.

Marginality, sensitivity, and exposure represent complementary dimensions of climatic risk within the CNFA framework. Marginality describes how climatically distinct the Askot landscape is relative to the regional climate, reflecting long-term adaptation to cool temperatures and monsoon-dominated precipitation. Sensitivity captures the degree of climatic specialization of ecosystems, indicating a narrow tolerance to deviations from current conditions. Exposure quantifies the magnitude of future climatic change. While marginality does not directly determine vulnerability, climatically marginal systems tend to be highly sensitive.

The scope of present study, to identify climatically vulnerable areas which may impact the ecosystem services in Askot landscape. Integrating CENFA with land-use/land-cover (LULC) projections—such as those derived from CA-Markov models—and carbon sequestration assessments via the InVEST model allows for a comprehensive understanding of how climatic and anthropogenic pressures converge to threaten carbon sinks and water resources by 2050 (Liang et al., 2021; Zhu et al., 2020).

5.2 Methodology

5.2.1 Climate Ecological Niche Factor Analysis (CENFA)

Climate change vulnerability assessments are techniques for determining how vulnerable a species, ecosystem, or ecosystem function is to climate change (Füssel, & Klein, 2006). For this study, Askot's vulnerability to climatic variables was calculated by following the CENFA approach, which was implemented by Rinnan and Lawler (2019). This approach derives (i) Sensitivity and (ii) Exposure to climate change, i.e., departure, (iii) a combination of departure and sensitivity is considered as vulnerability.

- ***Sensitivity to climate change***

Sensitivity is calculated as the array of environmental conditions an area tolerates concerning a given environmental variable. The rationale behind this metric is that the smaller the range of environmental conditions within an area, the smaller its width and, consequently, the more sensitive the area will be to strong deviations from climate change (Rinnan & Lawler, 2019).

The higher the overall climate sensitivity of an area, the smaller the climatic space that area has. If some part of Askot landscape only encompasses a narrow range of climatic conditions, it is reasonably expected the area to be more sensitive to the effects of climate change. The overall sensitivity reflects the average specialization in each variable and provides a useful measure for comparison with reference study area (Uttarakhand state), and Askot landscape.

- ***Exposure to climate change***

Exposure is calculated as a dissimilarity measure between present and future environmental conditions within an area: the higher such dissimilarity, the larger the amount of climatic change the area might experience.

- ***Vulnerability to climate change***

Vulnerability to climate change reflects the interaction between sensitivity and exposure to climate change. More details and equations used in the analysis are given in Rinnan and Lawler, (2019).

Following the CENFA framework, Sensitivity, exposure, and vulnerability were calculated for Askot landscape (Rinnan & Lawler, 2019) for SSP245 and SSP585 scenarios. All analyses were carried out using the "CENFA" R package using the *cnfa* function. For ease of understanding, each output maps were rescaled to categorize high, medium and low vulnerable areas.

5.2.2 Bioclimatic variables

Bioclimatic variables are derived from the monthly temperature and rainfall values to generate more biologically meaningful variables. These are often used for ecological modelling techniques (Hijman *et al.,* 2005). The bioclimatic variables were downloaded from the WorldClim 2.1 website (Fick & Hijmans, 2017) at a resolution of 30 arc-seconds (≈1 km^2). The downloaded dataset covers the temporal span of 1970 to 2020 (near present), providing average climatic conditions for this period. WorldClim's current climate data were generated by interpolating climate station data.

For future climatic scenarios, WorldClim's future climate data downscaled from the Global Circulation model (GCM) MIROC-E2SL based dataset were downloaded for 2041-2060 (mid-century) and 2081-2100 (end of the century). These projections were based on four distinct Coupled Model Intercomparison Project Phase 6 (CMIP6) derived Shared Socioeconomic Pathways (SSPs): SSP1-2.6, SSP2-4.5, SSP4-6.0, and SSP5-8.5. These SSPs represent various plausible future emission scenarios, considering diverse socioeconomic assumptions and potential trajectories. For this analysis, two pathways were considered, SSP245 (Middle of the road) and SSP585 (Worst-case scenario). Among the total 19 variables downloaded, recommended (Warren *et al.,* 2013) bioclim variables (Table 5.1) were selected that represent annual trends (BIO1 = Annual Mean Temperature, BIO12 = Annual Precipitation), extreme environmental factors (BIO5 = Max Temperature of Warmest Month, BIO6 = Min Temperature of Coldest Month, BIO16 = Precipitation of Wettest Quarter, BIO17 = Precipitation of Driest Quarter) and seasonality (BIO4 = Temperature Seasonality, BIO15 = Precipitation Seasonality) (Fig 5.1 & 5.2). Before conducting the analyses, all bioclimatic variables were spatially clipped using ArcGIS 10.8 to align with the specific boundaries of different biogeographic regions. Clipped bioclimatic variables were used as the reference area.

Table 5.1 List of bioclimatic variables used in the analysis

S. no.	Bioclimatic variables	Abbreviation	Remarks
1	Annual Mean Temperature	Bio1	Source: www.worldclim.org Resolution: 1km^2
2	Temperature Seasonality	Bio4	
3	Max Temperature of Warmest Month	Bio5	
4	Min Temperature of Coldest Month	Bio6	
5	Annual Precipitation	Bio12	
6	Precipitation Seasonality	Bio15	
7	Precipitation of Wettest Quarter	Bio16	
8	Precipitation of Driest Quarter	Bio17	

