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The Himalayan Treeline and the Associated Dynamics: Understanding the Ecological Challenges and Livelihood Threat to the Dependent Population

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Abstract

This study is a review article which examines the dynamics of the treeline shifts in the Himalayan region of India. It further looks at its impact on ecology, resources and the local communities. The previous studies have found that the Himalayan region is warming at rates faster than the surrounding lowlands. In Himalayas, changes in temperature and precipitation patterns over recent decades have led to significant alterations in treeline ecology, affecting both the landscape and the livelihoods of the communities. As per the previous studies, the Indian Himalayan treeline has shifted significantly upward from 1972-2014. Arunachal Pradesh now has the highest treeline at 4136m (shifted up 452m), followed by Jammu and Kashmir at 4121m (shifted up 441m). Uttarakhand's treeline moved up 411m to 3615m, while Himachal Pradesh and Sikkim both rose about 301m to reach 3520m and 3542m respectively. This study documents temporal changes in altitudinal treeline positions based on available literatures, its associated vegetation dynamics, and their socioeconomic implications for local and transhumant communities. The investigation of several literatures reveals that there has been an upward shift of the treeline in most of the Himalayan region. These shift varies from 300-600m spatially. This threatens alpine meadows, which are critical for local biodiversity and traditional pastoral practices. Grazing areas and other forest resources are becoming less productive and cannot meet the growing demands of both human and livestock populations. The research documents a decline in the availability of essential resources, including medicinal plants,

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timber, firewood, and grazing grounds, forcing collectors to venture into more remote areas. Additionally, based on number of studies, the article shows how climate-induced changes coupled with increased developmental activities such as road construction impact the treeline ecotone and associated livelihood patterns. The fragile mountain ecosystem, experiencing increased frequency of climatic anomalies has led to devastating effects on local communities. By integrating ecological and social dimensions, this study contributes to a holistic understanding of treeline dynamics and their implications for community well-being.

Introduction

The Himalayan ecological crisis has emerged as a significant concern for policymakers, environmental activists and academicians. The Himalayas are warming at a faster rate compared to the surrounding lowland areas, thus it presents a unique opportunity to assess the responses of natural vegetation to climate change and associated dynamics.[1] Addressing the issues related to the treeline necessitates a comprehensive understanding of the intricate interactions between social systems and ecological processes.[1] The study of treeline has been rapidly gaining attention. Often the study focuses on the current treeline shift and its socio-economic implications remains a major gap. Many of the Himalayan areas been witnessing changes in temperature and rainfall trends over the past few decades. As a result, it affects treeline directly or indirectly.[2] The changes in treeline would also change drastically the montane landscapes and the livelihood of their inhabitants. Alpine meadows are disappearing, which deeply concerns conservationists since these habitats are home to numerous rare and unique species and are critical to local livelihood. The social and economic dependence on and around Himalayan timberline area is huge for collection of timberline resources, as well as collection of medicinal plants for commercial use.[3] In recent decades, medicinal plant availability has diminished, alongside resources for community necessities including timber, fuel, herbal remedies, and pastures. This forces collectors to seek increasingly remote locations. Additionally, mountain transition zones face growing development pressures, particularly from infrastructure projects like roads, significantly affecting the subsistence of dependent local populations.[4]

Himalayas are the habitats of several tribes. Their main occupation is animal husbandry. The transhumant societies practice seasonal migration along with their livestock. Due to high altitude area, agriculture is limited. Therefore, since ancient time, transhumance, farming and animal husbandry is the main occupation of the tribal groups.[5] However, over the recent years, transhumance is passing through a change. Historically, transhumance herders in Himalayan region utilized resources from different ecological zones to sustain their way of life. However, grazing lands and forested areas are now experiencing declining productivity and can no longer meet the increasing requirements of both human populations and their livestock.[4-5] The fragile mountain ecosystem with increased frequency of climatic anomalies have led to devastating effects on the livelihood of the local communities, especially transhumant.[6] The meadows have been subjected to migratory nomadic grazing during snow free period. The livestock density and pastoralism are on decline in many areas due to decline in high altitude grasslands, hence, giving an opportunity to trees to move upslope in some areas.[7] Therefore, robust community-based agreements on natural resource stewardship are essential, particularly regarding the sustainable management of livestock feed resources. The continuous encroachment of vegetation into the alpine meadows is threatening the ecology.[3]

Majority of rural population in high altitude zone depend on treeline ecotone for at least part of their livelihoods. This also includes tribal population who constitute the poorest and the most marginalized section of the district. Most tribes are landowners and practice agriculture, horticulture and cultivation of medicinal plants as their primary means of livelihood.[1] They are also pastorals and own large flocks of sheep and goats, as a subsidiary occupation. Therefore, particular attention to the socio-economic problems of local and the transhumant communities is required.

Excessive livestock grazing, combined with inadequate oversight and maintenance, has significantly degraded pasture quality, necessitating comprehensive restoration and improvement efforts.[8] The climatic conditions have turned the treeline ecosystem highly vulnerable. There is urgent need to protect the traditional livelihood of the dependent population and provide people with better means of livelihood that preserve their culture and socio-economic structure. With the lens of its impact on livelihood of transhumance and other dependent community, this review article finds out the challenges based on various literatures. Consequently, this study aims to address research questions pertaining to the temporal changes in the altitudinal treeline and the associated dynamics on Himalayan ecology and society. By integrating ecological and social dimensions, this research endeavors to contribute to a holistic understanding of the treeline dynamics and their implications for the well-being of local and other dependent communities.

Study Area

The Indian Himalayan region represents a critical ecological frontier for studying treeline dynamics and their socio-economic implications. The Himalayas host some of the world's highest treeline, reaching up to 4900m in elevation. This region is warming at a faster rate compared to surrounding lowland areas. The Himalayan treeline varies significantly across the range due to regional differences in climate and topography. The western Himalayas, influenced by monsoon patterns, typically feature higher treeline compared to the drier eastern regions. The vegetation transitions from broad-leaved deciduous and evergreen forests at lower elevations through coniferous zones to alpine meadows above the treeline. This mountain system serves as a traditional homeland for numerous indigenous communities practicing transhumance pastoralism. These communities have historically managed the delicate balance between resource utilization and conservation through seasonal migration patterns. The region is also renowned for its rich biodiversity, including valuable medicinal plants and endemic species, making it a crucial area for both ecological conservation and livelihood sustainability.

