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Forest Degradation Index: A Tool for Forest Vulnerability Assessment in Indian Western Himalaya

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Abstract: The global climate is showing altered temperatures and precipitation levels. Forests can be a stabilizing force in climate change. They regulate the nutrient cycle, protect species and diversity, and support livelihoods that drive holistic growth. Presently, the forest ecosystem's capacity to withstand change is being undermined by the rate of change, along with anthropogenic pressures and the specificities of mountainous regions. Here, we attempted to design a 'forest vulnerability index' using field measurements and household surveys. A total of 71 quadrants were laid out, and 545 respondents were interviewed in 91 villages along the altitudinal gradient (altitude < 1200 m asl (Zone A), 1200–1800 m asl (Zone B), and >1800 m asl (Zone C)) of the Pauri district of Uttarakhand, India. The village-level data were normalized and combined to represent climate change impacts and the dimension of vulnerability. The IPCC (2014) protocol was used to assess forest vulnerability. The highest vulnerability was recorded in Zone 'B', and higher sensitivity, higher climate change impacts, and lower adaptive capacities were recorded in Zone 'B' and 'C'. The approach is comparable within the district and between the states. In enhancing our shared understanding of forest degradation, the results are of value to policy/decision-makers, implementers, and adaptation funding agencies, who can use them to assess the scale, cause, and actions for adaptation.

Keywords: climate change; forest vulnerability; indicators; Himalaya

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1. Introduction

The Himalayas are an ecologically rich range of mountains range that serve humans with a wide range of goods and services (Rasul 2014 [1]; Badola et al., 2015 [2]). The ecosystem hosts various natural resources and diverse habitats, with a considerable altitudinal variation. The naturally rich repository nourishes more than seven countries (Government of Uttarakhand, 2014 [3]), and is associated with social and economic benefits within rural Himalayan communities (Hoy et al., 2016 [4]). Overall, the Himalayas provide a plethora of goods and services to mountain communities and millions of downstream inhabitants. The ecosystem has become critical in contributing to the continuous flow of services.

Himalaya is projected to be extremely sensitive to climate change (Indian Network for Climate Change Assessment, 2010 [5]; Chaturvedi et al., 2011 [6]; Singh and Hietala 2014 [7]), as the changes are likely to alter the regulation of terrestrial biogeochemical processes, such as litter decomposition, nitrification, denitrification, nitrogen mineralization, nutrient uptake, fine root dynamics, and soil respiration and productivity (Jha 2020 [8]). Historical patterns have had the following effects: glaciers receding (Kumar et al., 2015 [9]), deterioration in water resources (Li et al., 2016 [10]), drying out of traditional water sources

(Palazzoli et al., 2015 [11]), forest degradation (Jha 2020 [8]), biodiversity loss (Jha 2020 [8]), alteration of agricultural systems (Jethi et al., 2016 [12]), reduction in crop yields (Jethi et al., 2016 [12]), an upward shift of apple orchards, increased vulnerability of winter cropping (ADB, 2010 [13]), loss of tree species (Wani et al., 2013) [14], changes in bird types and populations, and migration (Jha 2020 [8]). Climate-driven changes in ecosystem structure, function, and species distributions negatively affect Himalayan forests (Lewis 2006 [15]; IPCC, 2007 [16]). Some studies claim that elevated atmospheric CO_2 concentration, increased temperature, and altered precipitation has, at least to some extent, had a positive impact (productivity and diversity) on the forest ecosystem. This varies, however, according to species' tolerance (Das 2004) [17] and the availability of water and nutrients.

For a long time, Himalayan forests have been exposed to severe, natural, and anthropogenic catastrophes, such as landslides, forest fires, earthquakes, and flash floods (Kala, 2014) [18]. Anthropogenic interventions such as deforestation, infrastructure development, and urbanization have further aggravated environmental degradation, which has affected the quantity and quality of ecosystem services (Ahmed et al., 1990) [19]. The degradation of ecosystem services has severe repercussions and is likely to be exacerbated by climate change (Ravindranath et al., 2006 [20]).

For survival throughout the Himalayan range, communities rely on forests and forest-based resources (fodder, fuelwood, medicinal plants, fruits, and other associated items) (Jadin et al., 2016 [21]; Jha et al., 2018 [22]). In the last few years, increased anthropogenic activities have put pressure on the Himalayan ecosystems, causing changes in forest ecosystems (Jha et al., 2018 [22]; Jha 2020 [8]). As populations continue to expand, together with their reliance on forest products, forest ecosystems are now experiencing decreased density and diversity (Sharma and Vetaas 2015 [23]; Bruggeman et al., 2016 [24]) and changes in distribution (Upgupta et al., 2015 [25]; Chakraborty et al., 2016 [26]), biodiversity (Giam 2017 [27]), productivity (Alekhya et al., 2015 [28]), and forest degradation (Jha 2020 [8]). Further, the reliance on forest resources and the requirement for a life support system in the Himalayas varies with altitude; for example, the quantum of fodder is required more at low- and mid-altitude, and fuelwood is needed at high altitudes irrespective of the administrative boundary. Similarly, agriculture and allied activities are less extensive and beneficial at lower altitudes. At the same time, constraints increase with altitude. The challenges for water, even for drinking purposes, also increase with altitude. It is comparatively easy to manage water supply even in scarce seasons at lower altitudes because of the distance to headquarters, institutional set-up, and other facilities.

Forest degradation is exacerbated by climate change, natural and manmade disasters, and resource utilization patterns, implying the need for sustainable forest management in the Himalayan area. Given the importance of forests in sustaining local communities, several studies have conducted evaluations of forest-based goods and services in the Himalayan region. However, limited research has been undertaken to evaluate forest degradation using altitude-specific data. Studies have assessed the status of the forest using primary productivity (Upgupta et al., 2015 [25]; Sharma et al., 2018 [29]; Kumar et al., 2019 [30]), forest fire index (Jha et al., 2018 [22]), biomass and carbon stock (Jha 2020 [8]), factors that are highly specific and which, to a certain extent, limit and confine the assessment. These approaches could be strengthened by integrating multiple factors, enabling a clear identification of the actual status of the forest. Adequate knowledge of the determinants of forest degradation through time and space is critical for forest management and creating policies to improve local livelihoods and strengthen community disaster preparedness, particularly in the face of climate change.

The vulnerability assessment uses a bottom-indicator-based approach from national to even local levels. The national-level indexes for vulnerability assessment, such as HDI, HWI, PVI, etc., use different parameters, such as life expectancy, sustainability, and quality of life for defining vulnerability at a larger scale (state or nation) (Table 1). The number of variables in this category is relatively few. However, it compares the relative position of a state or country. Country rankings provide helpful information on the relative level of sustainability. Contrastingly, a single value is used for comparing vulnerability on a national level. Moreover, a county has considerable variability regarding exposure, susceptibility, impact, and other developmental parameters (Cutter and Finch 2008) [31]. However, the data used may not adequately represent the processes determining vulnerability (Eriksen and Kelly 2007 [32]); generally, it results in a restricted vulnerability measure.

Table 1. Indexes used for the assessment of vulnerability and adaptive capacity.

S. No.	Indexes	Brief Description
1	Environmental Vulnerability Index (Kaly et al., 1999) [33]	This index is based on three aspects of vulnerability: risks to the environment (natural and anthropogenic), the innate ability of the environment to cope with the risks (resilience), and ecosystem integrity (the health or condition of the environment as a result of past impacts).
2	Index of Human Insecurity (Lonergan et al., 2000) [34]	IHI was developed as a classification system that distinguishes the perception of vulnerability and insecurity of different countries, indicators from environment, economy, society, and institutions were used to calculate overall vulnerability.
3	Human Well-being Index (Prescott-Allen 2001) [35]	HWI measures the community (political rights, crime, internet users, peace and order) and social equity (gender and income). The index incorporates development/sustainability goals in five categories ranging from 'good' to 'bad'.
4	Environmental Sustainability Index (World Economic Forum, 2002) [36]	This index measures progress towards environmental sustainability of 142 countries through 20 indicators.
5	Water Vulnerability Index (Sullivan 2002 [37])	An interdisciplinary approach that produces an integrated assessment of water stress and scarcity, linking physical estimates of water availability with socioeconomic variables that reflect poverty.
6	Country-level Risk (Brooks and Adger 2003) [38]	Includes several proxies for risk associated with climate variability and change, based on numbers killed and affected by climate-related disasters.
7	Predictive Indicators of Vulnerability (Adger et al., 2004) [39]	The PIV link social vulnerability with climate adaptation.
8	Social Vulnerability Index (Vincent 2004) [40]	SVI is an index of five composite sub-indices: economic well-being and stability (20%), demographic structure (20%), institutional stability and strength of public infrastructure (40%), global interconnectivity (10%) and dependence on natural resources (10%)
9	Index of Social Vulnerability to Climate Change (Adger and Vincent 2005) [41]	A social vulnerability index with emphasis on water availability.
10	Environmental Sustainability Index (Esty et al., 2005) [42]	A composite index using 76 indicators to assess 146 nations' sustainability trajectory based on five major categories: environmental system, environmental stresses, human vulnerability to environmental stresses, the human capacity to respond to environmental change, and global stewardship.
11	Prevalent Vulnerability Index (Cardona 2005) [43]	Focuses on social, economic, institutional, and infrastructural capacity to recover from natural hazards or the lack thereof.
12	Disaster Risk Index (ISDR 2004) [44]	One of the United Nations' three global initiatives to raise awareness for integrated disaster mitigation. Aims to 'improve understanding of the relationship between development and disaster risk', 'enable the measurement and comparison of relative levels of physical exposure to hazard, vulnerability and risk', identify vulnerability indicators', and map international patterns of risk.
13	Human Development Index (UNDP, 2008) [45]	Includes life expectancy, health, education, and standard of living indicators for an overall assessment of well-being and human development on a country scale.