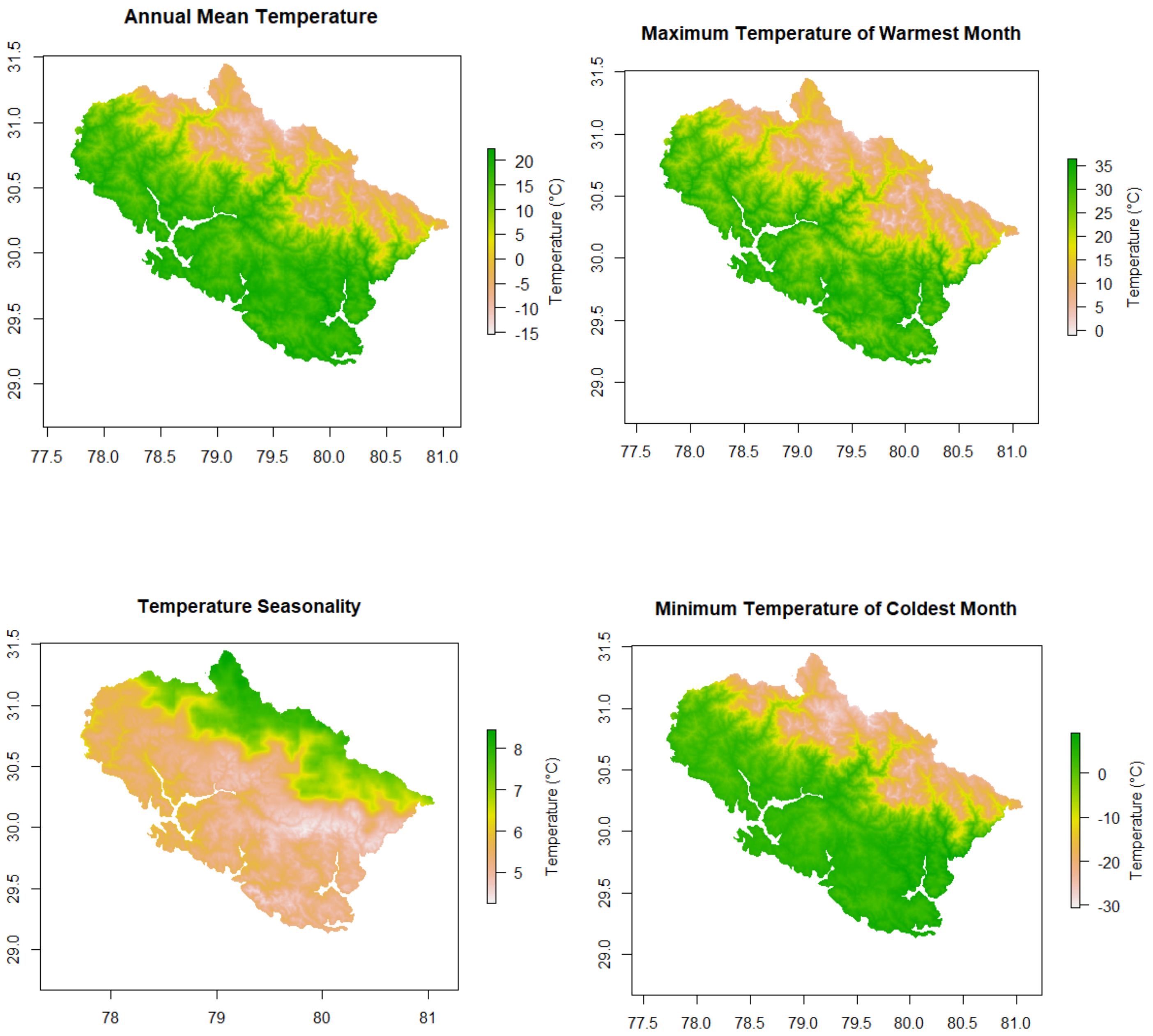


Fig 5.1 : Temperature related Bioclimatic variables

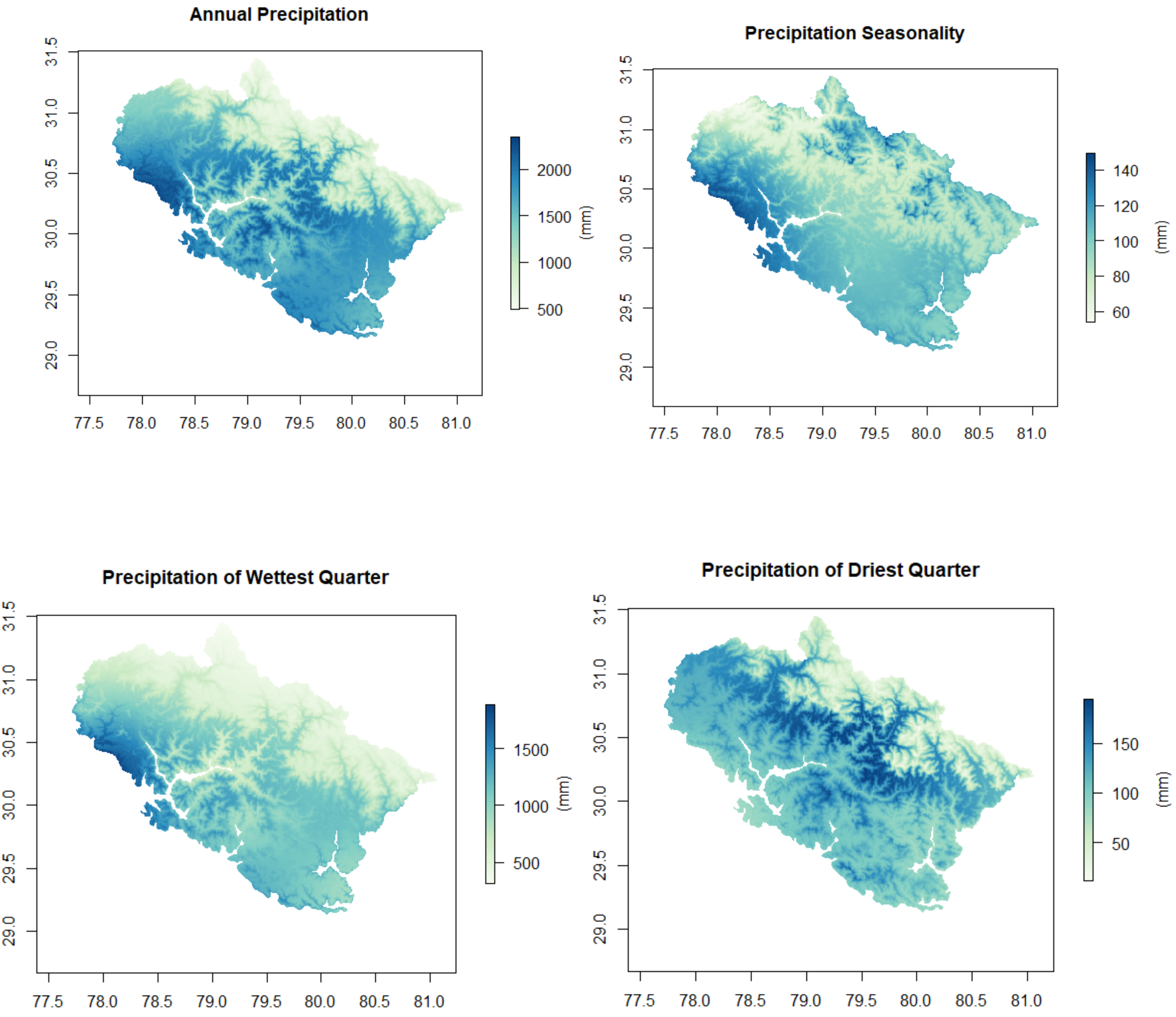


Fig 5.2: Precipitation related Bioclimatic variables

5.3 Results

5.3.1 Climatic Sensitivity, Exposure, and Vulnerability of the Askot Landscape

Bioclimatic Variable Contributions to Sensitivity

Sensitivity

Sensitivity analysis identifies a small set of bioclimatic variables that dominate ecosystem specialization in the Askot landscape (Table 5.2). Annual Mean Temperature (BIO1) ranked as the most influential variable, followed by Precipitation of the Wettest Quarter (BIO16) and Annual Precipitation (BIO12). These variables collectively indicate that Askot's ecosystems are highly specialized to cool thermal regimes and reliable monsoonal moisture. Temperature extremes—represented by Maximum Temperature of the Warmest Month (BIO5) and Minimum Temperature of the Coldest Month (BIO6)—also contribute notably, highlighting sensitivity to both warming and cold-season instability.

Table 5.2: Variable-wise ranking of climatic sensitivity in Askot

Rank	Bioclimatic Variable	Sensitivity Score	Interpretation
1	BIO1:Annual Mean Temperature	4.45	Strong ecosystem response to small temperature changes
2	BIO16: Precipitation of Wettest Quarter	4.12	High dependence on monsoon stability
3	BIO12: Annual Precipitation	3.58	Sensitivity of productivity and hydrological services
4	BIO5: Maximum Temperature of Warmest Month	2.76	Heat stress during growing season
5	BIO6: Minimum Temperature of Coldest Month	2.42	Sensitivity of snow-dependent and alpine processes

Bioclimatic Variable Contributions to Exposure (Future Climate Change)

The exposure analysis indicates (Table 5.3) that future climate change in the Askot landscape is primarily driven by alterations in precipitation regimes and temperature extremes. The highest exposure is associated with precipitation of the wettest quarter (BIO16), highlighting strong projected shifts in monsoon intensity and seasonality. Annual mean temperature (BIO1) ranks second, reflecting consistent regional warming under both SSP245 and SSP585 scenarios. Changes in annual precipitation (BIO12) further indicate increasing rainfall variability, while rising maximum temperatures during the warmest month (BIO5) suggest intensifying heat stress. The comparatively lower exposure of minimum temperature of the coldest month (BIO6) implies a reduction in cold extremes rather than abrupt winter warming. Overall, these patterns reveal that future exposure in Askot is dominated by hydroclimatic change coupled with progressive warming, with important implications for alpine systems, forest–meadow ecotones, and hydrological services.

Table 5.3. Variable-wise ranking of climatic exposure under future scenarios

Rank	Bioclimatic Variable	Exposure Score	Interpretation
1	BIO16: Precipitation of Wettest Quarter	4.68	Strong projected change in monsoon regime
2	BIO1: Annual Mean Temperature	4.33	Consistent warming under SSP245 and SSP585
3	BIO12: Annual Precipitation	3.96	Increasing rainfall variability
4	BIO5: Maximum Temperature of Warmest Month	3.05	Intensification of heat extremes
5	BIO6: Minimum Temperature of Coldest Month	2.67	Reduced cold extremes

Exposure patterns indicate that **future climate change in Askot is dominated by altered monsoon dynamics and rising temperatures**, with stronger impacts under SSP585.

Variable-wise ranking of Vulnerability

The vulnerability ranking indicates (Table 5.4) that precipitation- and temperature-related variables jointly control climate risk in the Askot landscape. The dominance of BIO16 and BIO1 highlights that ecosystems most dependent on stable monsoon rainfall and cool mean temperatures are the most vulnerable under future climate scenarios. Variables associated with thermal extremes (BIO5 and BIO6) further amplify vulnerability, particularly in high-elevation and transitional zones. This pattern confirms that climate vulnerability in Askot is driven not only by warming but by increasing variability and disruption of seasonal climate regimes.

Table 5.4. Variable-wise ranking of vulnerability

Rank	Bioclimatic Variable	Vulnerability Score	Interpretation
1	BIO16: Precipitation of Wettest Quarter	4.29	Highest combined risk due to marginality, sensitivity, and exposure
2	BIO1: Annual Mean Temperature	4.14	Persistent warming stress across elevations
3	BIO12: Annual Precipitation	3.75	Moisture-driven vulnerability
4	BIO5: Maximum Temperature of Warmest Month	2.60	Secondary thermal stress
5	BIO6: Minimum Temperature of Coldest Month	2.30	Lower relative vulnerability

* Vulnerability scores represent the combined effect of climatic sensitivity and exposure as derived from the CNFA framework.

The vulnerability ranking confirms that **precipitation seasonality and temperature increase together define climate risk in the Askot landscape**, rather than temperature alone.

Sensitivity and Vulnerability Scores under SSP245 and SSP585

Scenario-wise comparison shows a clear escalation of climatic stress from SSP245 to SSP585 (Table 5.5). Sensitivity values increase under future scenarios, indicating **progressive narrowing of climatic tolerance**. Vulnerability scores rise correspondingly, with the highest values observed under **SSP585 by end-century**, reflecting the combined effect of higher exposure acting on already climate-specialized ecosystems.

Table 5.5: Overall sensitivity and vulnerability scores

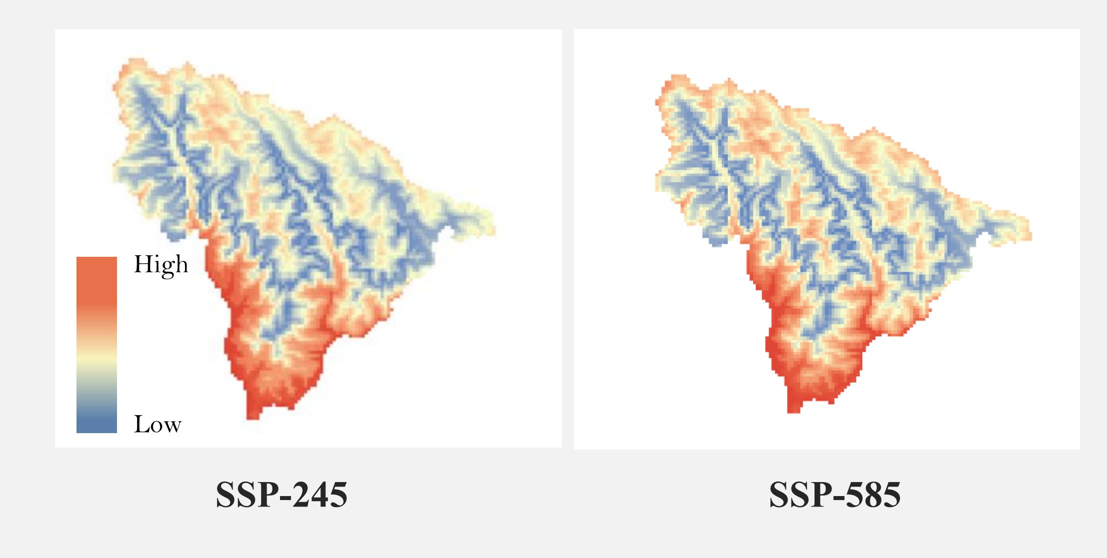
Scenario	Time Period	Sensitivity	Vulnerability
SSP245	Mid-century (2041–2060)	Moderate	1.57
SSP585	Mid-century (2041–2060)	High	1.60
SSP245	End-century (2081–2100)	High	1.61
SSP585	End-century (2081–2100)	Very High	1.67

The results demonstrate that climate vulnerability in the Askot landscape is primarily driven by temperature increase, monsoon destabilization, and rising climatic variability. The consistent dominance of BIO1, BIO12, and BIO16 across sensitivity, exposure, and vulnerability confirms that warming and precipitation changes act synergistically. The marked increase in vulnerability under SSP585 highlights that high-emission trajectories substantially amplify ecological risk, particularly for alpine meadows, forests, and transitional snow–barren zones.

5.3.2 Climatic Vulnerability Trends in the Askot Landscape (Mid- and End-Century)

The combined analysis of climatic vulnerability for the mid-century (2041–2060) and end-century (2081–2100) periods indicates a progressive intensification of climate stress across the Askot landscape (Table 5.6). During the mid-century period, high-vulnerability areas expand to approximately 1535.22 km², while medium-vulnerability zones decline to 2608.60 km², suggesting an ongoing transition of landscapes toward higher climatic risk. Low-vulnerability areas remain limited, covering only 352.80 km², indicating that relatively stable climatic conditions persist in a small portion of the watershed. By the end of the century (2081–2100), this trend becomes more pronounced. High-vulnerability areas increase substantially to 1762.58 km², reflecting a marked expansion of climatically stressed zones across the landscape. Concurrently, medium-vulnerability areas contract further to 2451.79 km², while low-vulnerability areas decline to 282.24 km², reinforcing the pattern of diminishing climate-resilient zones over time (Fig 5.3).