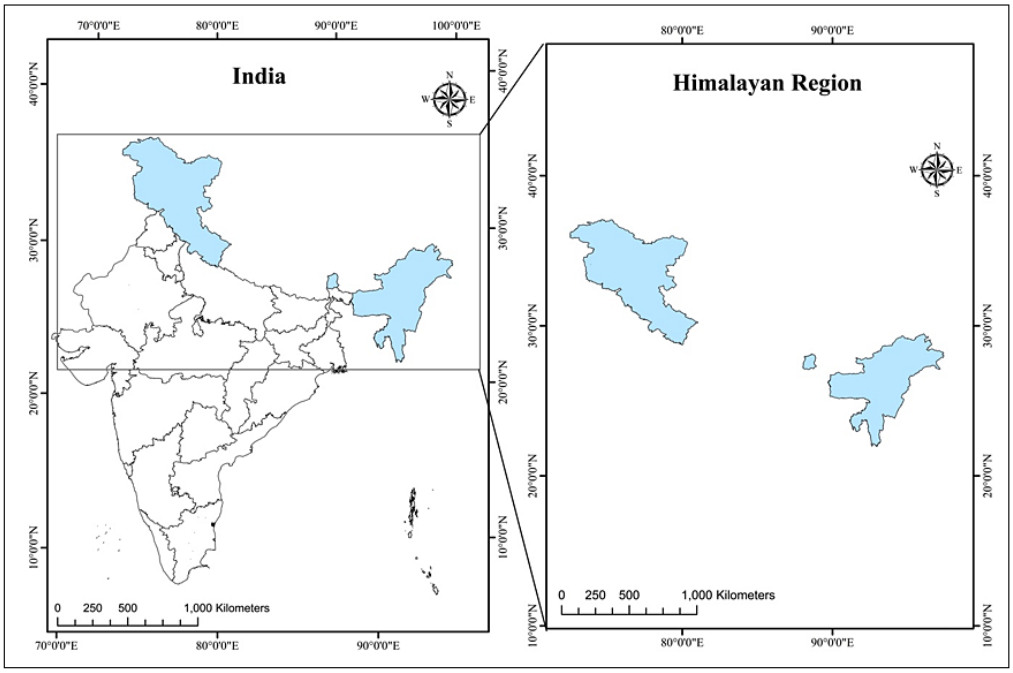

Fig. 1: Study area, Indian Himalayan region

Methodology

This study employs a systematic literature review approach to analyze the temporal changes in Himalayan treeline positions and their socioeconomic impacts on local communities in the Himalayan region. This review study utilizes descriptive research methods to gather literatures on treeline dynamics and their socioeconomic implications. The study identifies and used select research published on treeline shift. The research which focuses on treeline shift in the Indian Himalayan region from the 1970s to present has been referred. To link it with the social and livelihood impacts, the search terms included "Himalayan treeline," "treeline ecotone," and "high altitude livelihood." Information extraction focuses on three key dimensions, ecological parameters documenting treeline position changes and vegetation shifts, data capturing temperature trends and precipitation patterns and lastly the socioeconomic aspects related to resource availability and livelihood changes. To find out the socioeconomic impacts on local and trans-humant populations, the study compliments findings from review of interviews and surveys from relevant literature from published sources. Numerous research papers based on themes such as treeline ecotone, high altitude livelihood, economy, transhumance, livestock, fodder, and etc. were analysed that focuses on changes in resource availability, traditional pastoral practices, and livelihood patterns. Special emphasis was made on documentation of changes in availability of medicinal plants, timber resources, firewood access, and grazing grounds. This approach allowed for a holistic understanding of the complex interactions between ecological changes and community well-being in the Himalayan region. The figure below highlights the key themes for which articles were reviewed to draw findings.