Table 1. *Cont.*

S. No.	Indexes	Brief Description
14	Livelihood Vulnerability Index (Hahn 2009 [46])	Combines seven components or indicators for vulnerability: livelihoods, socio-demographics, social networks, health, natural disasters and climate variability, food, and water security assimilated into the dimension of vulnerability.
15	Household Social Vulnerability Index (Vincent and Cull 2010) [47]	An index of household-level social vulnerability to climate change, based on the multiple dimensions of the vulnerability identified in the sustainable livelihood framework.
16	Livelihood Vulnerability Index and the Livelihood Effect Index (Urothody and Larsen 2010 [48])	Both indexes reflect the relative differences between the two VDCs in terms of vulnerability to climate change impacts and factors contributing to it.
17	Climate Vulnerability Index (Pandey and Jha 2011 [49])	These indicators were assimilated into indices to the dimension of vulnerability and the IPCC (2007) protocol was used for vulnerability assessment.
18	Poverty and Vulnerability Assessment (Gerlitz et al., 2014) [50]	Combines general poverty predictors with relevant indicators in mountain contexts.
19	Climate Vulnerability Index (Aryal et al., 2014) [51]	An index used to assess and compare the vulnerability of transhumant communities in Nepal.
20	Multidimensional Livelihood Vulnerability Index (Gerlitz et al., 2016 [52])	A measure used to explore and describe livelihood vulnerability to climatic, environmental, and socio-economic change in the HKH region.
21	Adaptation Capability Index (Pandey et al., 2016 [53])	An approach to recognizing social and natural factors contributing to successful adaptation that addresses several household functions, such as social networking, livelihood strategies, resource availability, and accessibility.
22	Climate Vulnerability Index for Water (Pandey et al., 2015 [54])	An index to assess the climate-related water vulnerability of households in rural and urban settings, comprising three components—exposure, sensitivity, and adaptive capacity, and 14 sub-components.
23	Future Vulnerability Index (Upgupta et al., 2015 [25])	Index to assess forest ecosystem vulnerability to climate change across Himachal Pradesh under ‘current climate’ and ‘future climate’ scenarios.
24	Inherent Vulnerability (Shukla et al., 2016 [55])	Indices to assess the inherent vulnerability (internal) of agricultural communities at the village level based on sensitivity and adaptive capacity.
25	Climate Vulnerability Index, and Current Adaptive Capacity Index, (Pandey et al., 2017 [56])	These indices assess vulnerability using five forms of capital, i.e., human, natural, financial, social, and physical capital.
26	Forest Vulnerability Index (Thakur et al., 2020 [57])	An index for forest vulnerability using field-based observations with an integrated approach of multiple indicators.
27	Socio-ecological Vulnerability Index (Jha et al., 2021 [58])	An index to estimate socio-ecological vulnerability.
28	Climate Vulnerability Index (Jha 2020 [8])	An index used to calculate the vulnerability of sectors (socio-economic, agriculture, forest, and water), and the contribution of sectors to the overall vulnerability.
29	Vulnerability Index (DST, 2020 [59])	This index identifies the most vulnerable states and districts in India concerning current climate risk and the main drivers of vulnerability.
30	Vulnerability Index and Resilience Index (Jha et al., 2021) [58]	The indices assess the socio-ecological vulnerability and resilience of mountain communities residing in capital-constrained environments. Site-specific indicators were integrated into a sustainable livelihood framework in an attempt to calculate vulnerability and resilience jointly.
31	Ecosystem Services Index (Jha et al., 2022) [60]	This index quantifies ecosystem services.

Vulnerability indicators at the regional and local levels are also used in impact assessment. They are also instrumental in identifying threats or threatened systems, raising awareness, and prioritizing vulnerable sectors (Harley et al., 2008 [61]). The vulnerability indicators are further used to compare the relative vulnerability of places (Pandey and Jha, 2011 [49]), groups or communities (Sinha and Jha, 2017) [62], and sectors (Jha et al., 2018 [22]). Moreover, vulnerability indicators are widely used to prioritize vulnerable sectors and formulate adaptation options. Jha et al. (2017) [63] utilized vulnerability indicators to assess government-sponsored adaptation programs. The changes in household-level indicators of agriculture, water, and economic status due to Government-sponsored adaptation programs, i.e., MGNREGA, are aggregated and assessed.

Generally, the regional indicators-based assessment such as the Livelihood Vulnerability Index (Hahn et al., 2009 [46]); Livelihood Vulnerability Index and Livelihood Effect Index (Urothody and Larsen 2010 [48]); Climate Vulnerability Index (Pandey and Jha 2011 [49]); Poverty and Vulnerability Assessment (Gerlitz et al., 2014 [50]); Inherent Vulnerability (Shukla et al., 2016 [55]); Forest Vulnerability Index (Thakur et al., 2020 [57]); Vulnerability Index (DST, 2020 [59]); Vulnerability Index and Resilience Index (Jha et al., 2021) [58]; etc., identify and analyze the indicators with higher significance in related sectors and then normalize them into indices or components or sub-components or sectors (Table 1). Finally, these indices were assimilated into the dimension of vulnerability. The details on vulnerability indices are comprehensively discussed in Table 1, and vulnerability is discussed in Table 2. The tools for understanding forest degradation in the Himalayas are limited, and the available literature analyzed the degradation with minimal inclusion of ground surveys and issues that emphasize the needs of locals. Furthermore, several districts in the study state, Uttarakhand, have a wide range of altitudes. The study district is spread over 5400-km squared and has an altitudinal range of 300 to 3000 m above sea level. Therefore, understanding the present state of forest degradation along the altitude becomes critical. Our study explores forest degradation in the context of altitude and dependency. The study's primary aim was to examine forest vulnerability along the altitudinal gradient in the Pauri District, Uttarakhand, India. We addressed the following objectives based on broad themes: (i) to identify indicators contributing to forest degradation, (ii) to assess forest vulnerability along the altitudinal gradient, and (iii) to identify altitude-specific indicators for adaptation actions under impending forest degradation.

Table 2. Definitions of vulnerability.

S. No.	Author(s)	Definitions
1	Gabor and Griffith (1980) [64]	Threats (including chemical agents and the ecological situation of the communities, and their level of emergency preparedness) to which people are exposed.
2	Timmerman (1981) [65]	The degree to which a system acts adversely to the occurrence of a hazardous event.
3	UNDRO (1982) [66]	The degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude.
4	Susman et al. (1984) [67]	The degree to which different social classes are at different risk.
5	Pijawka and Radwan (1985) [68]	The degree to which hazardous materials threaten a particular population (risk) and the capacity of the community to reduce the risk or adverse consequences of hazardous materials releases.
6	Kates et al. (1985) [69]	The capacity to be wounded.
7	Bogard (1988) [70]	The inability to take effective measures to insure against losses.
8	Mitchell (1989) [71]	Vulnerability is the potential for loss.
9	Liverman (1990) [72]	Distinguishes between vulnerability as a biophysical condition and vulnerability as defined by society's political, social, and economic conditions.

Table 2. *Cont.*

S. No.	Author(s)	Definitions
10	Downing (1991) [73]	It refers to a consequence (e.g., famine) rather than a cause (e.g., are vulnerable to hunger); it is a relative term that differentiates among socioeconomic groups or regions rather than an absolute measure of deprivation.
11	Dow (1992) [74]	The differential capacity of groups and individuals to deal with hazards based on their positions within physical and social worlds.
12	Smith (1992) [75]	The risk from a specific hazard varies through time and according to changes in physical exposure and/or human vulnerability (the breadth of social and economic tolerance available).
13	Alexander (1993) [76]	A function of the costs and benefits of inhabited areas at risk from natural disasters.
14	Cutter (1993) [77]	The likelihood that an individual or group will be exposed to and adversely affected by a hazard.
15	Watts and Bohle (1993) [78]	Exposure, capacity, and potentiality.
16	Blaikie et al. (1994) [79]	The characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard.
17	Bohle et al. (1994) [80]	The aggregate measure of human welfare that integrates environmental, social, economic, and political exposure to a range of potentially harmful perturbations.
18	Dow and Downing (1995) [81]	Biophysical, demographic, economic, social, and technological factors such as population ages, economic dependency, racism, and age of infrastructure in association with natural hazards.
19	Eakin and Luers (2006) [82]	The lack of human capacity to avoid or reduce such adverse situations.
20	Gilard and Givone (1997) [83]	The sensitivity of land use to the hazard phenomenon.
21	Comfort et al. (1999) [84]	The circumstances that place people at risk while reducing their means of response or denying them available protection.
22	Weichselgartner and Bertens (2000) [85]	The condition of a given area concerning hazard, exposure, preparedness, prevention, and response characteristics to cope with specific natural hazards.
23	Adger (2006) [86]	The state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt.
24	Ciurean et al. (2013) [87]	The inability to withstand the effects of a hostile environment.
25	Wolf et al. (2013) [88]	A measure of possible future harm.
26	IPCC (2014) [89]	The degree to which a system is susceptible to and unable to cope with adverse effects of climate change, including climate variability and extremes.
27	Hong et al. (2016) [90]	A weak resistance and low resilience of ecosystems in response to external interference including natural and artificial factors at a specific spatial scale.
28	Jha et al. (2022) [60]	A suite of human-ecological factors reflects exposure (climate stress on households), sensitivity (the degree to which a system is exposed), and adaptive capacity (internal or external capacity to cope).