Mid-Century: 2041-2060



End of Century: 2081-2100

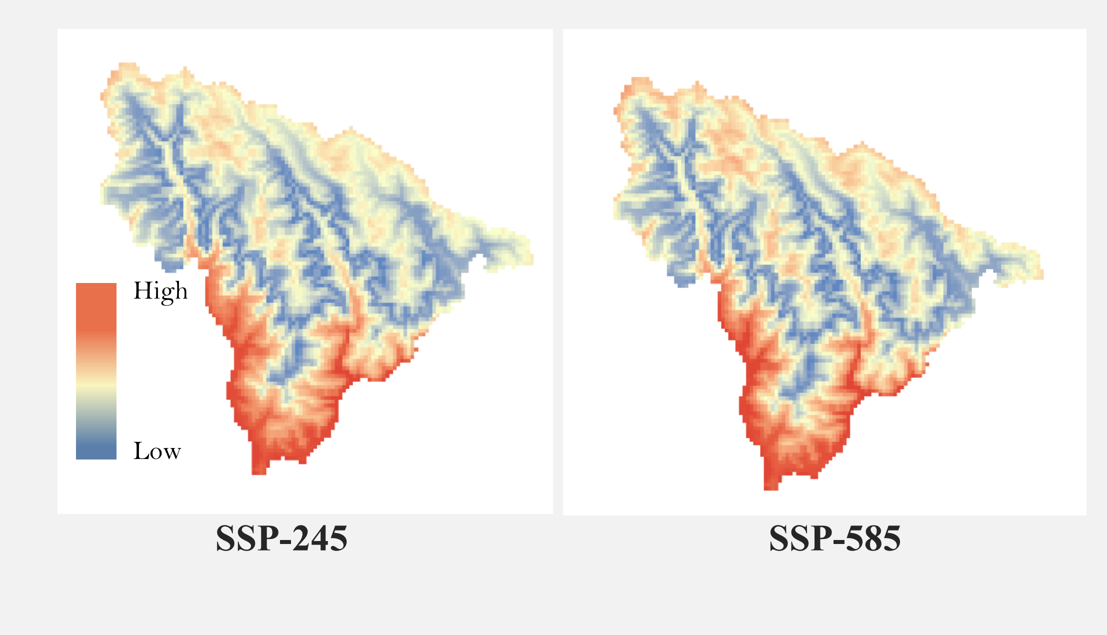


Fig 5.3:Climatically vulnerable region in Askot landscape under different scenarios

Table 5.6 Spatial Extent of Climate Vulnerability Classes in Askot

Mid-century (2041-2060)	**Area (sq.km)**	
Category	**SSP245**	**SSP585**
High	1266.72	1535.22
Medium	2854.94	2608.60
Low	374.96	352.80

End-of-century (2081-2100)	**Area (sq.km)**	
Category	**SSP245**	**SSP585**
High	1447.56	1762.58
Medium	2723.35	2451.79
Low	325.72	282.24

Overall, the temporal progression from mid- to end-century highlights a systematic shift from medium and low vulnerability classes toward high vulnerability, underscoring the growing exposure and sensitivity of the Askot watershed under projected climate change scenarios. This expansion of high-risk areas has significant implications for ecosystem stability and the sustained provision of ecosystem services, particularly regulating services such as above-ground carbon storage, water regulation, and habitat integrity. The results emphasize that climate impacts in mountain watersheds like Askot are not static but intensify over time, necessitating long-term adaptive planning and climate-responsive land-use and conservation strategies.

High sensitivity to mean temperature and wet-season precipitation, combined with increasing climatic departure under future scenarios—particularly SSP585—drives a steady rise in climate vulnerability. The spatial convergence of high sensitivity, exposure, and vulnerability in alpine meadows, forests at lower-mid elevations zones indicates considerable future threats for carbon losses.

5.4 Discussion

In this chapter, the sensitivity, exposure, and vulnerability scores of the Askot landscape was quantified. Findings indicate that lower to mid elevation (800-3000 m) exhibit higher climate vulnerability. Results also suggests that high-elevation (above 3000 m) ranges have higher exposure to climate change in the Askot region.

The landscape is defined by a fixed boundary, and with increasing temperature there will be changes in climate conditions. The spatial overlap between high-vulnerability zones identified through CENFA and areas projected to experience carbon loss in the InVEST analysis indicates a coupled risk to both biodiversity and ecosystem functioning.

The CENFA-based climatic vulnerability assessment reveals a distinct elevational pattern of vulnerability, closely aligned with vegetation distribution, land-use dynamics, and ecosystem service provisioning across the Himalayan landscape. Notably, low- to mid-elevation zones, which currently support the maximum forest cover, emerge as highly vulnerable climatic zones. This finding is particularly significant because these elevations constitute the primary contributors to Above-Ground Carbon (AGC) storage, thereby playing a central role in regional carbon sequestration services.

High climatic vulnerability within these forest-dominated belts suggests that even modest climatic deviations may trigger disproportionate ecological responses, including shifts in species composition, reduced biomass accumulation, and increased susceptibility to degradation or conversion. When coupled with observed and projected LULC transitions, such as forest-to-agriculture or forest-to-settlement expansion, climatic stress acts as a compounding driver, amplifying AGC losses beyond those attributable to land-use change alone. Thus, the convergence of high vulnerability and high AGC density indicates a critical risk zone where climate change may directly undermine ecosystem service stability.

CENFA further highlights upper-elevation regions, encompassing snow-covered zones and alpine meadows, as additional hotspots of climatic vulnerability. Although these areas contribute comparatively less to AGC storage, their vulnerability has far-reaching downstream implications. Accelerated warming in these cryosphere-influenced systems promotes snowline retreat, altered freeze–thaw regimes, and degradation of alpine vegetation, which collectively disrupt hydrological regulation. Such cryospheric changes exacerbate seasonal water stress in lower elevations and increase the likelihood of extreme hydrological events, including flash floods and landslides, thereby indirectly affecting forest stability and carbon dynamics downslope.

In contrast, morainic landscapes and sparsely vegetated high-altitude zones exhibit relatively lower climatic vulnerability under the CENFA framework. This pattern likely reflects their inherently low ecological marginality and limited vegetation dependence, rendering them less sensitive to climatic variability in functional terms. However, their apparent stability should not be interpreted as ecological resilience; rather, it underscores the uneven distribution of climate risk across ecosystem types, with biologically productive systems facing the greatest threat.

Overall, the integrated analysis demonstrates that climatic vulnerability is not uniformly aligned with elevation or vegetation density, but instead emerges from the interaction between climatic marginality, ecosystem sensitivity, and land-use pressures. By explicitly linking CENFA outputs with AGC ecosystem service assessment and LULC/vegetation change, this study underscores that climate change poses the most severe risks where ecosystem services are both concentrated and socio-ecologically valuable. These findings highlight the need for elevation-specific adaptation and conservation strategies, prioritizing forested low- and mid-elevation zones for carbon retention while addressing cryospheric vulnerability in upper elevations to safeguard hydrological stability and downstream ecosystem services.

Chapter 6: Significance, Way Forward and Policy Recommendations

6.1 Significance

This chapter presents as final remarks of this thesis, the key messages of this research, and significance of the study.

Analysis of multi-temporal LULC dynamics reveals a clear structural transformation of the Askot landscape, marked by progressive forest canopy degradation, contraction of alpine and snow-dominated areas, expansion of mixed moraines surfaces, and a measurable increase in settlement area. While the absolute extent of settlements remains small, their disproportionate ecological influence is evident, particularly in a steep, highly connected mountain watershed where even limited rural expansion can fragment habitats, alter hydrological pathways, and amplify the pressure on surrounding ecosystems. In Himalayan contexts such as Askot, dispersed rural settlements—often associated with road expansion, fuelwood extraction, grazing, and slope modification—pose a more pervasive ecological threat than compact urban growth, echoing emerging global evidence that rural settlement dynamics are an underappreciated driver of biodiversity loss.

Carbon stock assessment highlights the role of dense and moderately dense forests as key carbon reservoirs, while transitions toward open forest, scrub, and barren classes result in a net decline in above-ground carbon storage. This pattern underscores the climate mitigation value of maintaining forest structural integrity in mountain watersheds and cautions against interpreting forest persistence alone as ecological stability when canopy degradation is ongoing.

Forest conservation represents the most effective climate-mitigation strategy for the Askot landscape. Although forests occupy approx. 18% of the total area, they safeguard over 85% of the landscape’s above-ground carbon. Remarkably, oak forests alone cover only ~10% of Askot, yet store nearly 60% of total carbon stocks, underscoring their exceptional climate value.

The CNFA-based climate vulnerability assessment further indicates that the lower elevation forested patch is more sensitive to climate change as opposed to high-elevation alpine, snow, and transition zones. These forested regions exhibit elevated exposure and sensitivity, making them particularly vulnerable to ongoing warming and precipitation variability. These climate-vulnerable areas spatially coincide with zones undergoing land-cover instability, reinforcing the conclusion that climate stress and land-use change are acting synergistically to reshape ecosystem structure and function. Such changes have direct implications for regulating ecosystem services, including carbon sequestration, water regulation, sediment retention, and slope stability—services that are critical for downstream communities.

6.2 Ecosystem Service for Decision Making

Ecosystem services provide a practical framework for translating ecological functions into information relevant for decision-making. By quantifying benefits such as carbon storage, water regulation, soil retention, and habitat support, ecosystem service assessments help bridge the gap between ecological science and policy. In mountain landscapes like **Askot**, where ecological sensitivity intersects with livelihood dependence, this approach is particularly critical. Askot’s forests, alpine ecosystems, and river systems support downstream water security, climate regulation, and biodiversity conservation. Integrating ecosystem service assessments into planning enables identification of priority areas, evaluation of trade-offs, and formulation of climate-resilient strategies, thereby supporting informed, ecosystem-based decision-making in the face of rapid environmental change.

This research is designed to be operationally relevant within India's existing statistical and policy framework. *The spatially explicit carbon stock and sequestration estimated at the landscape scale for the Askot landscape can be directly positioned within the SEEA Central Framework as compilation of forest and ecosystem physical asset accounts at sub-national level*. By embedding carbon dynamics within an asset-accounting structure, the Askot case study demonstrates how local ecosystem service assessments can support the development of environment-adjusted economic indicators, such as Environment-adjusted State Domestic Product (ESDP), and inform climate and restoration focused policy decisions.

The use of widely accepted models (InVEST, CA-MARKOV), standardized land-use classifications, and data sources compatible with those of agencies such as the Forest Survey of India, MoSPI and the Central Statistics Office ensures that the results can be readily integrated into ongoing SEEA implementation efforts. This work moves beyond conceptual valuation to provide accounting-consistent, policy-ready evidence that can inform environment-adjusted economic indicators, state-level planning, and India's forest restoration and climate commitments.

In parallel, the Global Biodiversity Framework (GBF), through **Goal B and Target 11**, calls for restoring and maintaining nature's contributions to people. This study provides spatially explicit evidence from the Askot Himalayan watershed on how land-use change and climate variability affect ecosystem services critical for water security and disaster risk reduction. The findings directly support place-based implementation of India’s Nationally Determined Contribution (NDC) and GBF commitments through ecosystem services–informed watershed planning.