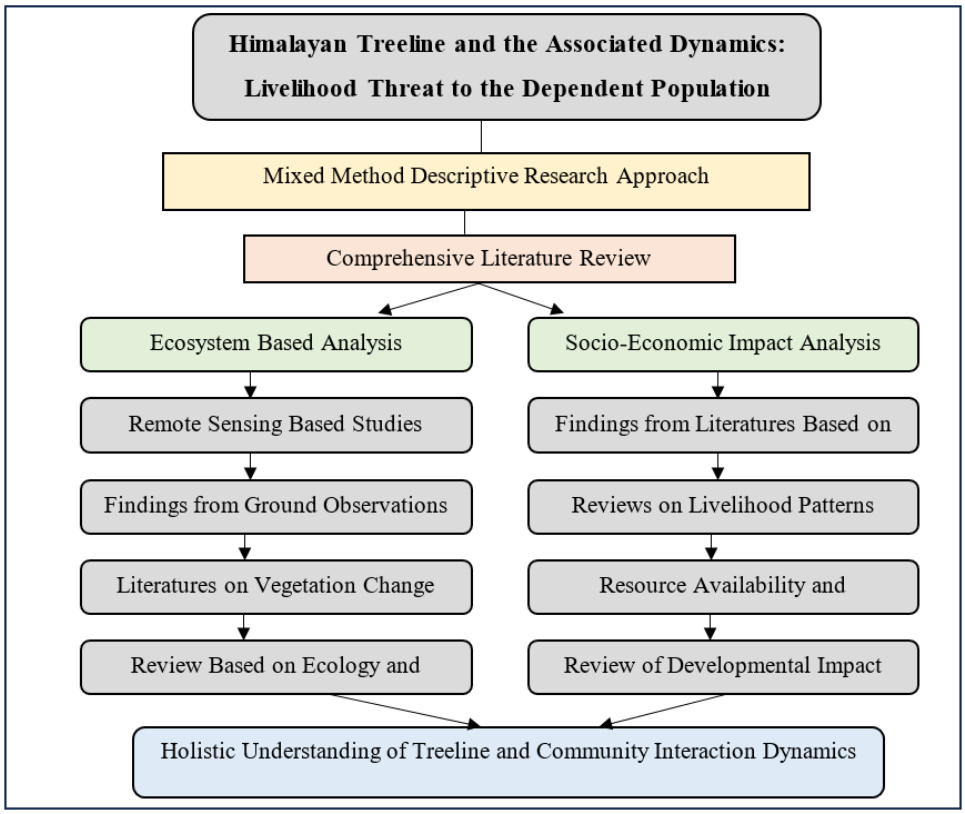

Fig. 2: Methodological Framework
Source: Author

Results and Discussion

Vegetation Patterns in the Himalayas

Vegetation dynamics are shaped by a complex interplay of climate, altitude, soil characteristics, and disturbance regimes, resulting in diverse and unique ecosystems across different elevational gradients.[8,9] Understanding the dynamics of the treeline and vegetation in the Himalayas is essential for unravelling the ecological processes driving ecosystem resilience, biodiversity conservation, and responses to environmental change.[9] The Indian Himalayan region exhibits distinct elevational vegetation zones, each characterized by specific plant communities adapted to local climatic conditions. At lower elevations up to approximately 2000m, subtropical forests dominate the landscape, featuring sal (Shorea robusta), chir pine (Pinus roxburghii), and diverse broad-leaved species that thrive in the warmer, more humid conditions. As one ascends to mid-elevations between roughly 2000-3000m, the vegetation transitions to temperate forests where oak (Quercus spp.), deodar cedar (Cedrus deodara), blue pine (Pinus wallichiana), and various rhododendron (Rhododendron spp.) species form the predominant canopy cover. Higher still, in the upper forest zone from approximately 3000-3500m, subalpine forests emerge, characterized by stands of fir (Abies spp.), spruce (Picea smithiana), birch (Betula utilis), and dense thickets of rhododendron that mark the approach to the treeline ecotone, beyond which woody vegetation gives way to alpine meadows.[2,10] Above the sub alpine zone lies the realm of the alpine ecotone, where only hardy species such as mosses, lichens, and cushion plants can survive in the harsh, windswept environment. The treeline in the Himalayas varies in elevation depending on factors such as latitude, aspect, and local climate conditions.[11] In the western Himalayas, where the climate is influenced by the monsoon, treeline tend to be higher compared to the drier eastern Himalayas. South-facing slopes receive more solar radiation and tend to have higher treeline, while north-facing slopes have lower treeline due to reduced solar exposure and colder temperatures.[11,12]

Additionally, local topographical features such as valleys, ridges, and microclimates can influence treeline dynamics, leading to variations in vegetation patterns across different landscape units.[13] The dynamics of the treeline and vegetation in the Himalayas are further influenced by human activities, including deforestation, grazing, agriculture, and infrastructure development.[14,15] Anthropogenic disturbances can alter natural vegetation patterns, disrupt ecological processes, and lead to habitat fragmentation and biodiversity loss.[16] Climate change poses additional challenges to Himalayan ecosystems, with rising temperatures, changing precipitation patterns, and melting glaciers threatening the stability and resilience of mountain ecosystems.[5] Research on treeline and vegetation dynamics in the Himalayas is essential for advancing our understanding of ecosystem responses to environmental change and informing conservation and management strategies.[17] Understanding these dynamics is crucial for effective conservation and management of Himalayan ecosystems in the face of environmental change and human pressures. Himalayas are characterized by ecological diversity, and intricate treeline and vegetation dynamics shaped by its unique geographical features and climatic conditions. Himalayas district encompasses a wide range of elevations, from lush valleys and temperate forests to alpine meadows and snow-capped peaks.[18] At lower elevations, Himalayas is adorned with dense forests of oak, rhododendron, deodar, and pine, which thrive in the temperate climate and abundant rainfall. These forests support a rich diversity of flora and fauna, including endemic species. As elevation increases, the vegetation transit to mixed coniferous forests dominated by species like spruce, fir, and cedar, which are adapted to cooler temperatures and higher elevations.[10] The treeline in Himalayas district marks the transition from forests to alpine vegetation types and varies depending on factors such as aspect, slope, and local climate conditions.[11-14,17] Alpine meadows and grasslands, characterized by species such as Himalayan blue poppy, juniper, and dwarf rhododendron, cover vast expanses of high-altitude terrain above the treeline, providing grazing grounds for livestock and habitat for specialized plant species adapted to harsh environmental condition.[19]

Understanding the 'Treeline'

The treeline in the Himalayas represents a critical ecological boundary which marks the upper limit of tree growth influenced significantly by climatic factors and topographical conditions. Various researchers define 'treeline' differently. Some consider it the

highest altitude where trees can survive. Others describe it as the maximum elevation where forests grow densely.[11,12] So it's either the upper limit for any tree growth or the boundary where thick forest ends. Overall, similarity can be observed in the definitions that the growth or germination of plants is restricted beyond a certain point due to challenges posed by extreme climatic conditions. The treeline can be seen at an extreme elevation beyond which vegetation cannot survive and is typically located on mountains.[11-13] The ecotone that represents the transition between the wooded vegetation and the alpine landscape without trees can be regarded as the treeline.[20] The boundaries of both, the timberline and the alpine landscape without trees are coupled, therefore, the mechanisms or the factors that affect their position can be considered similar. Many things affect where treeline form. Natural conditions and human activities both play a role. The two main factors that determine mountain treeline are heat and moisture.[21,22] The climate change has a profound effect on the growth of the vegetation. Thus, the role of climate in changing the vegetation structure of any region cannot be denied. As a result, the position of treeline can be used as an indicator of the past climatic variations. The changing scenario of the climate or the climatic variability that has resulted into warming condition will affect forest stand and growth patterns of the vegetation.[23] The growth of the vegetation is induced in warm climatic conditions and in such a case the higher elevations which were devoid of vegetation will develop growth and generation of the vegetation due to favorable and suitable conditions latitude.[12-14] The polar treeline that are found at high elevations are highly dynamic and have complex ecology and the studies have found that the treeline in those environments have shifted upwards owing to increase in global temperature.[24] Many instances of rapidly shifting treeline have been primarily caused by human activities rather than climate factors.[11,13] Anthropogenic forces are largely responsible for the upward movement of mountain forests across Europe. Conversely, in relatively pristine regions of the Canadian Rockies, climate influenced treeline are advancing to higher elevations. However, this upward migration involves more complex dynamics than just temperature changes, with wildfire patterns including both frequency and severity playing a crucial role in this ecological transformation.[25] Several studies provide a complex picture of the great variety and heterogeneity of altitudinal treeline.[21] The transition seasons are the period when Himalayas mainly withstands dry conditions. The macroclimates of the treeline have been altered due to variation in topography and elevation in the Himalayas.[11-14] It is being speculated that the rate of warming will enhance more at higher elevations in the coming decades. Thus, making mountains more vulnerable to the changes induced by it. The Himalayas are warming faster than most places on Earth. In the higher parts of these mountains, temperatures are rising by about 0.6 to 1°C every ten years.[26] There are number of research that has been carried out to find out the effect of changing precipitation and temperature on high altitude regions. The researchers have found that the temperature trends in the months of winter have increased over the decades by upto +0.8 °C.[26]