Source: Adapted from Cutter (1996) [91], Weichselgartner (2001) [92], Hogan and Marandola (2005) [93], Adger (2006) [86], Wolf et al. (2013) [88], Paul (2013) [94], Berrouet et al. (2018) [95].

Forest Degradation Indicators: Selection and Definition

An indicator constitutes information that is either readily available or easily obtained pragmatically. It is a variable and a measure of system behavior in the context of essential and perceptible attributes (Holling et al., 1978 [96]). Indicators have been used in several ways by authors: Marcus (1983) [97] described a sign as ′defined as something which stands for something to somebody in some respect or capacity‘; as a proxy—a function from an observable variable (McQueen and Noak 1988 [98]); a statistical measure (Tunstall 1992 [99]); a parameter—provides information on the state of the phenomenon and defines it as a value that is measured or observed (OECD, 1993 [100]); a piece of information (Bakkes et al., 1994 [101]); an index (Hammond et al., 1995 [102]); and a sub-index or component of an index (Ott 1978 [103]; Hahn et al., 2009 [46]; Pandey and Jha, 2011 [49]). In this study, an indicator is a perceptible local variable or piece of information chosen for its importance to livelihoods, the local economy, conservation, and resource management (availability, accessibility, and usability). Table 3 has more details on the indicators.

Table 3. Indices and indicators for climate change impacts and dimension of vulnerability (sensitivity and adaptive capacity) along the altitudinal gradient in Pauri District, Uttarakhan.

	Indices	Indicators	Explanation	Zone A	Zone B	Zone C
Climate Change Impacts	Temperature index	Increased summer temperature	Alters the phenology of forest tree species and also increases the probability of forest fire	0.760	0.100	0.900
		Increased February-March temperature	Alters phenology of forest tree species, agricultural and horticultural production	0.750	0.800	0.830
	Rainfall Index	Decreased number of rainy days	Lesser rainy days distress forest tree species and water availability	0.230	0.540	0.710
		Delayed monsoon rain	Results in water scarcity and alters the physiological character of the forest	0.110	0.290	0.340
	Extreme Event Index	Increased temperature resulting in forest fire	Increased temperature strengthens forest fire. It drives forest degradation and limits forest productivity	0.500	0.730	0.860
		Increased temperature and drought incidence	Water scarcity and restricted long-term water availability for agriculture and related activities	0.120	0.670	0.890
		Increased intensity and decreased frequency of rainfall	Increases runoff and erosion	0.990	0.920	0.770
		Uncertain extreme climatic events	These cause structural degradation and functional deterioration of forests	0.850	0.960	0.960

Table 3. *Cont.*

	Indices	Indicators	Explanation	Zone A	Zone B	Zone C
			Dimension of Vulnerability			
Sensitivity	Natural Resource Degradation Index	Frequency of forest fire (increased or decreased)	One of the major drivers of forest degradation, limits forest productivity, and restricts access to forest	0.480	0.950	0.870
		The intensity of forest fire (increased or decreased)	One of the major drivers of forest degradation, limits forest productivity, and restricts access to forest	0.430	0.900	1.000
		Lopped trees (Number/Hectare)	The higher number of lopped trees shows higher anthropogenic interference	0.651	0.609	0.477
		Grazing (%)	Reflects higher anthropogenic interferences, limits alter the ecological balance and affect the health of the forest	0.667	0.667	0.667
		Time spent on collection of forest resources	Shows that the distance between village and forest is increasing because of anthropogenic interference	0.500	0.900	0.960
		Distance travelled for collection of forest resources	A distant forest reflects more time spent on resource collection	0.490	0.910	0.910
	Resource susceptibility index	Concentration of dominance		0.373	0.633	0.545
		Evenness	Represents health, vigor and functioning of forest ecosystem	0.512	0.458	0.533
		Susceptible species	Susceptible species more prone to fire	0.620	0.560	0.170
		Regeneration rate	Higher regeneration represents better health	0.870	0.900	0.540
		Pure forest and dominant species	Pure forests are susceptible to change, and the fire-susceptible dominant species result in the loss of forest	0.420	0.870	0.590
		Age of the nearby forest (even or odd)	Even-aged forests are more susceptible to change	0.500	0.500	0.400
		Dependency on the natural water source	Natural water sources are susceptible to forest degradation and climate change	0.140	0.290	0.370

Table 3. *Cont.*

	Indices	Indicators	Explanation	Zone A	Zone B	Zone C
Adaptive Capacity	Resource collection index	Fodder and fuelwood collection	The natural support system is more susceptible to climate change and higher dependency (% respondents) on susceptible ecosystems results in vulnerability	0.430	0.400	0.450
		Collection of NTFP	NTFP (apart from fodder and fuelwood) is an additional income source and is also considered a food supplement	0.350	0.290	0.270
	Resource availability index	Sufficient fodder and fuelwood	Availability of and accessibility to sufficient fodder and fuelwood sources strengthen capacity to withstand change	0.430	0.600	0.780
	Strategy index	Individuals (Number/Hectare)	The higher the number of individuals, the higher the productivity of the forest	0.488	0.447	0.396
		Biodiversity (H)	Maintains structure and function of an ecosystem	0.593	0.389	0.350
		Species Richness	Supports species' ecological interactions and geographical ranges	0.557	0.482	0.389
		Biomass (Tons/Hectare)	Absolute reflection of forests' health; the higher the biomass, the better the health	0.505	0.447	0.412
		Alternatives to fodder during fodder scarce season (Summer and monsoon) (cultivation of fodder, use of previously stored fodder, or increased use of straw)	The availability of alternatives represents the self-sufficiency of a household	0.330	0.370	0.330
		Strategies during fuelwood scarcity (shifting to energy-efficient techniques like improved stoves, LPG, etc.)	Strategies reduce dependency and strengthen households' adaptive capacity	0.320	0.490	0.520

The term 'vulnerability' has scientific origins in geography and natural disaster studies. However, this concept has become crucial in fields such as natural hazard and disaster management, ecology, public health, poverty and development, secure livelihoods and famine, sustainability science, land change, and climate effects and adaptation. Several studies (Table 2) characterized vulnerability based on their research appropriateness. A simple, concise meaning derived from its Latin origins is frequently employed in the literature. The root of vulnerability is 'vulnerare', meaning 'to wound'; thus, Kates et al. (1985) [69] defined vulnerability as 'the capacity to be wounded'. Amartya Sen (1981) [104] emphasized the cause of the vulnerability. Defining it as a 'lack of entitlement (food security, sustainable livelihoods, social structures, etc.) due to restricted access to resources (institutional, political, and technological)'.

The IPCC defines vulnerability in its Second Assessment Report as 'the extent to which climate change may damage or disrupt a system', and states that system vulnerability 'depends not only on a system's sensitivity but also on its ability to adapt to changing climatic settings' (Watson et al., 1996 [105]). According to the report, socioeconomic systems are 'usually more vulnerable in developing nations with less favorable economic and institutional circumstances'. The existence of an inter-relationship between wealth (strengthens adaptive capacity) and poverty (begets vulnerability) in a region discussed deliberately in the Regional Impacts of Climate Change: An Assessment of Vulnerability (IPCC, 1997 [106]). The location and context specificity of vulnerability with uncertainty was highlighted by Handmer (1999) [107]. He underlined that uncertainty might be addressed by bold policy initiatives that address social and economic concerns while taking into account human behavior, culture, and the institutional capabilities of affected communities. At COP-6, Watson defined vulnerability as 'the amount to which a natural or social system is vulnerable to suffering damage from climate change', and it is a result of climate change magnitude, sensitivity, and adaptability (IPCC, 2000) [108].

Several definitions of vulnerability have been offered since 1980. It is generally defined as the ability to anticipate, resist, cope with, and respond to a hazard (Blaikie et al., 1994) [79]. It occurs due to various factors including disaster management, public health, poverty, food security, ecology, and climate change, including climate variability, change, and extremes (Fussel 2007 [109]). Goulden (2010) [110] defines the natural perspective of vulnerability as 'a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity and adaptive capacity'. The potential implications of climatic fluctuation and change are referred to as exposure; sensitivity is the extent to which the exposure affects rural communities; and adaptive capacity is the system's ability to adapt, tolerate, or recover from the effects of the exposure (Ebi et al., 2006 [111]). However, the definition does not precisely define the relationship among dimensions of vulnerability (Schauser et al., 2010 [112]). Sometimes researchers describe vulnerability as an exposure susceptibility–resilience complex when they view sensitivity as susceptibility and adaptive capability as resilience (Balica et al., 2012 [113]). Vulnerability measures a system's (a community's) defenselessness or propensity to be injured or hurt by climate change. The IPCC defines vulnerability as 'the propensity or predisposition to be negatively affected'. Vulnerability includes several factors, such as sensitivity or susceptibility to injury and a lack of ability to cope and adapt (IPCC, 2014 [89]). The IPCC 2014 report defines vulnerability as a characteristic, intrinsic system attribute. The exterior property, i.e., exposure, is inherent. Thus, it is not taken into consideration for the assessment. Exposure is an external element that increases vulnerability and is regarded as an inseparable component of vulnerability assessment, driving sensitivity and adaptive capacity.