6.3 Limitations

1. The carbon assessment in this study is limited to above-ground biomass and does not account for the full range of forest carbon pools, including below-ground biomass, soil organic carbon, and dead organic matter. Consequently, the reported carbon loss represents a partial estimate rather than total ecosystem carbon dynamics.

2. The analysis does not capture variations in carbon stocks across different forest types in relation to canopy density, as spatially explicit data linking forest type with density classes were not available for the study area.

3. The decadal assessment of past, present, and projected land-use scenarios shows relatively limited change in forest type extent, reflecting the inherent stability of forest types. As changes were primarily observed in canopy density rather than forest type conversion, projected future carbon losses appear lower compared to historical periods.

4. The study area is characterized by rugged and inaccessible terrain, which constrained the availability of cloud-free satellite imagery and limited the achievable classification accuracy. These topographic and atmospheric challenges are intrinsic to Himalayan landscapes and introduce unavoidable uncertainties in remote sensing–based analyses.

6.4 Way Forward & Policy Recommendations

The findings of this thesis reinforce that the **valuation of ecosystem services** is not merely an academic exercise, but a fundamental requirement for **sustainable economic governance**. Conventional national accounting systems remain narrowly focused on produced capital, systematically excluding society's dependence on natural ecosystems that function as essential life-support systems. As a result, critical services such as carbon sequestration, nutrient cycling, water regulation, and biodiversity conservation largely unpriced and outside formal markets- are treated as having negligible or zero economic value, fostering overexploitation and degradation of the natural resource base. Here are few recommendations:

A. Transition toward environment-adjusted economic accounting

There is the need to move beyond Gross Domestic Product (GDP) (mostly used indicator of a country's income) centric measures of growth toward **inclusive wealth accounting**, which incorporates reproducible, human, and natural capital. Traditional accounting frameworks, such as the System of National Accounts (SNA), record investments in built infrastructure while it fails to account for the depreciation of natural capital stock resulting from economic exploitation and environmental degradation. For example, the drainage of wetlands or loss of forests underlying urban expansion.

To correct this imbalance, India should accelerate the adoption of an **Environment-adjusted State Domestic Product (ESDP)** framework that explicitly deducts the costs of natural capital depletion and environmental degradation from economic aggregates.

Such an approach would provide a more accurate representation of development trade-offs and prevent growth trajectories that mask irreversible ecological losses.

B. Strengthening SEEA implementation in India

India has already taken important steps toward integrating the **System of Environmental-Economic Accounting (SEEA)** into its statistical and policy framework. Efforts led by the Central Statistics Office, the Ministry of Statistics and Programme Implementation (MoSPI) producing Natural Capital Accounting and Valuation of Ecosystem Services (NCAVES), including the development of Physical Supply and Use Tables (PSUTs) and asset accounts for land, forests, timber, and minerals, represent critical "do-ables" under the SEEA Central Framework.

- Adopting a **bottom-up approach** by implementing SEEA accounts at the state or watershed level—where planning and resource management decisions occur—before scaling up to the national level.

These initiatives should be strengthened and expanded to ensure consistency across states and sectors, enabling meaningful comparison and policy application at sub-national scales.

C. Moving from physical to monetary ecosystem accounts

The next and more challenging step involves transitioning from physical accounts to Monetary Supply and Use Tables (MSUTs). This requires addressing a major empirical gap: the absence of reliable estimates of **shadow prices**, or social values, of natural capital as factors of production. Without these values, ecosystem services remain invisible in fiscal decision-making.

- Future policy must therefore prioritize empirical valuation studies that quantify the economic contribution of non-market services such as water purification, soil fertility, and biodiversity.

D. Expanding the asset boundary and closing data gaps

Future environmental accounts must expand the current asset boundary to include non-monetized ecosystem services that are presently excluded from India's Integrated National Accounts. Equally important is the need to close persistent data gaps. Agencies such as the Wildlife Institute of India (WII), Forest Survey of India (FSI), the National Bureau of Soil Survey (NBSS), Central Ground Water Board (CGWB), Forest Departments and others require strengthened mandates and resources to generate regular, high-resolution data on forest regeneration, land degradation, soil nutrient loss, and ecosystem health.

E. Toward transformative environmental governance

Finally, this thesis argues that environmental accounting should not merely be used to optimize existing market failures, but to support a transformative shift in economic planning. By integrating ecosystem service values into national and state-level statistics, India can move toward development pathways that secure long-term human well-being, particularly for vulnerable populations who depend most directly on natural capital.

- Policy frameworks must recognize ecological thresholds and **identify "no-go" or inviolate areas** where natural capital loss would be irreversible.

Only by embedding these "soft" shadow prices into "hard" economic statistics can India fully recognize the true value of its natural wealth and ensure sustainability for future generations.

Conclusion

The Himalayan region plays a critical role in India's climate and biodiversity commitments by sustaining water regulation, carbon storage, slope stability, and climate resilience for downstream populations. India's Nationally Determined Contribution (NDC) emphasizes strengthening ecosystem-based adaptation and enhancing forest and natural carbon sinks, particularly in climate-sensitive mountain landscapes.

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Annexure

1. *Table 1: Species-specific C_{above} data from meta-analysis*

Veg Species/ Class	C Above (Mg/ha)	Sources
Quercus leucotrichophora (Banj mix)	28.83	Pala et al. 2013
Quercus leucotrichophora (Banj mix)	89.35	Kumar et al. 2016
Quercus leucotrichophora (Banj mix)	175.44	Vikrant et al. 2014
Quercus leucotrichophora (Banj mix)	24.81	Kumar et al. 2015
Quercus leucotrichophora (Banj mix)	17.84	Kumar et al. 2015
Quercus leucotrichophora (Banj mix)	139.57	Sharma et al. 2019
Birch (Betula utilis)	3.2	Sharma et al. 2016
Birch (Betula alnoides)	1.62	Sharma et al. 2016
Abies spectibilis (Fir)	41.33	Pala et al. 2012
Abies pindrow (Fir)	7.005	Dimri et al. 2018
Abies pindrow (Fir)	3.38	Dimri et al. 2018
Abies pindrow (Fir)	86.05	Kumar et al. 2016
Abies pindrow (Fir)	86.05	Kumar et al. 2015
Abies pindrow (Fir)	2.82	Sharma et al. 2016
Abies spectabilis	9.15	Sharma et al. 2016
Abies pindrow	12.38	Sharma et al. 2016
Abies pindrow	140.45	Sharma et al. 2010
Deodar (Cedrus deodara)	43.1	Kumar et al. 2015
Deodar (Cedrus deodara)	66.34	Kumar et al. 2015
Deodar (Cedrus deodara)	199.84	Sharma et al. 2010
Deodar (Cedrus deodara)	61.48	Kumar et al. 2015
Deodar (Cedrus deodara)	66.34	Kumar et al. 2015
Deodar (Cedrus deodara)	2.02	Bohara et al. 2018
Deodar (Cedrus deodara)	15.37	Bohara et al. 2018
Kharshu (Quercus semecarpifolia)	40.97	Pala et al. 2012
Kharshu (Quercus semecarpifolia)	81.535	Dimri et al. 2018
Kharshu (Quercus semecarpifolia)	38.07	Kumar et al. 2016
Kharshu (Quercus semecarpifolia)	38.07	Kumar et al. 2015
Kharshu (Quercus semecarpifolia)	198.85	Sharma et al. 2016
Kharshu (Quercus semecarpifolia)	103.15	Sharma et al. 2010
Kharshu (Quercus semecarpifolia)	38.07	Kumar et al. 2015
Kharshu (Quercus semecarpifolia)	163.59	Bohara et al. 2018
Kharshu (Quercus semecarpifolia)	191.41	Bohara et al. 2018
Mixed broadleaf (Myrica esculenta- Kafal)	14.58	Gwal et al. 2010
Mixed broadleaf (Myrica esculenta- Kafal)	11.76	Gwal et al. 2010
Mixed broadleaf (Myrica esculenta- Kafal)	40.24	Gwal et al. 2010
Mixed broad leaf (Lyonia ovalifolia)	12.16	Kumar et al. 2015
Mixed broad leaf (Lyonia ovalifolia)	20.5	Kumar et al. 2015
Mixed broad leaf	57.15	Sharma et al. 2010

Veg Species/ Class	**C Above (Mg/ha)**	**Sources**
Temperate Grassland	1.67	Yadav et al. 2024
Alpine scrub	26	Rashid et al. 2017
Moru Oak (Quercus floribunda)	53.31	Pala et al. 2013
Moru Oak (Quercus floribunda)	123.19	Dimri et al. 2018
Moru Oak (Quercus floribunda)	71.235	Kumar et al. 2016
Moru Oak (Quercus floribunda)	25.25	Sharma et al. 2016
Moru Oak (Quercus floribunda)	207.56	Sharma et al. 2016
Moru Oak (Quercus floribunda)	108.21	Sharma et al. 2010
Moru Oak (Quercus floribunda)	11.89	Bohara et al. 2018
Pine (Pinus roxburghii)	26.9	Pala et al. 2013
Pine (Pinus roxburghii)	23.63	Kumar et al. 2016
Pine (Pinus roxburghii)	61.15	Kumar et al. 2016
Pine (Pinus roxburghii)	40.43	Kumar et al. 2015
Pine (Pinus roxburghii)	110.34	Sharma et al. 2010
Pine (Pinus roxburghii)	40.83	Kumar et al. 2015
Pine (Pinus roxburghii)	18.74	Kumar et al. 2015
Pine (Pinus roxburghii)	56.6	Gosain et al. 2015
Pine (Pinus roxburghii)	57.7	Gina et al. 2008
Rhododendron arboreum	50.215	Pala et al. 2012
Rhododendron arboreum	1.81	Dimri et al. 2016
Rhododendron arboreum	4.54	Dimri et al. 2016
Rhododendron arboreum	27.32	Kumar et al. 2016
Rhododendron arboreum	33.87	Kumar et al. 2015
Rhododendron arboreum	58.25	Kumar et al. 2015
Rhododendron arboreum	7.41	Sharma et al. 2016
Rhododendron arboreum	7.62	Sharma et al. 2016
Rhododendron arboreum	4.56	Sharma et al. 2016
Rhododendron arboreum	33.87	Kumar et al. 2015
Rhododendron arboreum	58.25	Kumar et al. 2015
Rhododendron arboreum	4.79	Bohara et al. 2018
Alnus nepalensis (Uties)	74.865	Kumar et al. 2016
Alnus nepalensis (Uties)	1.36	Sharma et al. 2016
Alnus nepalensis (Uties)	77.45	Limboo 2022
Alnus nepalensis (Uties)	74.73	Limboo 2022
Alnus nepalensis (Uties)	81.87	Limboo 2022
Alnus nepalensis (Uties)	58.23	Limboo 2022
Sal (Shorea robusta Roxb.)	124.22	Shahid et al. 2017
Sal (Shorea robusta Roxb.)	166.57	Shahid et al. 2017
Sal (Shorea robusta Roxb.)	147.69	Shahid et al. 2017
Sal (Shorea robusta Roxb.)	187.4	Kongkham et al. 2021
Sal (Shorea robusta Roxb.)	199	Kongkham et al. 2021
Sal (Shorea robusta Roxb.)	191.95	Kongkham et al. 2021