Similarly, the trends of increase in maximum temperatures have been observed during pre-monsoon season over entire Himalayan Arc.[1,12] The Himalayas are known for frost conditions throughout the year, however, the increasing temperature leading to warming conditions have significantly affected the frost days. The frost days in the Nepal Himalayas has decreased in the past few decades. The increasing trends of maximum temperature over the Himalayan Arc have subsequently led to increase in the number of growing days, especially at altitudes between 2200-3600 m.[27] The trends of decadal temperature change have further affected the trends of annual precipitation. The western Himalayas have experienced 20 percent less rainfall as compared to previous century, thus showing negative trend of precipitation as well.[26,27] The changing trends of weather elements have also caused meteorological and environmental hazards. Pre-monsoon drought and floods events have been reported from western Nepal Himalaya since 1980s.[23,26] However, the change of annual precipitation shown by eastern Himalaya are negligible. It is due to increase of the day temperature in high mountains of central Himalaya that has led to substantial warming, and the decreasing trend of mean minimum temperature is also being experienced by some region. Thus, the Himalaya reflects the trends of both, the increasing and decreasing rainfall.[26] The drought stress has intensified during pre-monsoon season due to increase in evapotranspiration as a result of rising temperature and decreasing precipitation.[28]

The growth of trees and seedlings gets suppressed in a condition of pre-monsoon drought. Globally, the meta-analysis of treeline has shown that treeline at majority of regions are advancing poleward or upwards. Thus, the regional responses of treeline can be attributed to the changing local or regional elements that shape the treeline positions. However, not all places have had similar effects.[29,30] There may be number of possible causes for such variations, such as, the local or regional climate at the particular site may not be in correspondence to the global trends,[20] the climate may not be the dominant factor that is controlling the treeline positions within the site, fires caused occasionally either naturally or due to other reasons or incapability of tree species to adapt with the ongoing changes.[11] The highest treeline are found in the Himalayas (in case of northern Hemisphere), at an altitude of 4900 m. Until recently, the studies conducted on vegetation in the Himalayan region lacked the term treeline.[25] As compared to many parts of the world, the treeline in the Himalayan regions is remotely located due to its height. Therefore, the scientific measurements and monitoring becomes difficult and expensive. The relation between climate change and treeline have been generally examined with the view of upslope advancement of vegetation due to changes in precipitation and temperature trends.[31]

There are number of studies that documents the upslope movement of treeline with respect to changing climatic conditions. Globally, an upward shift of vegetation has been observed in about 52 percent of the studies, the remaining studies showed position of the treeline to be stationary.[32] Trees have long life and have a long-time lag, therefore, the response of the trees to the nearby changes may not be seen immediately.[32] However, all the literatures available on high altitude treeline have regarded treeline as a landmark. The factors affecting growth and regeneration of vegetation on high altitudes have been studied by several authors.[22] The forms, structure and causes of treeline formations have also been dealt widely. However, all parts of the world exhibit upward growth but,[11,13] most of the studies are region specific (as most of them have been conducted on Alps, Andes). The ecology of high-altitude forests and altitudinal gradient have been explored in the past. However, the Himalayan ecology lacks in-depth studies.[29] The studies along the treeline ecotone in the western Himalayas indicates increase or decrease in vegetation along the treeline zone. The shift in altitudinal structure and change in vegetation has been attempted in the western Himalayas based on remote sensing tools.[2]

The treeline can be regarded as the system that can be used to deepen and broaden the knowledge of a particular place. The altitudinal position of the trees doesn't only provide the environmental history of the place but also a number conditions and situations related to it. The change in the availability of soil nutrients, evaporation and evapotranspiration rates, soil temperature and other natural factors govern the tree growth.[11] Further research can explain the role of these factors at different levels. Treeline help scientists track how landscapes respond to climate change. As the climate warms, trees can grow at higher elevations, pushing treeline upward.[33] Studies show that warming happens faster at higher elevations. Because of this, treeline in polar regions and high mountains are moving upward, even though treeline ecology is complex.[11-14] The Himalayas have rough terrain, causing big differences in temperature and rain across small areas. This creates varied treeline heights throughout the region. Mountain treeline mainly move uphill when temperatures rise.[2] However, several factors can stop treeline from advancing higher, including temperature, rainfall, sunlight, wind, and soil nutrients. Temperature is usually the most important factor affecting plant growth patterns.[17] The common method of monitoring treeline shift involves monitoring and an analysis of remotely sensed data.[2] Remote sensing helps to overcome the difficulties posed to direct observation by the poorly accessible terrain. From 1972 to 2014, the treeline in the Indian Himalayas has moved higher up the mountains in several Himalayan states.[2,10,34] The average height of the current treeline is different in each region. in Jammu and Kashmir it is around 4121 meters above sea level, in Himachal Pradesh it is 3520 meters, in Uttarakhand it is 3615 meters, in Sikkim it is 3542 meters, and in Arunachal Pradesh it is the highest at 4136 meters.[34] During this period, the treeline has shifted upwards by different amounts in each state. In Jammu and Kashmir, it has moved up by about 441 meters (±71 meters). In Himachal Pradesh, the shift is about 301 meters (±77 meters), in Uttarakhand around 411 meters (±79

meters), in Sikkim also 301 meters (±66 meters), and in Arunachal Pradesh by approximately 452 meters (±74 meters).[34] This upward movement of treeline shows how climate change and anthropogenic pressure is affecting the natural environment in these mountainous areas.[10,34] Another Study show treeline in Uttarakhand moved upward by 388 meters between 1970 and 2006.[2] Understanding how climate change and land use work together is key to predicting treeline changes. Trees growing in previously treeless areas above human-made forest boundaries are directly linked to climate change.[10,34] These rapid mountain changes affect more than just the mountains themselves. Since mountains provide water for many people living downstream, these changes impact both people and nature. In Himachal Pradesh, farmers are adapting to climate change by planting apple orchards at higher elevations because lower areas no longer get cold enough.[35] Early winter snow (December to early January) helps apple trees by providing about 10 weeks of temperatures below 5°C, which apple buds need to properly develop in spring. The farmers also changed their cultivation pattern by adopting the farming of peas, potatoes and plum in the lower altitude areas.[35] The few vegetables that were only possible in the low altitudes can now be seen grown in mid altitudes, generally above 1500m.[35]