There have been few vulnerability assessment studies based on the IPCC 2014 framework, with most using the IPCC 2007 framework and measuring exposure as an inseparable component of vulnerability (Simane et al., 2016 [114], Kumar et al., 2016 [115], Jha et al., 2017 [63], Jha et al., 2018 [22], Pandey et al., 2018 [116], Jha 2020 [8]). The indicators used for vulnerability assessment are shown in Table 1. These investigations are based on the queries 'who is vulnerable?', 'what is vulnerability?', and 'vulnerability to what?' (Malone and Engle 2011 [117]), whereas new vulnerability assessment paradigms strive to answer the question 'vulnerability to what?' Updated assessments are not related to exposure and are a system's distinguishing feature, demonstrating its current internal condition (Sharma et al., 2013 [118]). Vulnerability, in this construct, is regarded as an inherent attribute of the system, consisting of sensitivity and adaptive capability.

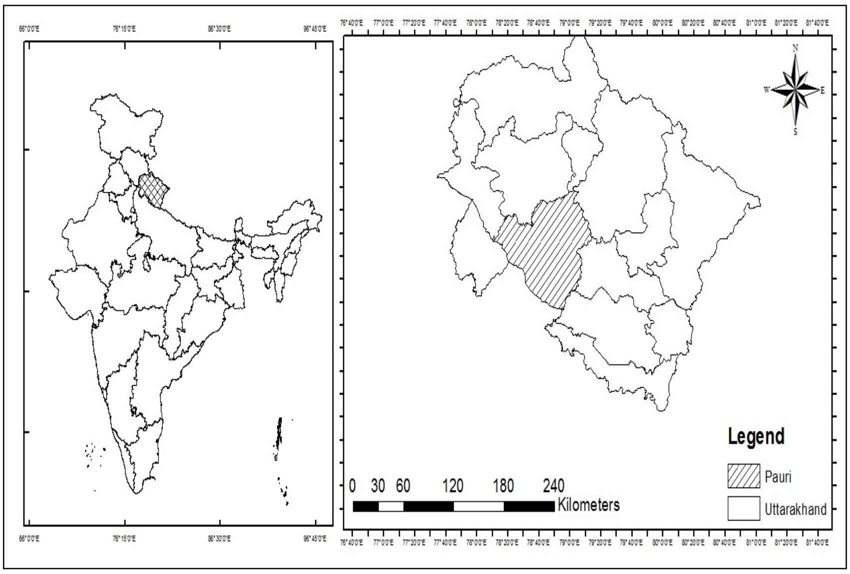
The current study evaluates vulnerability as a pre-existing, system-specific attribute. We measured vulnerability using hazard-specific indicators for sensitivity and adaptive capability after identifying likely and prospective dangers. Climate change is currently regarded as a hazard, and factors that directly or indirectly affect and/or influence sensitivity and adaptation ability were considered for the evaluation. The indications were aggregated into indices, which were then categorized as ‘possible repercussions of climate change’.

2. Methodology

2.1. Study Area

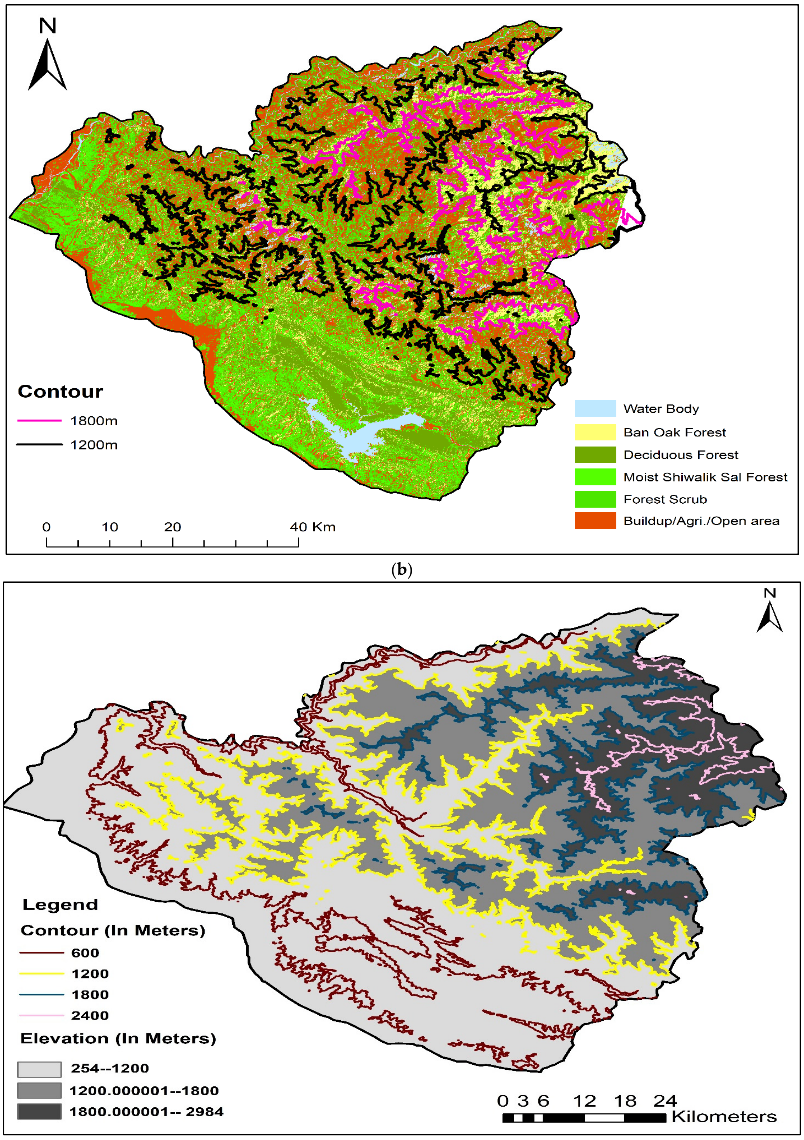
The research was carried out in the Pauri district of Uttarakhand, India. The district (29°20′–30°15′ N; 78°10′–79°20′ E) has an average elevation of 1800 m above sea level (m asl) (range 210–7817 m asl) and occupies a land area of 5230 km^2 (FSI, 2019 [119]). The district’s population is 686,527, with a density of 129 persons per km^2, and the sex ratio is 1103 females per 1000 males. The district has reported a negative population growth rate (−1.51%). The district has an 82.59 percent literacy rate (males 93.18 percent, females 73.26 percent), compared to 74.04 percent in India (males 82.14 percent, females 65.46 percent) (Census of India, 2011 [120]). With a mean annual temperature of 25–30 °C (45 °C in June and 1.3 °C in January) and a mean annual rainfall of 2180 mm, the area has a sub-temperate to temperate climate, with over 90% of precipitation falling during the monsoon season (July–September).

The district has a hilly topography. The fluvial valleys have a convex shape, with steep valleys, interlocking spurs descending the main river, and terraced agricultural fields on the valley sides’ moderate slopes. The people, who stay in the area, are primarily involved in agriculture, rely on forest resources for their survival, and are locally known as Garhwali. Tourism and animal husbandry are supplementary income sources in the region. The Garhwal region is predominantly rural, with scattered housing patterns and a mixed economy. The landholding is scattered and small, and per capita land availability is 0.68 ha in the hilly districts and 1.77 ha in the plain districts. Out of the total reported land, only 14.02% is under cultivation, and more than 55% is rainfed. The existence of different topographical and orographic elements has resulted in exceptional biodiversity in the region. The state is well-forested and consists of about 34,652 square kilometers (64.78%) of forest cover; the study district has 3269 square kilometers (61.34 %) of forested area. Out of the total, 519 km square (15.87%) is very dense forest; 1954 km square (59.77%) is moderately dense forest; and 672 km square (24.35%) is open forest. The district contributes 13.48% of forest area to the state, and its share in national forest cover is 03.45%. The per capita forest area in the district is 0.0047 km square per person, much higher than the state’s per capita forest area, i.e., 0.0024 km^2 per person (ISFR, 2021) [121]. The forest type (Figure 1b) in the district shows a considerable higher difference. The forest of the study district is differentiated into moist Shivalik sal forest, deciduous forest, and ban-oak forest.



(**a**)

Figure 1. *Cont.*



(**b**)

(**c**)

Figure 1. (**a**) Study site location district and state, (**b**) land use and land cover map depicting forest type along the contour map of the study district, (**c**) contour and elevation map of the study district.