2. Paper published

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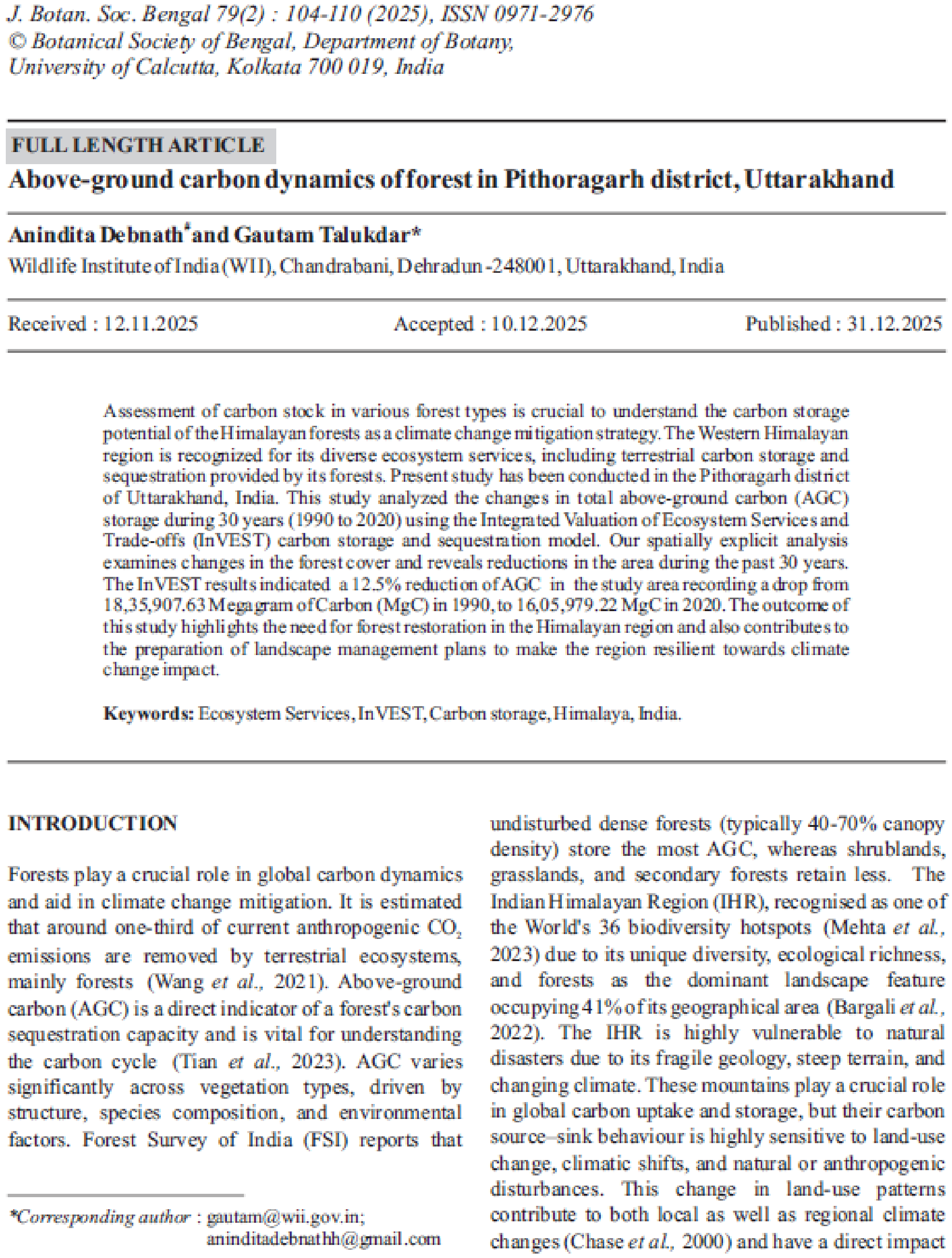

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FULL LENGTH ARTICLE

Above-ground carbon dynamics of forest in Pithoragarh district, Uttarakhand

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Assessment of carbon stock in various forest types is crucial to understand the carbon storage potential of the Himalayan forests as a climate change mitigation strategy. The Western Himalayan region is recognized for its diverse ecosystem services, including terrestrial carbon storage and sequestration provided by its forests. Present study has been conducted in the Pithoragarh district of Uttarakhand, India. This study analyzed the changes in total above-ground carbon (AGC) storage during 30 years (1990 to 2020) using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) carbon storage and sequestration model. Our spatially explicit analysis examines changes in the forest cover and reveals reductions in the area during the past 30 years. The InVEST results indicated a 12.5% reduction of AGC in the study area recording a drop from 18,35,907.63 Megagram of Carbon (MgC) in 1990, to 16,05,979.22 MgC in 2020. The outcome of this study highlights the need for forest restoration in the Himalayan region and also contributes to the preparation of landscape management plans to make the region resilient towards climate change impact.

Keywords: Ecosystem Services, InVEST, Carbon storage, Himalaya, India.

INTRODUCTION

Forests play a crucial role in global carbon dynamics and aid in climate change mitigation. It is estimated that around one-third of current anthropogenic CO_2 emissions are removed by terrestrial ecosystems, mainly forests (Wang *et al.,* 2021). Above-ground carbon (AGC) is a direct indicator of a forest's carbon sequestration capacity and is vital for understanding the carbon cycle (Tian *et al.,* 2023). AGC varies significantly across vegetation types, driven by structure, species composition, and environmental factors. Forest Survey of India (FSI) reports that undisturbed dense forests (typically 40-70% canopy density) store the most AGC, whereas shrublands, grasslands, and secondary forests retain less. The Indian Himalayan Region (IHR), recognised as one of the World's 36 biodiversity hotspots (Mehta *et al.,* 2023) due to its unique diversity, ecological richness, and forests as the dominant landscape feature occupying 41% of its geographical area (Bargali *et al.,* 2022). The IHR is highly vulnerable to natural disasters due to its fragile geology, steep terrain, and changing climate. These mountains play a crucial role in global carbon uptake and storage, but their carbon source–sink behaviour is highly sensitive to land-use change, climatic shifts, and natural or anthropogenic disturbances. This change in land-use patterns contribute to both local as well as regional climate changes (Chase *et al.,* 2000) and have a direct impact

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on biodiversity and biogeochemical cycles (Romshoo, 2004; Kumar *et al.*, 2022). Quantifying above-ground carbon in diverse vegetation types is fundamental for effective forest management, climate modeling, and policy.

The Western Himalaya hosts diverse forest types ranging from tropical forests at lower elevations, below 1000 meters (m), to alpine and sub-alpine forests above 3000 m. Tropical Subtropical zones (1000–2000 m) are characterized by *Pinus roxburghii* (Chir Pine), while the temperate montane forests (2000–3000 m) feature broad leaved species like *Quercus leucotrichophora* (Banj Oak), *Cedrus deodara* (Deodar), *Pinus wallichiana* (Blue Pine), and *Abies pindrow* (Fir). In the subalpine zone (3000–4000 m), conifers such as *Picea smithiana* (Spruce) and firs dominate, alongside hardwoods like *Quercus semecarpifolia* (Kharsu Oak), *Acer* spp. (Maples), and *Betula utilis* (Himalayan Birch). Rhododendrons, including *R. campanulatum* and *R. arboreum*, are widespread in the upper reaches, with junipers marking the transition to alpine scrub (Dhar *et al.*, 1997).

The amount of carbon stored in a forest varies among different species – (Kaushal and Baishya, 2021) and is influenced by several factors, including stand structure, stem density, species composition, and growth characteristics (Sharma *et al.*, 2010). Different methods have been used to estimate forest carbon stock/biomass such as estimates based on forest inventories (Salunkhe *et al.*, 2018) or using allometric equations (Nyamari and Cabral, 2021). Remote sensing spatial approaches (Fu *et al.*, 2023) or integrated models (Dang *et al.*, 2019) are also widely used. Although field-based measurement of aboveground biomass (AGB) is the most accurate way to quantify forest and vegetation biomass, it is time-consuming, laborious, and difficult to scale to vast areas (Ma *et al.*, 2024). In recent advances, carbon mapping and valuation model, i.e., In VEST (Integrated Valuation of Ecosystem Services and Tradeoffs), have emerged as reliable technique providing promising results for stakeholders and decision-makers. Earlier carbon quantification studies are available at a coarse-scale (Sharma *et al.*, 2010). The current study aims to fill the knowledge gap in the data deficient region of the Western Himalaya, by incorporating a comprehensive approach and quantification of AGC at a landscape level.

MATERIALS AND METHODS

Study area

The landscape lies between the Gori-ganga and Kuti catchment, in Pithoragarh district of Uttarakhand, in the Western Himalaya. It encompasses an area of approximately 4500 square kilometer (sq.km) and shares an international border with the Tibet in the north (Fig. 1). Kali River forms the southeastern border of the landscape as well as an international border between India and Nepal (Samant *et al.*, 1998). The landscape has a wide altitudinal range from 600 m to above 7000 m. Elements of the Western Himalaya, the Central Himalaya, and the Tibetan Plateau converge in this landscape, making it a regionally important site for its species richness and biological distinctiveness (Dhar *et al.*, 1997). The landscape is majorly snow-covered while the forested area possesses various forest types viz. sub-alpine forest, temperate broadleaved forest, sub-tropical forest, moist mixed deciduous Forest, Himalayan chirpine forest, banj-kharsu oak forest etc. (Champion and Seth, 1968; Bisht *et al.*, 2023). The 'Askot Wildlife Sanctuary' is the only protected area in the landscape (Verma *et al.*, 2024).

Data acquisition and processing

Multi-temporal satellite data was acquired to map the forest of the landscape. The cloud free satellite data LANDSAT Thematic Mapper (TM) acquired for 1990 and SENTINEL-2A for 2020 (Table 1). The data is downloaded from United States Geological Survey (USGS) Earth Explorer Programme website (https://earthexplorer.usgs.gov/). On-screen visual interpretation method was employed using Google Earth and ArcGIS desktop (v10.8.0) software to map the changes in spatial extent. The resulting change layer is stored in both raster and vector formats for subsequent analysis (ISFR, 2023).