Other than climatic factors, treeline is affected by several factors.11 However, in most cases, pastoral abandonment, Changes in land use patterns or other changes in human impact also influences treeline dynamics.[12] The image below presents a chronological overview of research efforts and advancements in the treeline studies. It started from the 1970s and progresses through various decades. It highlights key developments, approaches, and areas of focus in the field of time series analysis. The altitude where the alpine treeline is present varies in mountains due to several underlying factors that influence the treeline.[29] Over the past few decades, a variation in the treeline has been observed around several regions of the world. There are number of studies that shows that the treeline has been shifting upwards. This upward shift of the treeline has been mainly attributed to climate change that has affected the global temperature and precipitation.[17] Treeline are moving towards higher latitudes and upward in mountains as a result of climate change, as rising temperatures enable trees to flourish in formerly colder areas. This change modifies ecosystems, impacting species composition and biodiversity. The vegetation or the species of plants are slowly adapting themselves to prevailing conditions and they are growing in the regions where they were not found previously. The favorable conditions due to rise in temperature has induced the growth of vegetation.[20,33]

The upward shift of the treeline alters the ecological landscape of the region. It poses threat to ecology of the mountains. The encroachment of the new species into meadows heavily destructs the grassland vegetation and induces land use changes in a region. Changing climates and land use practices alters the socio-economic conditions of associated people as well.[29] It is a well-established scientific fact that the changes in climatic variations are happening. The worldwide changes in climatic variability are shaping the landscape of the marginal inaccessible and fragile ecosystems. There are number of research that has found that there have been regional changes in weather elements at global level. The changes in weather patterns that shapes the climate have been found to be altered. These changes cause number of changes in the earths system.[31] The natural systems are being altered by unwanted alterations due to changes at global level. The higher altitudes being more sensitive to the changes are experiencing rapid changes that is inducing landscape transformation slowly and gradually. The treeline in the Himalayan region are found usually at the height above 3500 m elevation from the mean sea level, whereas, at higher latitudes the treeline is found at lower elevation (as low as 500– 800 m around 50° N latitude).[10] The Himalayan zone is highly ecologically rich and is also known as the hotspot of the biodiversity. Over the past few decades, the sensitive environment of the Himalaya is witnessing number of challenges that is affecting its rich culture that it is known for. There is a declining trend of precipitation in Himalayas due to which vegetation development and regeneration is being affected in the Himalaya. As a result, the regeneration of saplings and flowering time is getting affected.[36] Vegetation is shifting to higher elevations due to anthropogenic activities and climate change. Thus, altering ecosystems and biodiversity.[36]

Climate Induced Effects

The world is witnessing the change in climate. There has been an increase in the mean global temperature and it is further estimated to increase. The effects of the changes induced by the change in climate can be many, such as, increased or decreased precipitation, annual variability and increased or decreased frequency of wet and the dry periods.[37] The effects of the changes have been reported from many parts of the world. The tropical countries have witnessed erratic rainfall patterns as uncertainty of the arrival has become common. There has been a change in the duration as well as the intensity of the precipitation.[38] The changes affect the growth and production of plants and soil conditions. The terrestrial ecosystem such as the forests and grasslands are affected much as altered precipitation directly affects the moisture availability of the soil.

People in mountain rely heavily on interconnected climate-vulnerable sectors specifically agriculture, animal husbandry, and forest resources for their sustenance and economic survival.[39] Excessive grazing pressure, widespread fire, seasonal drought and poor quality of soil are the main agents for lowering treeline in Himalaya. The treeline in the Himalayas are changing due to human activities. In places like Kashmir, Himachal Pradesh, and Uttarakhand, sheep and goats play a big role in shaping these areas. When these animals graze in the mountains during summer, they often prevent trees from growing higher up the slopes. But things are changing. In some Himalayan areas, fewer people are keeping livestock and practicing traditional herding.[16] This means trees now have a chance to grow at higher elevations in these places. At the same time, glaciers across the Himalayas are getting smaller.[26] These changes matter a lot for local people who depend on forests for their living. The Climate variability and its effects can be seen in the figure 3 below. It shows how the climate vulnerability is linked to several aspects of social and economic security.

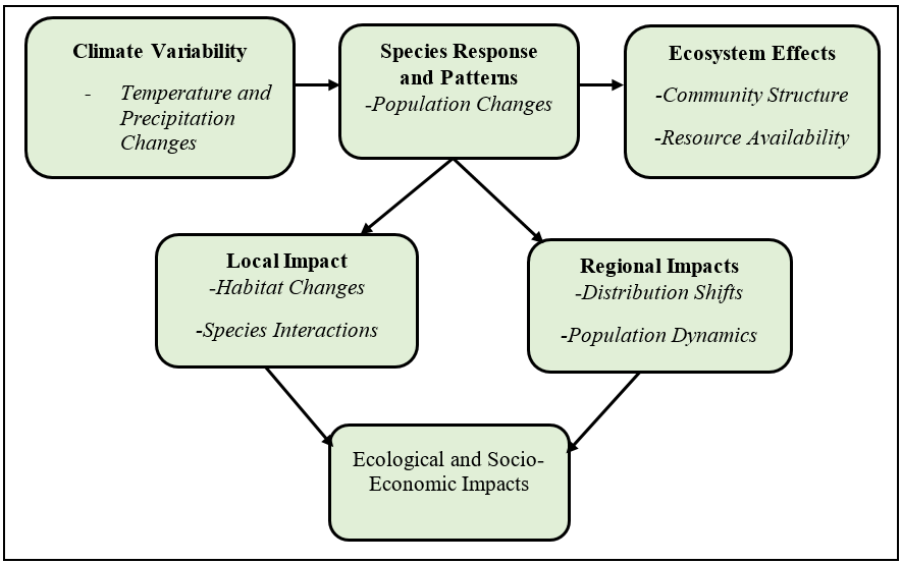

Fig. 3: Climate variability and ecosystem response.
Source- Author

Every summer, millions of people visit the high mountain meadows and treeline areas in Uttarakhand, Nepal, and Tibet. Many people come to collect Cordyceps (a valuable fungus).[40] While digging for this fungus, they damage the plants growing on the ground. They also gather firewood from treeline areas, further affecting these sensitive environments.[4,16] Plants growing at higher altitudes have shorter growing seasons than those at middle elevations. Villages near Himalayan treeline take substantial resources from nearby forests. They mainly collect firewood for heating and cooking,

fodder for their animals, and forest litter for various household uses.[40] However, in recent years, these natural resources have become increasingly scarce, creating challenges for local communities.[10] Since the climate change challenges are big, therefore, the conservation of natural resources, agriculture system and livestock production systems, food security, societal health and stability are of particular interest. Agriculture supports the livelihoods of the largest number of people worldwide and is vital to rural development and poverty alleviation.[40]

The Himalayan ecosystem stands out worldwide as a special place with many unique plants and animals. While farming takes up only a small part of the land in the Himalayas, it forms the backbone of village life. Local people grow what they need to survive, and their livestock raising depends heavily on forest resources.[4,16] When treeline change, it affects the forest resources and natural benefits that locals rely on to support their agricultural and livelihood practices.[40] The figure 4 below shows how mountain treeline are moving upward due to climate change. It displays the historical treeline and the present treeline, which has shifted higher up the mountain as temperatures have warmed. In mountains, the trees are now growing at higher elevations than before. As this shift continues, trees are gradually replacing alpine shrubs and meadows that previously dominated these high-elevation zones, changing the mountain's ecological makeup in response to warming temperatures.