The moist Shivalik sal forest, i.e., Zone A, comprises the Tarai–Bhabar area of the adjacent Gangetic plain, and outer and sub-Himalayan tract up to 1200 m asl. The forest types of these zones consist of (a) *Shorea robusta* forest, (b) *Acacia-Dalbergia* forest, (c) *Acacia-Shorea robusta* forest, (d) *Holoptelea* forest, (e) Bamboo (*Dendroclamus*) brakes, and (f) *Anogeissus latifolia-Spondias pinnata* forest and scrubs, associated with various evergreen and deciduous tree species. Zone B, 1200–1800 m asl has mountainous topography and the forest type is a deciduous forest comprising of (a) Pine forest, (b) Oak forest, (c) Pine-Oak forest, (d) Oak-*Lyonia* forest, (e) Deodar Forest, (f) Deodar-Pine forest, and (g) mixed forest. Zone C, i.e., more than 1800 m asl usually known as the sub-Himalayan peaks, has a ban-oak forest type consisting of (a) oak forest, (b) deodar forest, (c) rhododendron forest, (d) spruce forest, and (e) mixed forest.

2.2. Sampling Strategies

Inter- and intra-structural indicators of forest degradation were examined over an altitudinal gradient for vulnerability assessment. The patterns of land use and resource utilization were explored in detail. As basic requirements differ with altitude in the mountains, the present investigation divided the district into three zones (A–C) based on altitude and forest distribution. The zones were defined as altitude < 1200 m asl (zone A), altitude 1200–1800 m asl (zone B), and altitude > 1800 m asl (zone C) (Figure 1c).

Questionnaires and face-to-face interviews, ideally with the head of the household, were used to gather information on households in randomly selected villages in each zone. Multiple villages in each zone were chosen to retain the villages' variability. Large samples are difficult to gather in mountainous areas, since households are sparsely scattered and typically engage in their livelihood throughout the day. In the study district, 91 villages (30 in Zone A, 32 in Zone B, and 29 in Zone C) were surveyed. The villages were chosen because of the inhabitants' reliance on the forest. A minimum of five and a maximum of ten respondents from each participating village were chosen for the interview to avoid similarities in responses. For data collection, 545 respondents were questioned from the three designated altitudinal zones (182 in Zone A, 187 in Zone B, and 176 in Zone C).

With the help of a local person, the interviews were conducted in Hindi and the local language. The questionnaire addressed topics and concerns regarding the forest and its ability to provide a livelihood. A phytosociological study was also conducted to determine the forest's condition in density, regeneration, species richness, variety, lopped branches/trees, and biomass. Along the altitudinal gradient, the investigation was conducted in the open (OF), moderately dense (MDF), and dense forests (DF). To prevent uniformity and cover more area in each zone, a total of 71 quadrants (19 in Zone A (OF 5, MDF 9, DF 5), 22 in Zone B (OF 8, MDF 10, DF 4), and 30 in Zone C (OF 19, MDF 5, DF 6)) of 500 m^2 each (20 m × 25 m) were set out at intervals of 500 m elevation. The primary data and field measurements were transformed into indicators and incorporated into the forest vulnerability indices.

2.3. Analytical Framework

A bottom-up, indicator-based approach was used in the study (Hahn et al., 2009 [46]). The underlying assumption was that local knowledge and advice are essential to identifying drivers of vulnerability and indicators that may help the forest ecosystem become less vulnerable. These indicators are sympatric, indicating susceptibility at a local level (Jha et al., 2017 [63]). Multidimensional Vulnerability (Sullivan and Meigh 2005 [122]), Livelihood Vulnerability Index (Hahn et al., 2009 [46]), Livelihood Effect Index (Urothody et al., 2010 [48]), Climate Vulnerability Index (Pandey and Jha 2011 [49]), Capacity Assessment Index (Jha et al., 2017 [63]), and Vulnerability and Capacity Assessment (Sinha and Jha, 2017 [62]) are two vulnerability assessment methodologies that include indications from several components to show both sectoral and overall vulnerability. The current study integrated field measurements with primary data (household questionnaires) to develop a method for assessing forest vulnerability. Most indicator-based techniques employ balance-weighted averages, assuming that each indicator contributes equally to the aggregate index (Sullivan 2002 [37]; Pandey and Jha 2011 [49]; Jha et al., 2017 [63]) and are thus comparable and relevant.

Our approach was designed to assess the vulnerability of forests that provide abundant goods and services to communities. Household dependency on the forest was studied through resource degradation, susceptibility in terms of sensitivity, forest resource availability, collection, and strategies as adaptive capacities. Previous studies on forest degradation in the Himalayas are limited. The vulnerability of natural systems can be attributed to multidimensional factors (Jha 2020 [8]), with each dimension associated either positively or negatively (Jha et al., 2017 [63]). Change or variation in a single dimension may or may not influence others and a change in the dimension of vulnerability can impact households differently depending on their existing endowments (Pandey and Jha, 2011 [49]).

The present study employed a participatory evaluation technique that included participatory assessment (household surveys, participatory rural appraisals, focus group discussions) and field measurements (phytosociological analysis) (Table 3). Diversity was studied along with richness, regeneration, individuals, evenness, the concentration of dominance (CD), and biomass to represent the forest ecosystem's long-term health, vigor, and functioning (Solbrig 1991 [123]; Lee and Chun 2016 [124]). These variables are also important ecological characteristics, strongly correlated with environmental and anthropogenic variables (Gairola et al., 2008 [125]; Rawat and Chandra 2012 [126]). Indicators were created through primary qualitative and quantitative data. These indicators were identified through a combination of literature specific to the area or similar regions (e.g., Sharma et al., 2009 [127]; Urothody et al., 2010 [48]; Pandey and Jha 2011 [49]; Tse-ring et al., 2012 [128]; Sandhu and Sandhu 2014 [129]; Pandey et al., 2015 [54]; Gerlitz et al., 2016 [52]; Pandey et al., 2016, 2017 [53,56]; Jha et al., 2017 [63]) and through expert consultation. The indicators were originally in different units or scales, and they were standardized depending on their functional relationship with vulnerability, e.g., whether vulnerability increased with an increase in the value of the indicator (positive relationship; Equation (1)) or decreased with an increase in the value of the indicator (negative relationship, Equation (2)). The current state of the forest ecosystem was then described in terms of vulnerability using the IPCC vulnerability assessment technique (IPCC, 2014 [89]), which consists of eight indices and 30 site-specific indicators. The higher the indicator's value, the bigger the vulnerability, it was thought.

$$\text{Index}_{\text{sv}} = \frac{S_v - S_{min}}{S_{max} - S_{min}} \tag{1}$$

$$\text{Index}_{\text{sv}} = \frac{S_{max} - S_v}{S_{max} - S_{min}} \tag{2}$$

where S_V is the average value of the indicator at the village level, and S_{min} and S_{max} are the minimum and maximum values of the indicator.

The indicators were averaged after standardization using Equation (3) to calculate the score for the indexes:

$$M_V = \frac{\sum_{i=1}^{n} Index}{n} \tag{3}$$

where, M_V is one of the indices for the dimension, Index is the value of the ith indicator, and n is the number of indicators for the dimension.

Dimensions of vulnerability (sensitivity (Se) and adaptive capacity (Ac)) are calculated separately by taking a simple average of indexes using Equation (4):

$$N_v = \frac{\sum_{i=1}^{n} Dimension\ of\ Vulnerability}{n} \tag{4}$$

where N_V is one of the dimensions of vulnerability, the dimension of vulnerability is the value of the ith indexes, and n is the number of indexes for the dimension.

The overall vulnerability is calculated with sensitivity and adaptive capacity, consisting of site-specific indicators in the context of climate change using Equation (5). Here the data for indicators were gathered through household surveys which capture opinions or perceptions of the communities and field measurements in the nearby forest.

$$Vulnerability = Sensitivity - Adaptive\ Capacity \tag{5}$$

3. Results and Discussion

A detailed analysis of the historical climate trend (1951–2018) using INRM multi-model ensembles, along with communities' perception of climate, and forest vulnerability based on a bottom-up indicator-based approach using IPCC assessment protocol was employed in this investigation. The result is presented in two sections, the first section discusses the historical climate trend and communities' perceptions while forest vulnerability is discussed in the second section.

3.1. Historical Climate Trends

According to INRM multi-model ensembles (RCP 4.5), from 1951 to 2018, the average rainfall of the district decreased with low confidence for pre-monsoon, post-monsoon, and winter months, while the decrease was more significant in monsoon months. In contrast, very heavy precipitation and simple rainfall intensity index have been increased. The minimum temperature for winter, pre-monsoon, and monsoon seasons indicated an increasing trend with low confidence. At the same time, the post-monsoon minimum temperature is rising with high confidence. The average maximum temperature for winter and monsoon decreased with low confidence, while the pre- and post-monsoon maximum temperature increased. The district's maximum and minimum daytime temperatures indicated increasing trends (Figure 2).