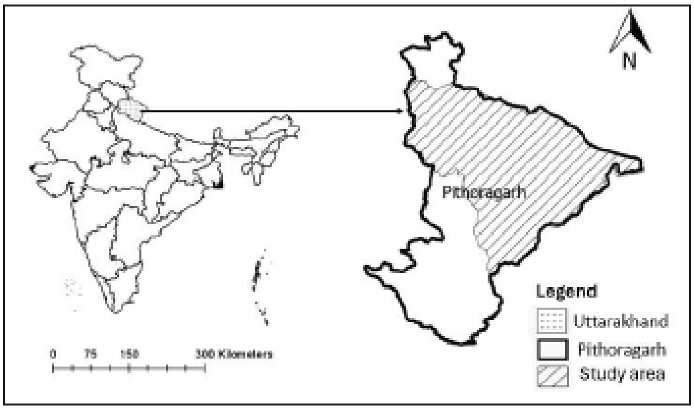

Fig. 1. Study area map

Table 1. Information of geospatial data used in the study

Sl.No.	Satellite/Sensor	Source	Date of acquisition	Resolution	Number of Bands
1.	LANDSAT 5 TM	USGS Earth Explorer	23.10.1990 15.11-1990	30 m	3
2.	SENTINEL-2A	Copernicus	22.11.2020 14.11.2020	10 m	3

Data analysis

The biomass carbon content was compiled through a meta-analysis of various research articles, reports and published documents (Verma *et al.*, 2024) assuming that carbon densities in above-ground pool have not changed over the different scenarios and an average value was taken (from 1990 to 2020).The InVEST (Integrated Valuation of Ecosystem Services and Trade-offs) carbon storage and sequestration (CS & S) model (v3.12.0) is used in this study to estimate the carbon stock (static) over time (dynamic) of the landscape based on above-ground biomass (AGB) (Natural Capital Project, 2022). In equation (1), AGC_{1990} and AGC_{2020} are the static carbon stocks in 1990 and 2020 respectively, which shows the amount of carbon storage and change happened over the years.

$$\text{Carbon}_{Change} = AGC_{(1990)} - AGC_{(2020)} \qquad \text{......(1)}$$

RESULTS

Analysis of forest area

The data shows the forested area declined between 1990 and 2020. The forest of this region primarily composed of *Quercus leucotrichophora* (Banj Oak), *Cedrus deodara* (Deodar), *Shorea robusta* (Sal), *Pinus roxburghii* (Chir Pine). The forested area reduced from 249 square kilometer (sq.km) to 223 sq.km. Hence, the decline in forest area indicates habitat loss, signifying ecosystem degradation in the study area (Fig. 2).These species are found in low to mid-elevation ranges in the landscape. Decline in their area reflects deforestation, overexploitation for fuelwood/fodder, and climate-induced stress. Rising temperatures are causing upward shifts in suitable habitat zones, as species track cooler climatic conditions at higher elevations. Concurrently, anthropogenic pressures—including the expansion of agricultural land and the growth of settlement areas—are further modifying the landscape. Together, these climatic and land-use drivers are contributing to significant alterations in habitat distribution and ecosystem structure. The concerning biodiversity loss and ecosystem service degradation in the region necessitate urgent conservation interventions.

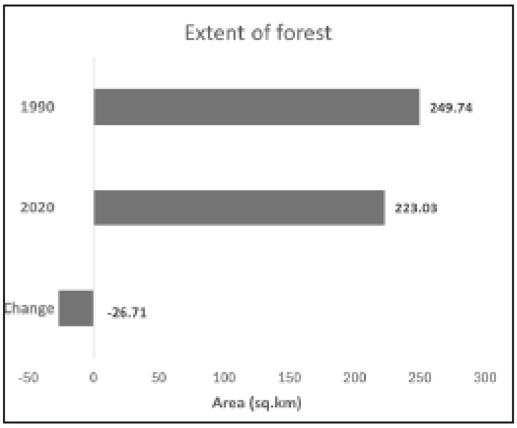

Fig. 2. Extent of forest in Askot landscape

Carbon Storage Dynamics

The aboveground carbon (AGC) content varied notably among the dominant forest types. From the meta-analysis it was found that, *Shorea robusta* exhibited the highest AGC value indicating its substantial carbon storage potential owing to its dense biomass and large tree size. This was followed by *Quercus leucotrichophora* and *Cedrus deodara*, while *Pinus roxburghii* contained lower AGC value. The total carbon storage declined from 1,835,907.6 Megagram of Carbon (MgC) in 1990 to 1,605,979.2 MgC in 2020, indicating a net loss of approximately 229,948.4 MgC over three decades. An overall decrease of approximately -12.5% over the three-decade period has been observed. Change in above-ground carbon storage is shown in Fig 3. The spatial extent of forest, carbon storage, and changes over the years in Pithoragarh is presented in Table 2.

DISCUSSION

Recent decades show that climate change is accelerating and affecting ecological systems and livelihoods worldwide – (Joshi and Singh, 2020). Several studies confirm the observed decline in carbon storage across dominant forest types in the Himalayan forests – (Dar and Parthasarathy, 2022; Verma *et al.*, 2024). Major drivers include land-use change such as,expansion of infrastructure, agriculture (Rashid *et al.*, 2017; Kumar *et al.*, 2022), forest degradation-(Pandey *et al.*, 2020), and climate-related stresses e.g., suitable habitat reduction (Hamid *et al.*, 2018), range shift to higher altitudes (Malik *et al.*, 2022). The focus of the present study was on

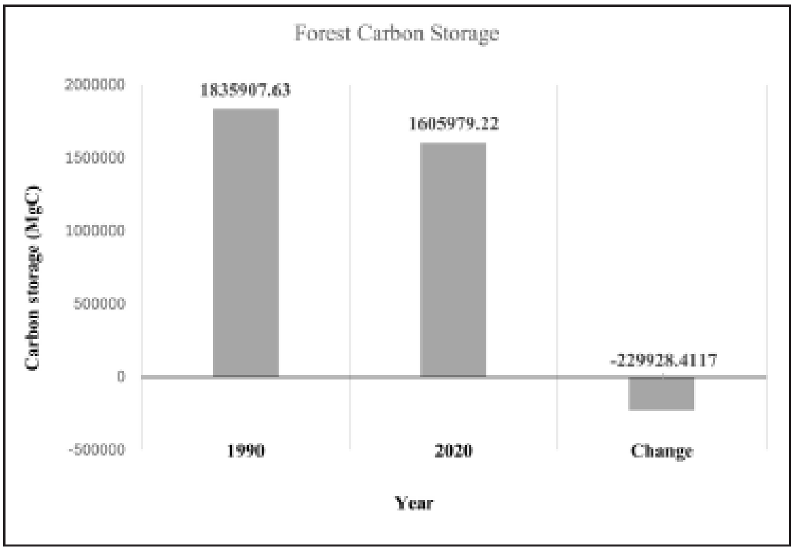

Fig. 3. Above-ground carbon storage of forest in 1990 & 2020

Table 2. Area Statistics and Above-Ground Carbon Storage of Forest in the study area for 1990 and 2020

Sl.No.	Category	1990	2020	Change
1	Forest Area (sq.km)	249.74	223.03	-26.71
2	Forest Carbon Storage (Megagram of carbon, MgC)	1835907.63	1605979.221	-229928.4117

quantifying AGC CS & S of selected species, to understand the dynamics of carbon storage. The present study reports the progressive loss of above-ground carbon across dominant forest types in the region supporting trends from previous studies,the landscape experienced a steady decline in above-ground carbon, losing nearly -76,643 MgC every decade over the 30-year period. The landscape is prone to anthropogenic pressures such as cutting, lopping, fire, and grazing, as well as natural adversities like floods, landslides, and droughts, leading to significant ecological degradation and biodiversity loss (Bisht *et al.,* 2023).These disruptions weaken the natural structure of ecosystems and reduce their ability to maintain climatic balance. The fragile Himalayan landscape is prone to natural hazards, which, when combined with anthropogenic pressures, accelerate forest vulnerability and biodiversity loss (Kanwar and Kuniyal, 2022). As these threats directly impact the tree-biomass, hence the above-ground carbon (AGC) continues to decline over the years. Reviews and meta-analyses confirm that forest structure, disturbance, and climate change are driving a downward trend in carbon sequestration potential and overall carbon stocks in the Indian Himalayan Region (Kumari *et al.,* 2021). Himalayan forests are experiencing a decline in carbon stocks, driven by anthropogenic activities, land-use change, and increased disturbance, with significant implications for climate mitigation and ecosystem health (Dhiman and Kumar, 2024).

Understanding the underlying drivers of these patterns is crucial for forest carbon management and conservation across diverse ecological zones including the Central Himalaya (Khanal *et al.*, 2024).

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DISCLAIMER

The author(s) declare no conflict of interest in the work.

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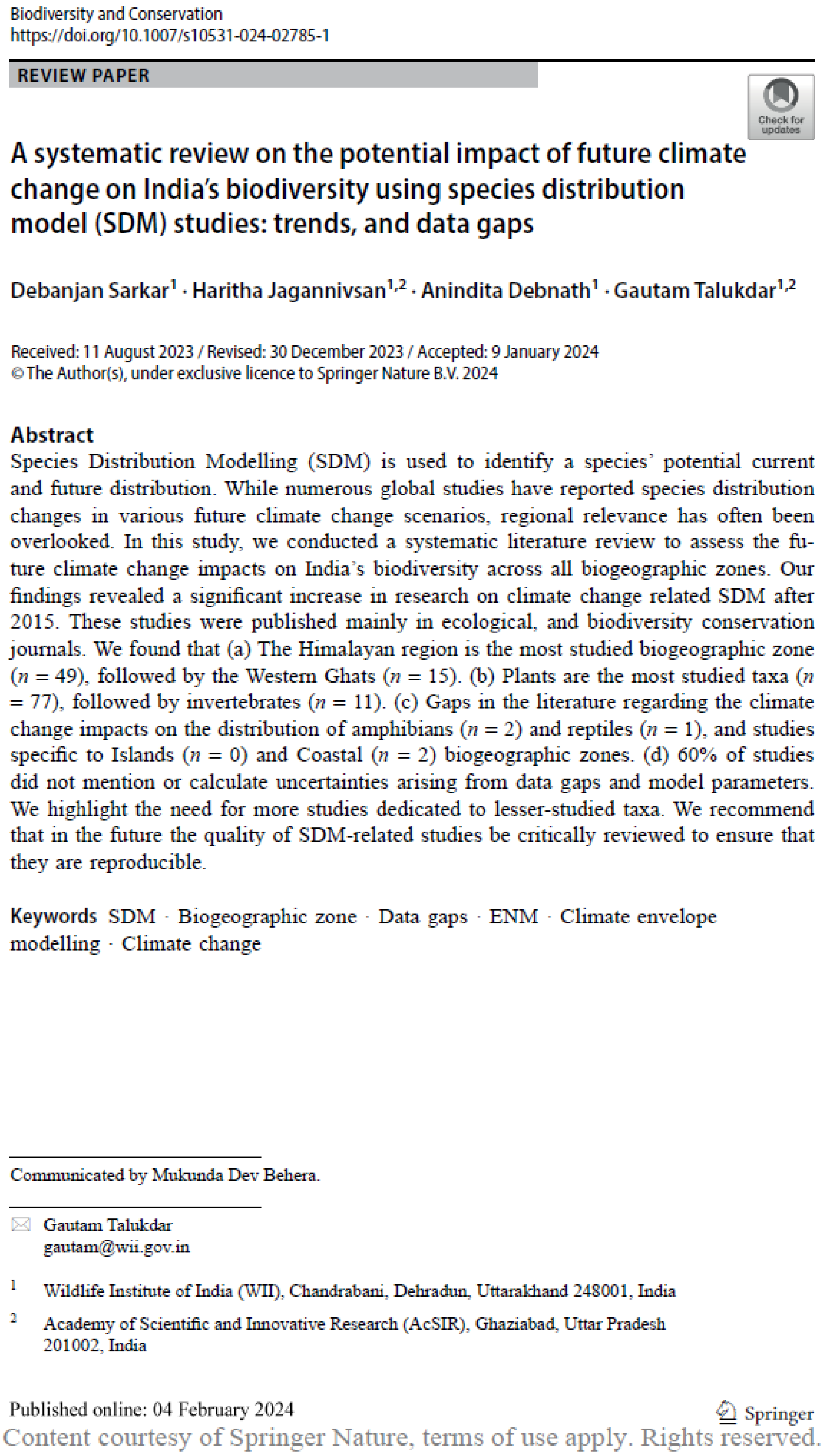
2. Sarkar, D., Jagannivsan, H., **Debnath, A.,** & Talukdar, G. (2024). A systematic review on the potential impact of future climate change on India's biodiversity using species distribution model (SDM) studies: trends, and data gaps. Biodiversity and Conservation, 1-17. 10.1007/s10531-024-02785-1 (ONLINE ISSN: 1572-9710)