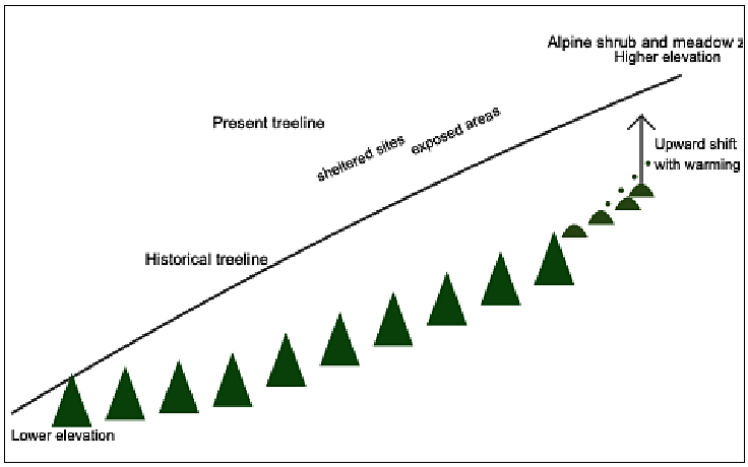

Fig. 4: Teeline responses to climate warming
Source- Author

The Central Himalayan region in India has a long tradition of self-sufficient farming. Most people here over 70 percent of the population depend on a combination of growing crops and raising animals for their livelihood.[41,42] People living in mountainous areas must constantly adapt to changing conditions. They need to develop new ways to survive, especially in farming. One major challenge they face is longer dry periods, particularly after the monsoon season ends. These dry spells cause water shortages and make it harder to grow enough food.[18] Perhaps the clearest sign of this problem is the declining water sources that livestock depend on, making animal husbandry increasingly difficult particularly in alpine pastures. Forests and grazing areas as experienced by the pastoralist communities of high-altitude villages in Himalayas have reduced.[5] Mountain regions worldwide, including the Himalayas, are facing serious weather changes. Many areas now get less rain, or rain falls at different times than before. These changes lead to failed crops, less food and fodder for animals, and fewer healthy livestock.[43] As a result, traditional ways of making a living have become much harder for local families. Fruit growing and production has also suffered. Important crops aren't producing as well as they used to because of climatic variability.[40] This problem is increasing in certain parts of the Himalayas. These changes have greatly reduced the income that mountain families can earn from their land.[4,18]

Climate induced changes are reshaping nature in many ways (Table 1). As temperatures rise, growing seasons get longer, especially in high mountain areas. Some plants can now grow in places that were once too cold, while others struggle to survive. These changes break up natural habitats and make it harder for many native species to thrive. Meanwhile, hardy invasive plants often move in and take over. Changes in rainfall create more problems. Dry conditions affect local crops and reduce water sources. Many wetlands are drying up. Native medicinal plants used by local communities are becoming scarce. As these changes continue, plants and animals migrate to better areas. This creates new mixes of species that haven't existed before, making it hard to predict what will happen to these ecosystems in the future. These cascading effects illustrate (table 1) how climate variability fundamentally reshapes natural systems in ways that ripple through entire ecosystems.

Table 1: Climate variability and the potential effects

Climate-Induced Effects	Types of Change	Consequences
Temperature changes	Changes in ecosystem	Changes in growing season
	Productivity of biomass	Increased horticulture and vegeculture at high altitudes
	Alteration in habitats	Degradation and fragmentation of landscape
	Biodiversity loss	Extinction of less tolerant species
	Rise in invasive species	Ecotone changes at high altitude
	Phenological changes in plants	Unusual timing of growth in certain species
	Decrease in native species	Decrease in traditional medicinal plants
Precipitation Changes	Dry condition	Impact on local crop
	Humidity changes	Dried grasses and shortage of fodder
	Loss of wetlands	Degradation of water sources
	Plant successional changes	
	Specie migration	

Source- Prepared by Author

For generations, local herders have used Himalayan meadows for their animals. Their traditional grazing methods helped both people and nature thrive together. These communities developed ways to manage the grasslands that supported their way of life while preserving the rich variety of plants and animals. Human activities have changed where trees can grow in many areas.[39] The meadows, which provide excellent nutrition for livestock, are essential for herders who move their animals between different elevations with the seasons. Now these meadows face a serious threat as less desirable shrubs begin to take over the grasslands.[3] This change endangers the livelihoods of the herding communities who have depended on these nutritious meadows for centuries.[5] When people stop using traditional ways to manage the land, unwanted shrubs often start taking over.[10,13] Although grasslands across the Himalayas are declining in quality, but there is a lack of clear understanding of what's causing this change. The places where animals graze heavily tend to have more problems with shrubs moving in. This happens because when grazing removes the existing plants, it creates open spaces where shrubs can more easily take root and grow.[44] This pattern shows how complex the relationship is between human activities, animal grazing, and changes in mountain plant communities.