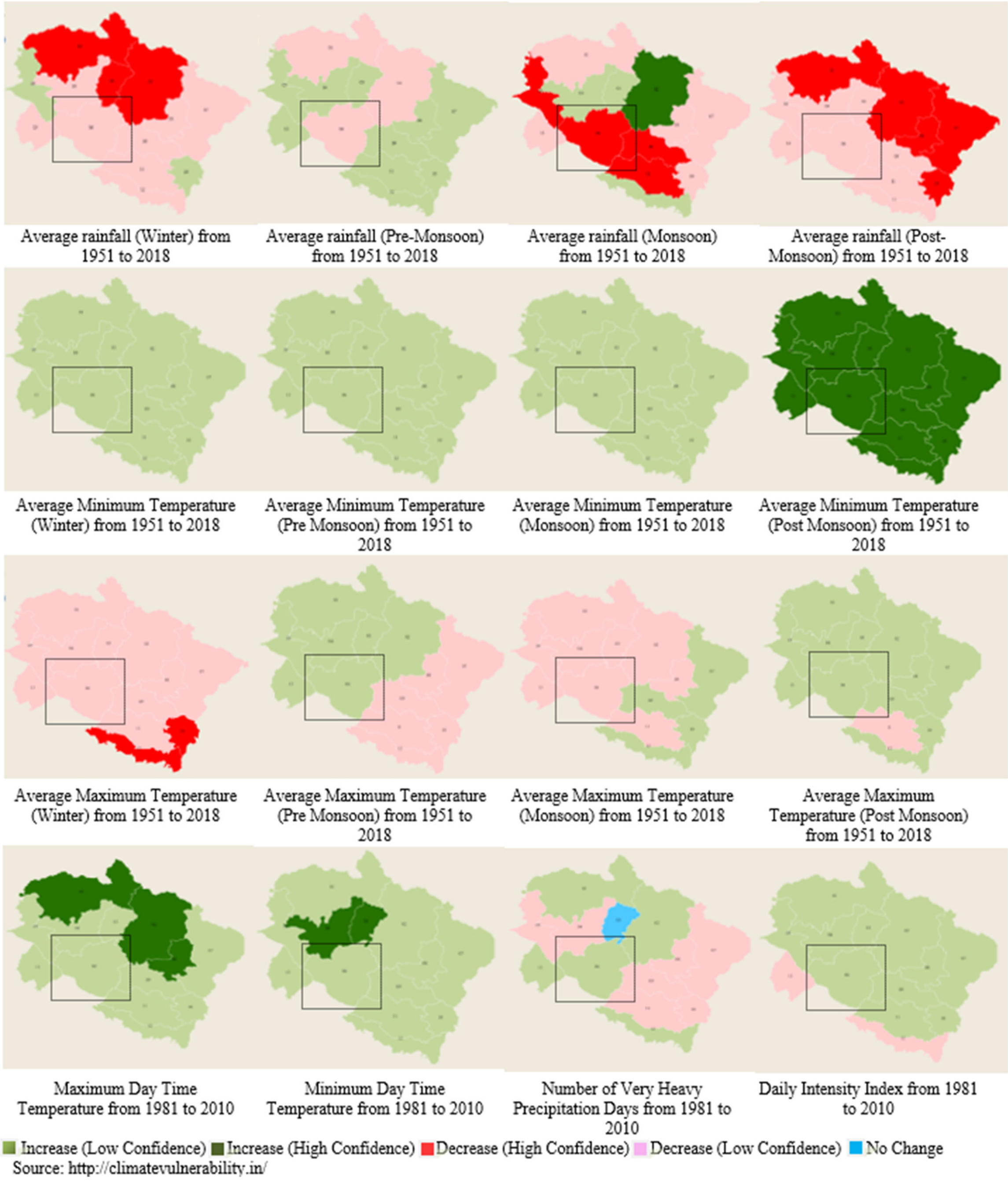

Average rainfall (Winter) from 1951 to 2018
Average rainfall (Pre-Monsoon) from 1951 to 2018
Average rainfall (Monsoon) from 1951 to 2018
Average rainfall (Post-Monsoon) from 1951 to 2018
Average Minimum Temperature (Winter) from 1951 to 2018
Average Minimum Temperature (Pre Monsoon) from 1951 to 2018
Average Minimum Temperature (Monsoon) from 1951 to 2018
Average Minimum Temperature (Post Monsoon) from 1951 to 2018
Average Maximum Temperature (Winter) from 1951 to 2018
Average Maximum Temperature (Pre Monsoon) from 1951 to 2018
Average Maximum Temperature (Monsoon) from 1951 to 2018
Average Maximum Temperature (Post Monsoon) from 1951 to 2018
Maximum Day Time Temperature from 1981 to 2010
Minimum Day Time Temperature from 1981 to 2010
Number of Very Heavy Precipitation Days from 1981 to 2010
Daily Intensity Index from 1981 to 2010
🟩 Increase (Low Confidence) 🟩 Increase (High Confidence) 🟥 Decrease (High Confidence) 🟪 Decrease (Low Confidence) 🟦 No Change
Source: http://climatevulnerability.in/

Figure 2. Climate trend in Uttarakhand highlighting study district in a box (district number 06).

3.1.1. Climate Perception

Further, communities' perception was also studied with the help of indicators. The indicators or set of information were normalized and converted into indices and finally assimilated into components of climate. Climate perception was recorded with the help of changes in the indicators of maximum and minimum temperature, rainfall, and extreme events over the previous 15–20 years.

3.1.2. Temperature Perception (Maximum and Minimum)

The local communities confirmed the variation in the district's climate. They noted that the climate was changing, with temperature increases and variations in rainfall (frequency and intensity). These were analyzed using a temperature index (A—0.76; B—0.45; C—0.87), rainfall index (A—0.17; B—0.42; C—0.53), and extreme event index (A—0.62; B—0.82; C—0.87). Each of the indices consisted of a set of indicators, with the temperature index consisting of 'increased summer temperature' and 'increased February-March temperature'. The most significant increases in summer temperature were reported in Zone C (0.90), followed by Zone A (0.76) and Zone B (0.10). Official data for India (MoEF, 2012 [130]) have also reported substantial increases in temperature in the Himalayan region. The study district's mean, minimum and maximum temperatures, both annually and during the summer, indicate increasing trends (Jha et al., 2020 [131]). Furthermore, this increasing trend has been highlighted above 4000 m asl. in eastern Nepal and Tibet (Shrestha and Devkota 2010 [132]). The overall temperature in the Himalayan area is expected to rise at a pace of 0.06 degrees Celsius every year (Shrestha et al., 2012 [133]).

The most significant increases in February-March temperature were reported in Zone C (0.83), followed by Zone B (0.80) and Zone A (0.75). Indeed, a previous study has similarly found an increase in January-March temperatures in the Eastern Himalayan area (Sharma 2012 [134]). Jha et al. (2020) [131] reported that winter temperatures in the Pauri district are also increasing aside from the annual average. Increased winter temperatures in the Himalayas directly influence the permafrost cover and snow melting rate. Accelerated melting will likely increase river discharge, indirectly affecting water availability (Nepal and Shrestha 2015 [135]). Based on the current warming and GHG emission rates (ICIMOD, 2019 [136]), the Himalayas could lose two-thirds of its glaciers by 2100.

3.1.3. Rainfall Perception

The rainfall index, comprising a decreased number of rainy days and delayed monsoon rain, reflected the most significant overall variation in rainfall in Zone C (0.53), followed by Zone B (0.42), and Zone A (0.17), indicating an increasing trend from Zone A to C. The scores for decreased number of rainy days and delayed monsoon rain were 0.23 and 0.11 (Zone A), 0.54 and 0.29 (Zone B), and 0.71 and 0.34 (Zone C).

The World Bank (2012) [137] has reported a decline in monsoon rainfall and an increase in the frequency of severe rainfall events since the 1950s. Several studies in the Indian Himalayan region suggest temperature increases, more seasonal variations, milder winters, and variations in the magnitude, intensity, and duration of precipitation (Goswami et al., 2006 [138]; Sharma et al., 2009 [127]; Xu et al., 2009 [139]; Pandey and Jha, 2011 [49]; Pandey et al., 2017 [56]; Jha 2020 [8], Jha et al., 2020 [131]).

3.1.4. Extreme Events Perception

Meanwhile, the extreme event index was composed of increasing temperatures that triggered forest fires, increased temperature and drought incidence, increased rainfall intensity and frequency, and unexpected, extreme climatic events. Previous research reporting climatic data (Jha et al., 2020 [131]) and residents' perceptions of climate variance in the district have verified this (Rao et al., 2018 [140]; Jha et al., 2020 [131]). Furthermore, official statistics from India (MoEF, 2012 [130]) have revealed visible alterations in the Himalayan climate pattern.

Scores were reported in direct proportion to the altitude (Zone A—0.62; B—0.82; C—0.87). The first two indicators, higher incidence of forest fire and drought owing to increasing temperature, followed a similar pattern, with higher scores in Zone C (0.86 and 0.89) than in Zone B (0.73 and 0.67) and Zone A (0.50 and 0.12). Zone A (0.99) had higher scores for increased rainfall intensity and decreased rainfall frequency than Zone B (0.92) and Zone C (0.92). (0.77). Finally, extreme climatic event uncertainty was found to be almost equivalent in Zone B (0.96) and C (0.96) but greater in Zone A. (0.85) (Table 3).

With increasing altitude, the overall impact increased (Zone A—0.51; B—0.56; C—0.75). The increased effect in Zone C might likely be attributed to its closeness to and reliance on the climate-sensitive natural support system. IPCC (2014) [89] clearly states that natural support systems are relatively more vulnerable to climate change, making those dependent on vulnerable ecosystems more susceptible. Moreover, variation in climate parameters and its uncertainty also alters composition and structure (Gaire et al., 2017 [141]), phenology (Bajpai et al., 2016 [142]), budburst and flowering (Amano et al., 2010 [143]), and forest productivity (Alekhya et al., 2015 [28]).