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REVIEW PAPER

A systematic review on the potential impact of future climate change on India's biodiversity using species distribution model (SDM) studies: trends, and data gaps

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Received: 11 August 2023 / Revised: 30 December 2023 / Accepted: 9 January 2024

Abstract

Species Distribution Modelling (SDM) is used to identify a species' potential current and future distribution. While numerous global studies have reported species distribution changes in various future climate change scenarios, regional relevance has often been overlooked. In this study, we conducted a systematic literature review to assess the future climate change impacts on India's biodiversity across all biogeographic zones. Our findings revealed a significant increase in research on climate change related SDM after 2015. These studies were published mainly in ecological, and biodiversity conservation journals. We found that (a) The Himalayan region is the most studied biogeographic zone (n = 49), followed by the Western Ghats (n = 15). (b) Plants are the most studied taxa (n = 77), followed by invertebrates (n = 11). (c) Gaps in the literature regarding the climate change impacts on the distribution of amphibians (n = 2) and reptiles (n = 1), and studies specific to Islands (n = 0) and Coastal (n = 2) biogeographic zones. (d) 60% of studies did not mention or calculate uncertainties arising from data gaps and model parameters. We highlight the need for more studies dedicated to lesser-studied taxa. We recommend that in the future the quality of SDM-related studies be critically reviewed to ensure that they are reproducible.

Keywords SDM · Biogeographic zone · Data gaps · ENM · Climate envelope modelling · Climate change

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Communicated by Mukunda Dev Behera.

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3. Conference attended

National

(I) Debnath, A., Ramachandran, A., and Talukdar, G. (2025). Spatiotemporal Dynamics and Prediction of Land Use Land Cover Change in a Himalayan Watershed Using Land Change Modeler. ISG-ISRS National Symposium 2025: Geomatics and space innovations towards Atmanirbhar Bharat: Insights and Frontiers, IIT Kharagpur Research Park, W.B. India, 25-27 November 2025

ISRS

ISG ISRS National Symposium 2025
on
Geomatics and space innovations towards Atmanirbhar Bharat: Insights and Frontiers

Certificate

Prof./Dr./Mr./Ms. Anindita Debnath of Wildlife Institute of India attended ISG ISRS National Symposium and presented a paper titled Spatiotemporal Dynamics and Prediction of Land Use Land Cover Change in a Himalayan Watershed Using Land Change Modeler organised during 25-27 November, 2025, by ISG Kharagpur local chapter, Regional Remote Sensing Centre (RRSC) - East, Kolkata and IIT Kharagpur.

Dr. Prakash Chauhan
President, ISG

Prof. MD Behera
Organising Secretary

Dr. CP Singh
Secretary, ISG

ISG-ISRS National Symposium 2025
Geomatics and space innovations towards **Atmanirbhar Bharat**: Insights and Frontiers
25th – 27th November 2025, IIT Kharagpur Research Park

Abstract ID: 410

Spatiotemporal Dynamics and Prediction of Land Use Land Cover Change in a Himalayan Watershed Using Land Change Modeler

Anindita Debnath[1], Aishwarya Ramachandran[2], Gautam Talukdar[1]

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Land use and land cover (LULC) changes influence the global terrestrial ecosystems to a great extent. Hence, assessing LULC change is crucial for understanding ecosystems and aiding in their management. The Himalayan region is significant for conservation; nevertheless, it experiences many forms of landscape modification, and there is a paucity of studies addressing this issue. The present study evaluates the LULC dynamics in the Askot Landscape of Western Himalaya, quantifies the changes, identifies probable drivers behind the changes, and predicts the future trends. The spatial analysis was performed using multi-temporal satellite datasets for 1999, 2011, and 2020, and the CA-Markov chain analysis was performed in Land Change Modeler (LCM) for predicting future changes. The future LULC prediction has been generated for the year 2050. In accordance with the historical trend, the projected change also indicated that all forested land classifications have decreased, while the area under the non-forest category has expanded. As compared to 2020, the Oak Forest is projected to decline by 1.56%, and Temperate Forest showed a decline of 11.15%, indicating high stress on high-elevation species like *Rhododendron*, *Cedrus deodara* (Deodar), and *Pinus spp*. Mixed-Broadleaf Forest exhibits the highest degradation with a 15.43% reduction, threatening ecologically valuable species in the region. In contrast, Non-Forest areas are expected to increase by 7.21%, reflecting reduction in permanent-snow cover areas and expansion in barren land, landslide-zones, settlement, agricultural areas. Although anthropogenic disturbances are a major source of stress, our findings also indicate that high-elevation forested areas are increasingly at risk from climate-related vulnerabilities. Given that the region is already prone to natural disasters, the loss of forested areas will further increase its susceptibility to such events.

Keywords: LULC, Askot, Future modelling, Conservation

(II) Debnath, A., and Talukdar, G. (2024). Land Use and Land Cover Changes Over Three Decades (1990-2020) in the Western Himalaya: A Case Study of the Askot Landscape. **IEEE** India Geoscience and Remote Sensing Symposium **(InGARSS),** National Institute of Technology, Goa, India, 2-5 December, 2024.

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has successfully completed and actively participated in the:

InGARSS 2024

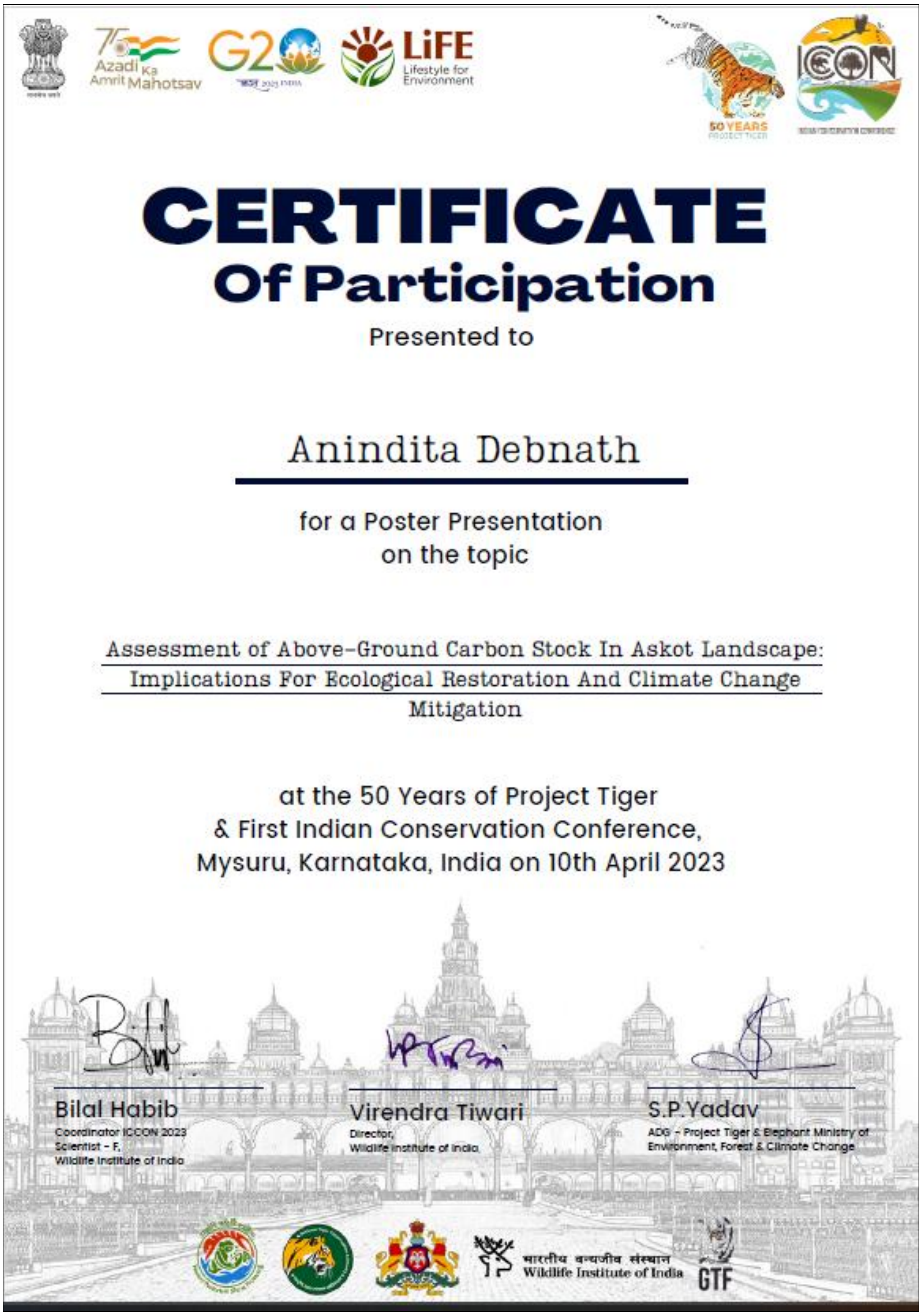
Held from 2 to 5 Dec, 2024

We extend our sincere appreciation for their enthusiasm, dedication, and meaningful engagement throughout the event.

Gulab Singh

General Chair

(III) Debnath, A., and Talukdar, G. (2023). Assessment of aboveground carbon stock in Askot Landscape: Implications for ecological restoration and climate change mitigation. First Indian Conservation Conference (**ICCON**), Mysuru, Karnataka, India, 9-11 April, 2023.