Transhumance Livelihood and Biophysical Systems

Transhumance is a tradition in which the pastoralists move their livestock seasonally from one pastoral region to another in search of grazing resources. This

tradition is very old in the fragile mountainous regions that is being practiced by indigenous communities in order to sustain in such harsh environmental conditions.[18] The livestock-based production has proved to be economically beneficial for these communities in the Himalayan ecosystem.[39] It can be seen as one of the best adaptation strategies in extreme climatic conditions as it involves movement from one elevation to other depending on the season.[39] Since mountains are known for immense biodiversity, it is also known as 'climate change hotspot' due to visible impacts of climate change. Thus, impacting the ecosystem, human population, settlements and economy of associated population.[45] Transhumant pastoralists have a long history and have been practiced by several Mediterranean European nations such as, Spain, France, Switzerland, Germany, Carpathians, Balkan countries and Italy.[46] The pressure of the grazing animals on summer and winter pasture lands has a huge effect on the quality and quantity of the forage, communities and species diversity in the region, and on vegetation dynamics.[47] The practice of transhumance has a long history in west Africa. Today also, it represents a dominant system of livestock production. The most widespread and numerous pastoralists having long tradition of animal herding in West Africa are the 'Fulani's'.[48] These are an ethnic cross border herders who have been following a particular transhumance corridor as a tradition. However, at present this traditional system of transhumance is under a threat as a result of large-scale changes in land use or land cover practices.[48] The pressure on the resource such as grazing land and water is huge, and it also results into cross border conflicts between land users and the pastoralists.[49] The environment of the mountains harbors diverse flora and fauna, most of them are native to that environment.[20] Similarly, this type of regions is highly vulnerable to land use and climate changes as well as due to anthropogenic impacts. Most of the mountainous region of the world inhibits transhumance and traditional system of land use practices, thus, urgent attention is needed to deal environmental concerns along with socio-economic changes.[50] The environment and the climate continuously influence transhumance in time and space. The figure 5 below shows the different elements of transhumance system. It highlights the drivers of transhumance and its impact on local landscape.

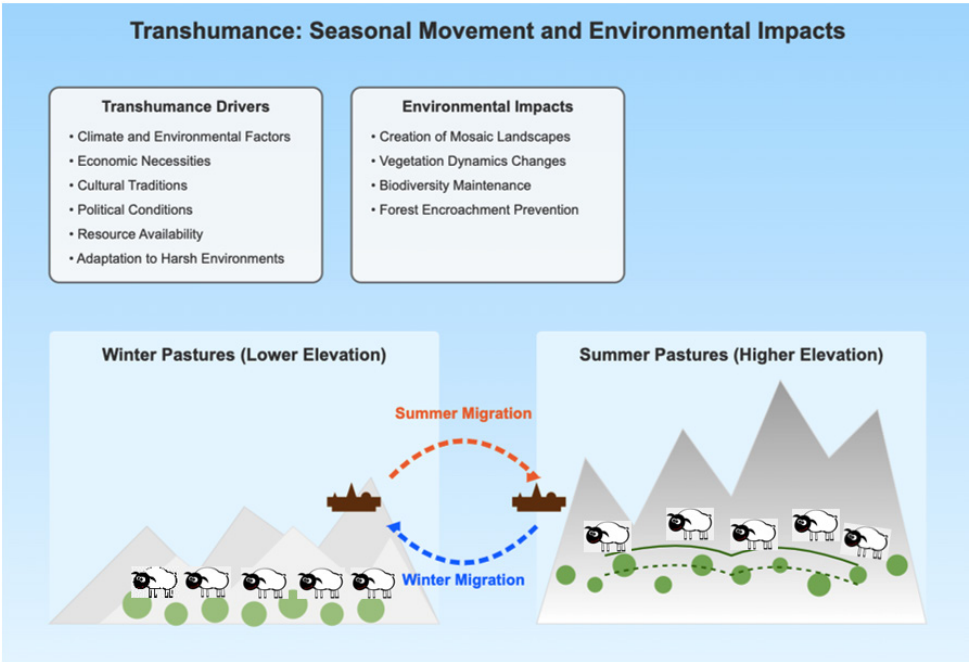

Fig. 5: Dynamics of Transhumance
Source- Author

The effects of grazing can also be seen on the processes of ecosystem and landscape dynamics as it impacts heterogeneity of vegetation. The magnitude of these changes due to transhumant pastoralists is considered to be a major factor in landscape formation rather than just a mechanism for ecological disturbance.[3] The Reduced grazing can lead to the expansion of forests and scrublands to the detriment of semi-natural grasslands.[51] The mountainous regions have a higher poverty rate as compared to the plains. Since agriculture is difficult in the high-altitude zones, the livestock are regarded as the main assets of the people as it represents wealth and power of an individual.[52] However, demographic, socio-economic and cultural changes have modified the livelihood opportunities. The qualities of pasture lands have also decreased which have affected the plant-pasture interactions. There are two ways in which the climate change can affect the livestock, the quality of available fodders can be affected and the change in temperature itself can affect the livestock.[53] Thus, in the extreme weather conditions, it becomes important to study the relationship between the climate change and the livestock. If the proper attention is not paid, the practice may disappear completely. The indigenous communities can better adapt and respond to the challenges posed by climate change.[54] Recent research suggests that disadvantaged populations in developing nations employ diverse and context-specific adaptation and coping mechanisms. Consequently, localized studies are essential to ensure that development policies are relevant and effective. In this changing environmental condition and social context, this study is aimed to explore the observed changes in the altitudinal variation of the treeline and further explore how it has affected the local practices and livelihood patterns.[55] Herders who move with their animals between different elevations have noticed less snow in high mountain meadows in recent years. This has caused many important fodder plants to grow poorly. About 30 to 35 years ago, these herders could stay in one pasture for many days. Now, they keep moving their animals between multiple grazing areas to find enough food. Water has also become scarce.[6] Streams and small water sources along migration routes and overnight camping spots have diminished. Many villages have seen their year-round water sources either dry up completely or flow only during certain seasons due to decreased rainfall.[3]

Human activities heavily impact the treeline areas in the Himalayas. In Arunachal Pradesh, both treeline and higher alpine regions face serious pressures from people, causing widespread damage. During summer, many migrating herders visit these areas, grow seasonal crops, and build temporary shelter.[39] They also collect forest products, especially medicinal plants. Herders take their sheep and yaks to graze in pastures between 4000 and 4500 meters in elevation. Recently, fewer households continue these herding traditions. With more education and changing perspectives, people are finding new livelihood opportunities and adopting different lifestyles.[6] Changes in economic and social conditions are driving this shift away from traditional practices. This trend extends beyond Arunachal Pradesh to other regions including Nepal, where traditional communities are seeing fewer families involved in animal grazing as lifestyles change.[53] Traditional practices make efficient use of seasonally available resources in harsh environments without causing degradation. These practices need support from local policies to continue within sustainable limits. Traditional knowledge systems and community institutions could be starting points for sustainable resource management. This could be accomplished by studying local cultural practices and incorporating their useful aspects into modern resource management approaches.[4] The analysis of land-use practices and management is critical for sustainable output. Such evaluation becomes more important in the Himalayan region as the physical constraints poses enormous difficulty to gather and update information within a shorter period of time. The traditional livestock-based farming is directly dependent on forests for fodder and manures. In addition to provision of agricultural and livestock support, forests also offer number of other services that is essential for mountain people.[6] However, sustainability must be ensured and healthy exchange must take place. During the past few decades, the environmental degradation is on peak in the Himalayan ecosystem. The forest lands are shrinking as a result of extension of agricultural lands. The threat to Himalayas puts the dependent communities more at the risk.[43] Sustainable practices not only promote sustainable livelihood but also sustainable land use management. The threat to Himalayas would not only affect its local inhabitants but far beyond this. It will also affect the highland-lowland interaction system that feeds millions of populations.