3.2. Forest Vulnerability

The forest vulnerability index, which includes characteristics or dimensions of vulnerability such as sensitivity and adaptive capacity, was employed in this investigation.

3.2.1. Sensitivity

Sensitivity along the altitudinal gradient in the Pauri district was assessed using the natural resource degradation index and resource susceptibility index (Figure 3). Natural resource degradation was reported to be very similar in Zone B (0.82) and C (0.81) and comparatively less in Zone A (0.54). This index consists of grazing (%), time spent collecting fodder and fuelwood, distance travelled for resource collection, especially fodder and fuelwood, forest fire frequency and intensity, and lopped trees (number/hectare). Grazing was a significant cause of degradation and was found in similar volumes (0.667) in all three zones (A to C). Furthermore, forest degradation reduced services and impacted hydrological functioning by contributing to rainfall interception, infiltration, purification, evapotranspiration, and groundwater recharge (Locatelli, 2016 [144]).

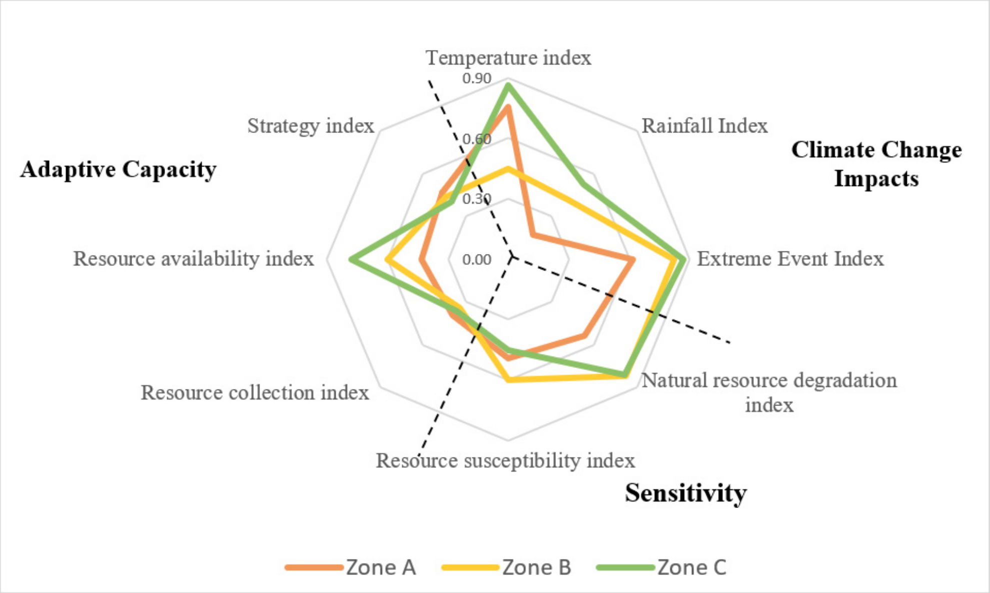


Figure 3. Indices of climate change impacts, sensitivity, and adaptive capacity along the altitudinal gradient in the Pauri district.

The increasing demand for resources and their extensive harvest undermines the forest in the designated zones. Zone C (5 to 6 h/day, up from 2 to 3 h/day) experienced the largest increase in average time spent collecting fodder and fuelwood compared to Zone B (3 to 4 h/day, up from 1.5 to 3 h/day) and A (1 to 1.5 h/day, up from 0.5 to 1.2 h/day). Indeed, it is probable that the time spent on collection (fodder and fuelwood) has increased due to the increased travel distance required. In the past, respondents traveled around 3–5 km/day to collect resources, but the distance has grown to 0–4 km/day. Zone C (7–10 km/day, up from 3–5 km/day) had the largest increase, and overall, the normalized values for time spent and distance traveled were highest in Zone C (0.96 and 0.91), followed by Zone B (0.90 and 0.91) and Zone A (0.50 and 0.49) (Table 3).

Zone B (0.95) had the most increased frequency of forest fires, followed by Zone C (0.87) and Zone A (0.48), whereas Zone C (1.00) had the highest increased intensity, followed by Zone B (0.90) and Zone A (0.48). Pauri is among the districts most affected by these fires, with approximately 38% of the state's forest fires reported to have occurred here. The Kotdwar block of the district had the highest number of forest fires (712) (Hussain, 2018) [145], the bulk of which were human-caused for reasons such as encouraging fodder gathering (Jha et al., 2018 [22]).

The number of lopped trees was determined along an altitudinal gradient, with Zone A (0.65) being the most, followed by Zone B (0.61) and Zone C (0.48). Forest degradation is said to be exacerbated by the livelihood concerns of millions of impoverished people living in and around the forest (Maikhuri et al., 2001 [146]; Davidar et al., 2010 [147]), which is believed to be highest in Zone C due to greater dependency.

Zone B (0.60) has the highest score for the resource susceptibility index, followed by Zone A (0.49) and Zone C (0.45). This index was composed of seven indicators: concentration of dominance (CD), evenness, fire-susceptible species, regeneration, dominant species, forest age, and reliance on natural water resources. CD was found to be greater in Zone B (0.63) than in Zone C (0.54) and A (0.37), while evenness was found to be quite comparable in Zone A (0.51) and C (0.53), and lower in Zone B (0.45). Fire-susceptible species decreased with altitude; the maximum number was recorded in Zone A (0.620). The dominant forest tree species in Zone A and B were susceptible to fire, as demonstrated by Jha et al. (2018, 2020) [22,131]. Indeed, the significance of forest composition to fire occurrences has been studied previously and was initially highlighted by Shank and Noorie (1950) [148]. The Himalayan area has seen a 90 percent rise in forest fires and increased numbers of fires started intentionally (Levine et al., 1999) [149].

The area under forest was recorded highest in Zone B (0.87), followed by Zone C (0.59) and Zone A (0.42). Regeneration was limited in Zone A (0.87) and B (0.90) due to the dominance of *Pinus roxburghii,* while more effective regeneration was reported in the oak forests of Zone C (0.54). The forests of Zone A (0.50) and B (0.50) were evenly aged, and slight variation was recorded in Zone C (0.40). Other significant determinants of vulnerability can be found in water availability, accessibility (Rajesh et al., 2014 [150]), and storage (Connor 2015) [151]. It may be anticipated that households who rely on a natural water supply (e.g., river, spring, etc.) are more sensitive to rising climate catastrophe and related repercussions. Dependence on a natural water source was found to be highest in Zone C (0.37), followed by Zone B (0.29), with Zone A (0.14) being nearly half that of Zone B (Table 3). Deforestation, rising global temperature, intensified precipitation, and seasonal droughts are other site-specific variables related to water scarcity (Tambe et al., 2011) [152], all of which contribute to natural springs drying up and stream base flow dropping (Rawat et al., 2011) [153].

3.2.2. Adaptive Capacity

Forests provide a broad set of goods and services for sustenance in the mountains (Jha et al., 2018 [22]) and strengthen their capacity to withstand changes. Adaptive capacity in the Pauri district was assessed using 03 indices and 09 indicators. Greater adaptive capacity was reported in Zone A, followed by Zone B and C. The resource collection index consists of fodder and fuelwood collection and non-timber forest products (NTFPs) (Figure 3). The majority of the households in the study area collect fodder and fuelwood from the forest; the collection was reported to be slightly higher in Zone C than in Zone A and Zone B, and fuelwood was found to be preferable for cooking, water heating, space heating, etc., for economic reasons (Kanagawa and Nakata, 2007) [154]. Extraction of fuelwood was reported to be higher in winter (November to February) due to higher consumption levels and limited labor requirements in agriculture and allied sectors, while minimum extraction was reported in the monsoon season due to the availability of green fodder in close proximity (Bhatt and Sachan 2004) [155]. Dependence on the collection of NTFPs was significantly less throughout the district, although a few households in each zone reported collecting NTFPs from a nearby forest. NTFP accessibility and collection were lowest in Zone A, producing a higher normalized score for the zone. At the same time, the harvest of NTFPs was comparatively superior in Zone B and C.

The availability of resources, i.e., fodder and fuelwood, was found to be highest in Zone A, followed by Zone B and C, with more dependents in Zone B and C than in Zone A. A higher number of dependents indicates greater competition and a lower proportion of households acquiring sufficient fodder and fuelwood. Indeed, Jha et al. (2020) [131] have reported similar findings about resource accessibility, availability, and sufficiency. The strategy index, which comprised six indications, was determined to be greatest in Zone C, followed by Zone B and Zone A. Zone C had the most individual trees (number/hectare), followed by Zone B and Zone A; Zone C also had the highest density of trees. The dense forest in Zone A had a stem density of 716 trees/ha, which is within the range described by Sharma et al. (2011) [156] for Indian forests and Saxena and Singh (1982) [157] for a forest in the Kumaun Himalaya. However, this result was lower than the range reported by Gairola et al. (2011) [158] for a forest in the Western Himalayas. The aggregate tree density in Zone B varied from 286 to 907 trees/ha, and the tree density of Quercus leucotrichophora (273 trees/ha) in Zone B (1200–1800 m asl) was lower than reported by Gairola et al. (2011) [158] and Pandey (2001) [159]. The dominating species in Zone C was found to be *Quercus leucotrichophora*, a dominance at high altitudes that have also been documented by Sharma et al. (2009) [127] (Garhwal Himalaya). Detailed analysis on individuals (trees/hectare), above-ground biomass density (AGBD), species richness, and biodiversity in dense, moderately dense, and open forests in the selected zones (A, B, C) of the study district is presented in Figure 4.