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Assessment of Above-Ground Carbon Stock In Askot Landscape:
Implications For Ecological Restoration And Climate Change
Mitigation

at the 50 Years of Project Tiger
& First Indian Conservation Conference,
Mysuru, Karnataka, India on 10th April 2023

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ADG - Project Tiger & Elephant Ministry of Environment, Forest & Climate Change

भारतीय वन्यजीव संस्थान
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International

(I) Debnath, A., Talukdar, G. (2024), Tracking Carbon Over Decades: Monitoring Ecosystem Services in the Askot Landscape, Indian Himalayas. 5th ESP Europe Conference, Ecosystem Services: One Planet, One Health, Wageningen, The Netherlands, 18-22 November, 2024

5th ESP
Europe Conference
ECOSYSTEM SERVICES: ONE PLANET, ONE HEALTH
18-22 NOVEMBER 2024
WAGENINGEN, THE NETHERLANDS

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Wildlife Institute of India

For attending and presenting at the 5th ESP Europe 2024 Conference in Wageningen, The Netherlands, 18-22 November 2024

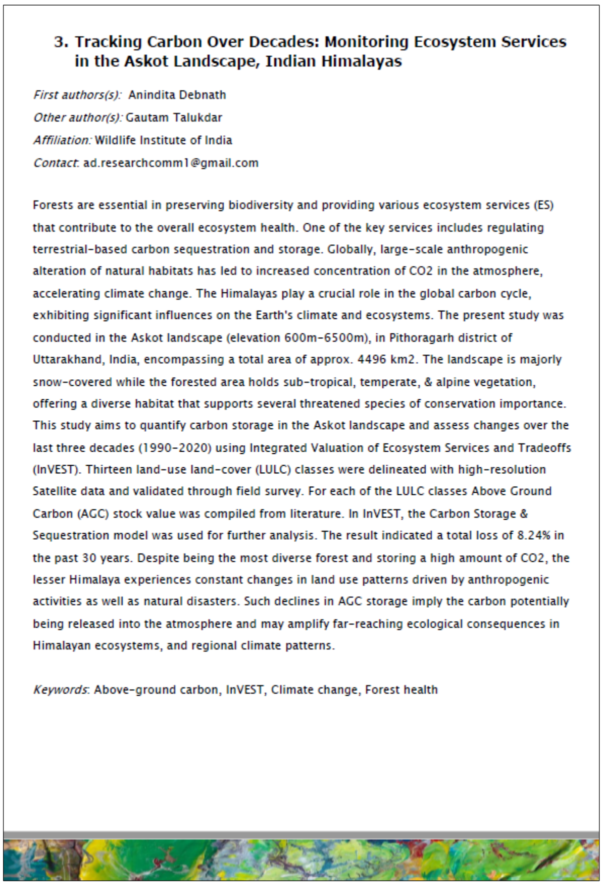
Presentation title: *Tracking Carbon Over Decades: Monitoring Ecosystem Services in the Askot Landscape, Indian Himalayas*

Rudolf de Groot

Mieke Siebers

ESP
Ecosystem Services Partnership

Foundation for Sustainable Development



3. Tracking Carbon Over Decades: Monitoring Ecosystem Services in the Askot Landscape, Indian Himalayas

First authors(s): Anindita Debnath
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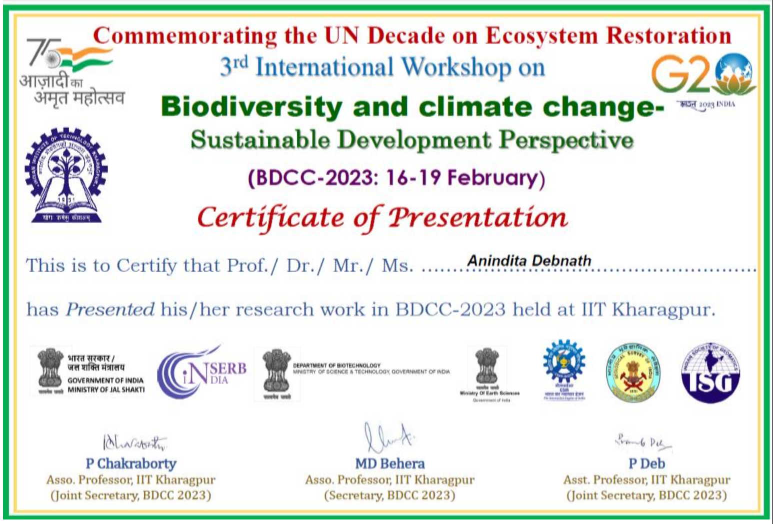
Forests are essential in preserving biodiversity and providing various ecosystem services (ES) that contribute to the overall ecosystem health. One of the key services includes regulating terrestrial-based carbon sequestration and storage. Globally, large-scale anthropogenic alteration of natural habitats has led to increased concentration of CO2 in the atmosphere, accelerating climate change. The Himalayas play a crucial role in the global carbon cycle, exhibiting significant influences on the Earth's climate and ecosystems. The present study was conducted in the Askot landscape (elevation 600m-6500m), in Pithoragarh district of Uttarakhand, India, encompassing a total area of approx. 4496 km2. The landscape is majorly snow-covered while the forested area holds sub-tropical, temperate, & alpine vegetation, offering a diverse habitat that supports several threatened species of conservation importance. This study aims to quantify carbon storage in the Askot landscape and assess changes over the last three decades (1990-2020) using Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST). Thirteen land-use land-cover (LULC) classes were delineated with high-resolution Satellite data and validated through field survey. For each of the LULC classes Above Ground Carbon (AGC) stock value was compiled from literature. In InVEST, the Carbon Storage & Sequestration model was used for further analysis. The result indicated a total loss of 8.24% in the past 30 years. Despite being the most diverse forest and storing a high amount of CO2, the lesser Himalaya experiences constant changes in land use patterns driven by anthropogenic activities as well as natural disasters. Such declines in AGC storage imply the carbon potentially being released into the atmosphere and may amplify far-reaching ecological consequences in Himalayan ecosystems, and regional climate patterns.

Keywords: Above-ground carbon, InVEST, Climate change, Forest health

(II) Debnath, A., Sarkar, D., and Talukdar, G. (2023). Modelling climatically vulnerable areas in Askot Landscape- A case study in the Indian Himalayan Region. 3rd International Workshop on ‘Biodiversity and Climate Change – Sustainable Development Perspective (BDCC 2023), IIT Kharagpur, W.B. India,16-19 February, 2023.



Commemorating the UN Decade on Ecosystem Restoration

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Asso. Professor, IIT Kharagpur
(Joint Secretary, BDCC 2023)

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(Secretary, BDCC 2023)

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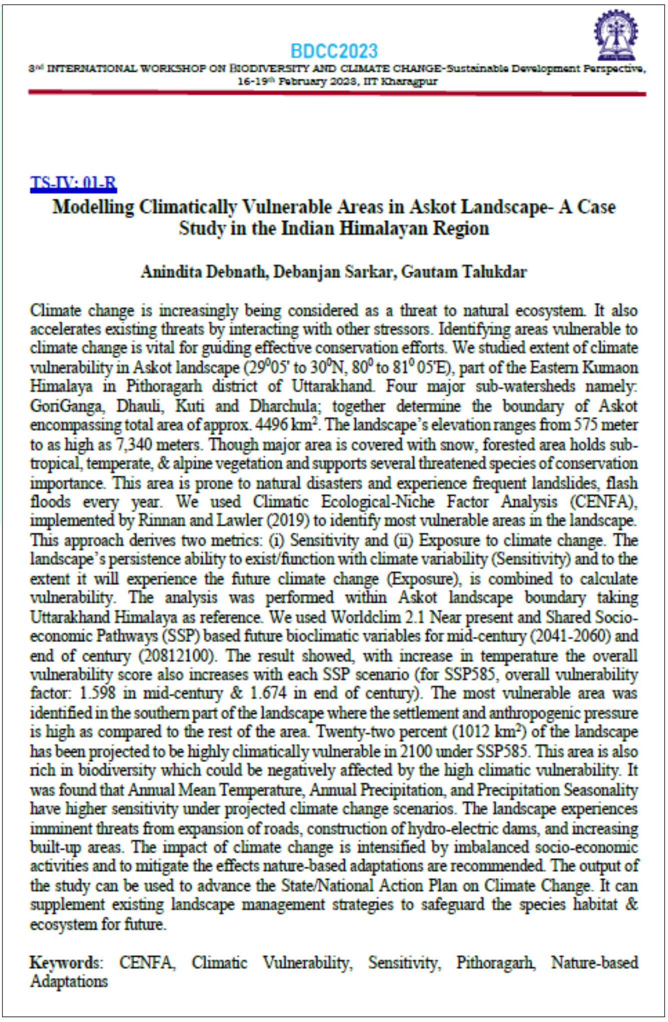

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16-19th February 2023, IIT Kharagpur

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Modelling Climatically Vulnerable Areas in Askot Landscape- A Case Study in the Indian Himalayan Region

Anindita Debnath, Debanjan Sarkar, Gautam Talukdar

Climate change is increasingly being considered as a threat to natural ecosystem. It also accelerates existing threats by interacting with other stressors. Identifying areas vulnerable to climate change is vital for guiding effective conservation efforts. We studied extent of climate vulnerability in Askot landscape ($29^0 05'$ to 30^0N, 80^0 to $81^0 05'$E), part of the Eastern Kumaon Himalaya in Pithoragarh district of Uttarakhand. Four major sub-watersheds namely: GoriGanga, Dhauli, Kuti and Dharchula; together determine the boundary of Askot encompassing total area of approx. 4496 km^2. The landscape's elevation ranges from 575 meter to as high as 7,340 meters. Though major area is covered with snow, forested area holds sub-tropical, temperate, & alpine vegetation and supports several threatened species of conservation importance. This area is prone to natural disasters and experience frequent landslides, flash floods every year. We used Climatic Ecological-Niche Factor Analysis (CENFA), implemented by Rinnan and Lawler (2019) to identify most vulnerable areas in the landscape. This approach derives two metrics: (i) Sensitivity and (ii) Exposure to climate change. The landscape's persistence ability to exist/function with climate variability (Sensitivity) and to the extent it will experience the future climate change (Exposure), is combined to calculate vulnerability. The analysis was performed within Askot landscape boundary taking Uttarakhand Himalaya as reference. We used Worldclim 2.1 Near present and Shared Socio-economic Pathways (SSP) based future bioclimatic variables for mid-century (2041-2060) and end of century (20812100). The result showed, with increase in temperature the overall vulnerability score also increases with each SSP scenario (for SSP585, overall vulnerability factor: 1.598 in mid-century & 1.674 in end of century). The most vulnerable area was identified in the southern part of the landscape where the settlement and anthropogenic pressure is high as compared to the rest of the area. Twenty-two percent (1012 km^2) of the landscape has been projected to be highly climatically vulnerable in 2100 under SSP585. This area is also rich in biodiversity which could be negatively affected by the high climatic vulnerability. It was found that Annual Mean Temperature, Annual Precipitation, and Precipitation Seasonality have higher sensitivity under projected climate change scenarios. The landscape experiences imminent threats from expansion of roads, construction of hydro-electric dams, and increasing built-up areas. The impact of climate change is intensified by imbalanced socio-economic activities and to mitigate the effects nature-based adaptations are recommended. The output of the study can be used to advance the State/National Action Plan on Climate Change. It can supplement existing landscape management strategies to safeguard the species habitat & ecosystem for future.

Keywords: CENFA, Climatic Vulnerability, Sensitivity, Pithoragarh, Nature-based Adaptations