Huge efforts have been made to understand this pattern of change and its implications.[49] There is huge Socio-economic dependence on and around timber-line area in the Himalayan region for Collection of timber and firewood, as well as Collection of medicinal plants for commercial use which puts high pressure on forests.[3]

In recent times, the treeline ecotone has been subjected to increased developmental activities, such as road construction.[16] Therefore, the collectors move to new sites which occur in more remote areas than before. These have a major impact on livelihoods of forest-dependent community. The collection and sale of NTFPs form the core of forest-based livelihoods. Climate change is making the weather more unpredictable, which threatens local communities' ability to make a living.[40] Many jobs are at risk from more frequent and severe weather events like floods and storms.[7,16] Long-term changes in weather patterns can turn good farmland into barren wasteland because of extended droughts and irregular or absent rainfall. This is why it's important to understand how climate changes and economic development affect each other, so communities can adapt. Mountain regions like the Himalayas are especially vulnerable, particularly poor rural communities that depend on natural resources for survival.[39] As temperatures rise, the treeline in mountain areas is expected to move higher up the mountains. However, it can be difficult to tell whether these treeline changes are happening because of climate change or because of how humans are using the land. The timberline ecotone in the Himalayas remains under immense pressure due to resource use by the people as the livelihood options are limited and based on vegetation and biodiversity of the region. This dependence also degrades the timberline ecotone in several ways. There is social and economic stagnation in the Himalayan region, therefore, livelihood status of the people residing nearby timberline needs to be improved through exploring other livelihood opportunities.[55]

Ecological Degradation in Treeline Ecotone and Consequences

The Himalayan region is also affected by deforestation. Deforestation has occurred at particular places at different time and space as patches of forests have been removed. In the developing countries, there is a growing concern as it is expected that the forest degradation and deforestation will increase over time. However, the studies on the mid-Himalayan region have indicated that the key problem in the area is the degradation of the forest, not deforestation.[56] The severe disturbance mat not always led to deforestation as it depends on the local practices of the communities. The communities may adopt traditional practices of conserving degraded forest. When we talk about degradation, the degradation in Himalayan region is much different as compared to the nature of degradation seen in other region.[43] The Himalayan degradation will have devastating effect on the local. The Himalayan ecosystem has always remained a global topic and public debates. The deforestation and degradation of forests can be seen with different perspectives. The cutting down of forest can be related to commerce, whereas, the degradation of forests can be seen in terms of poverty.[10]

The local people that live in or nearby the forests have their living through forest. The logging causes less degradation as compared to extraction of resources from forests. Extracting forest-based resources or clearing patches of forests for traditional practices of shifting cultivation practiced by indigenous communities have profound effect on forest.[4] The demands of fodder and fuel is increasing day by day, the people of the Indian Himalayan region obtain a very small amount of biomass at a fixed period of time to ensure that the forest is not exploited.[10,16] The people further have livestock to support their sustenance and thus, grazing is practiced to fulfill livestock's need. The disturbance caused by grazing animals on the grazing land is chronic as compared to the deforestation which causes acute disturbances.[3] The severe disturbance in the ecosystem due to anthropogenic interference doesn't give plenty of time to recover and this disturbance continues. Such disturbances have adverse effects on forest and nearby areas even when the carrying capacity of the forests is enough.[18] The cutting down of the whole tree is uncommon and people rather cuts twigs and tree branches. Such type of disturbance is common in the Himalayan arc and it includes states such as, Kashmir, Himachal Pradesh and Uttarakhand. The nature of disturbance in the Eastern Himalayas is between acute to chronic. Shifting cultivation continues to

affect forest as the return period of the people to the burnt site has reduced to 5-6 years as compared to 25 years in the past.[8] The world today has reached an 'Anthropocene' era. The human footprints on the ecosystem have increased in an extraordinary way, especially on ecosystems that are rich in biodiversity. Therefore, it is very important to understand the effects of such level of footprints on the ecosystem functioning and dynamics in order to develop appropriate strategies for the sustainable conservation and management of the ecosystem. The importance of the forest and associated wealth can be understood with the fact that around 40 percent of the people in the tropical area and substantial proportion of population all over the world depends on this wealth for their sustenance and livelihood.[57] However, with the progress of human society or development, the wealth or resources are declining under human pressure. The tropical forests which are highly rich in biodiversity and harbor numerous endemic species are falling at rapid rate. The global area under forest in 1990s was around 4128 million hectares or almost 30 percent of the total earths land area, which reduced to 3999 million hectares in the year 2015.[57] The natural forests which account for more than 90 percent of the total area under forest has also reduced by 6.5 million hectares per year between 2010 and 2015. This shrinkage of forest can be related to the expansion of agricultural land use.[57] The forest wealth continues to shrink with an increase in human population at an alarming rate. Thus, this imbalanced relation between human population and forest wealth has put the livelihood and sustenance of around 200 million population in tropics at risk. It is expected that the global food requirement will increase by nearly 50 percent till the year 2050.[58]

Conclusion

The Indian Himalayan Region faces significant challenges in balancing ecological preservation with community livelihoods. The mountainous terrain, while rich in biodiversity and natural resources, presents unique challenges for development and timely information dissemination. The region's local communities heavily depend on traditional practices of agriculture and forest-based resources for their sustenance. However, this dependence, coupled with haphazard resource exploitation and global environmental changes, has led to increased degradation of ecotone areas and timberline zones. The situation is particularly concerning given that many of the population lives in poverty and face unemployment. While there is widespread recognition among academicians, conservationists, and policymakers about the importance of mountain development and ecological conservation, efforts to diversify and improve livelihood systems have been slow and limited in their approach. The growth of tourism, while providing economic opportunities, has added further stress to these fragile ecosystems. Moving forward, there is a critical need for comprehensive strategies that can balance the preservation of these unique mountain landscapes with sustainable livelihood opportunities for local communities.

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Author Contributions

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- **B.W Pandey:** Conceptualization,
- **Veer Singh:** Formal analysis, Writing original draft preparation
- **Mohan Lal Meena:** Resources, Writing review and editing

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