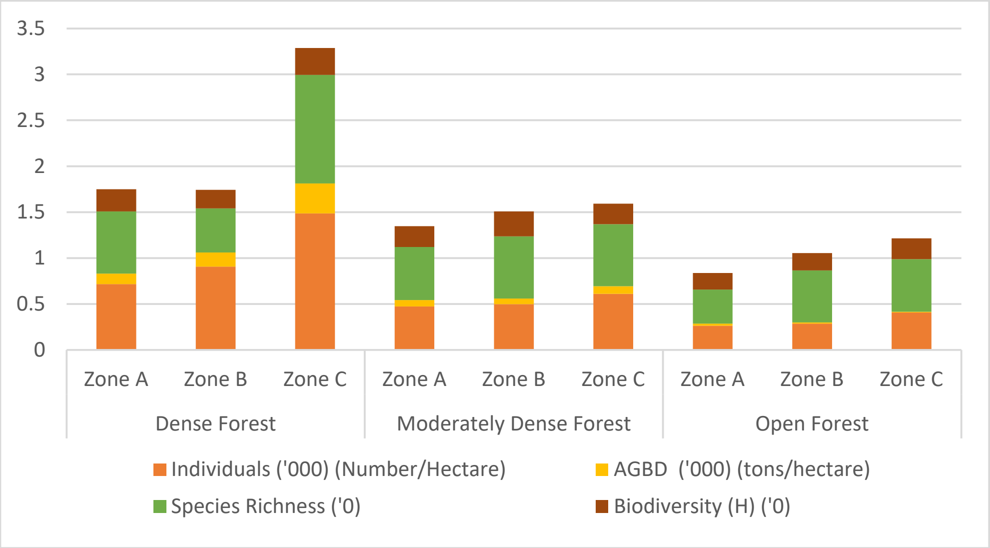


Figure 4. Individuals, above-ground biomass density (AGBD), species richness, and biodiversity in dense, moderately dense, and open forests along the altitudinal gradient of the Pauri district.

The biomass production increased with altitude, from 43 tons (t)/ha in Zone A, to 47.50 t/ha in Zone B, to 88 t/ha in Zone C. Biomass production by *Pinus roxburghii* in Zone A (112 t/ha) was shown to be more than that indicated by Rana (1985) [160], and similar to that reported by Chaturvedi and Singh (1986) [161] and Chaturvedi (1983) [162] for the Kumaun region of India. *Pinus roxburghii* contributed more than 57 percent of the biomass in Zone B. The above-ground biomass density for *Pinus roxburghii* (153.44 t/ha) was lower in the present study than that reported by Gairola et al. (2011) [158] (183.05 t/ha) and Kumar et al. (2019) [163] (213 t/ha) for Pauri Garhwal. Haripriya (2000) [164], on the other hand, observed an even lower above-ground biomass density for *Pinus roxburghii* (69.50 t/ha). The highest above-ground biomass density in Zone C was recorded for *Cedrus deodara*. In a previous study, Sundriyal et al. (1994) [165] reported an above-ground biomass density range of 368–682 t/ha in the higher altitude forests of Eastern Himalaya. Moreover, the above-ground biomass density estimated for *Cedrus deodara* forest was lower than that reported by Sharma et al. (2010) [166] for the Garhwal forest.

Species richness and biodiversity were reported to be higher in Zone C than Zone B and Zone A. Species richness increased with the density of the forest, suggesting that dense forest has the highest degree of species richness. According to Singh et al. (1994) [167], the maximum species richness was found in *Pinus roxburghii* mixed broadleaf forests, whereas the lowest was found in high-elevation forests. The species richness value observed in this study did not differ significantly from the values reported by Semwal et al. (2010) [168] and Raturi (2012) [169].

The highest biodiversity was found in the dense forest of Zone C, followed by the moderately dense forest of Zone B. Indeed, similar findings on biodiversity and species richness have been presented by Kumar and Ram (2005) [170] and Pandey (2003) [171] in Kumaun Himalaya. However, the values recorded in the present study were higher than those of Sanjeev and Sankhayan (2006) [172] in Mussoorie Dehradun, Dhar et, al. (1997) [173], and Kumar and Ram (2005) [170] in Kumaun Himalaya, and lower than those of Gairola et al. (2011) [158] in Garhwal Himalaya. The lowest diversity value was found in Zone A. This lower degree of biodiversity might be attributed to high anthropogenic disturbances. Semwal et al. (2010) [168] reported a relatively low species diversity in the Himalayan forest, while a higher range was reported by Singh and Singh (1987) [174] in the Chir pine mixed forest of Central Himalaya, by Rawat and Chandhok (2009) [175], and by Raturi (2012) [169] for temperate mixed forests and sub-tropical forests. Biodiversity can also vary based on biogeography, habitat, and disturbance (Sagar et al., 2003 [176]). According to Srivastava et al. (2008) [177], community characteristics can differ in aspect, slope, and altitude, even within the same vegetation type.

Availability of fodder during the scarce season was reported to be about similar in Zone A and C and lower in Zone B, but access to fuelwood during the scarce season was found to decrease with altitude. As previously discussed, most of the households in this region possess traditional livestock, which is directly or indirectly dependent on the forest for fodder. The storage of fodder was common traditional practice for the villagers, who were generally found to collect more fodder after the monsoon and then store it for the fodder-scarce season. The fodder storage practice was generally more prevalent in Zone C, which was believed to be one of the best solutions to combat fodder scarcity. Furthermore, several strategies have been adopted to reduce forest dependency in Zone A, including adopting efficient technologies. However, relatively few alternatives and strategies for fodder scarcity were adopted in Zone B and C. Almost all villages surveyed had fuelwood alternatives, i.e., LPG, while fuelwood remained the most economical choice for cooking, water, and space heating. Fuelwood extraction increased in winter (November to February) due to higher consumption and limited labor requirements in agriculture and allied sectors. There was also a tendency to store fuelwood for the upcoming months. On the other hand, minimum fuelwood extraction was reported in the monsoon season. Overall, there were fewer strategies to combat fuelwood scarcity in Zone B and C.

3.2.3. Vulnerability

The highest vulnerability was recorded in Zone B due to higher sensitivity and lower adaptive capacity (Figure 5). The households in Zone B disproportionately relied on the forest to sustain their livelihood. Climate change threatens the Himalayan Forest, and the dominance of *Pinus roxburghii* exacerbates sensitivity and increases vulnerability. Limited understory vegetation in pine forests restricts the availability of fodder and fuelwood and constitutes a potential cause of lopping. Moreover, pine needles are highly susceptible to forest fires, and the incidence of forest fires is comparatively higher in this zone. The possession of livestock is a traditional practice, and most households will have 2–3 livestock and subsequently depend on the nearby forest for fodder and grazing. The higher anthropogenic pressure for resource collection is a prime cause of forest degradation, indicated by the increased distances between the forest and the villages and the increased time spent collecting forest resources. The anthropogenic pressure then alters the zone's biodiversity, richness, and biomass and is reflected by a lower adaptive capacity.

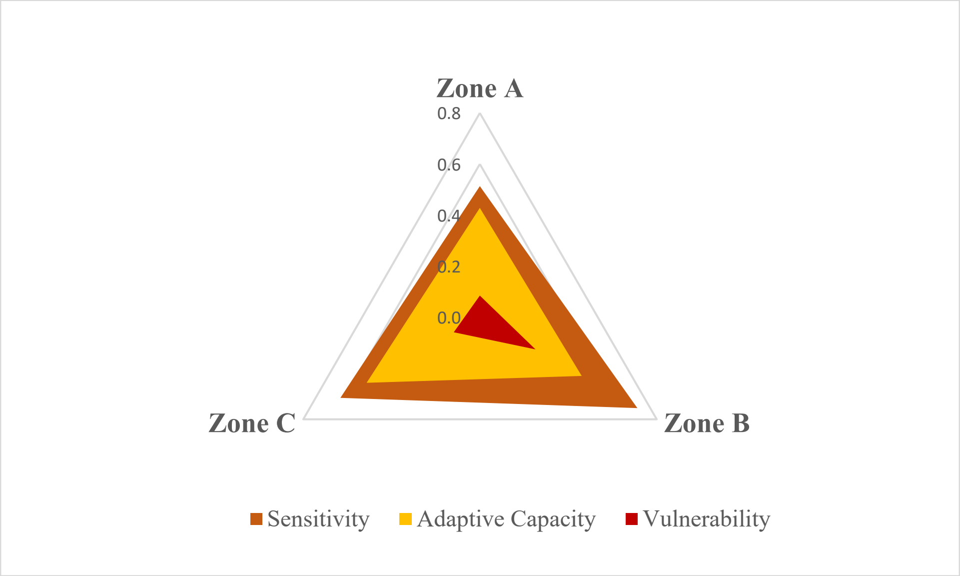


Figure 5. Sensitivity, adaptive capacity, and vulnerability of the Himalayan forest along the altitudinal gradient in the Pauri district.

The vulnerability in Zone C is lower than in Zone B and higher than in Zone A (Figure 5). The vulnerability of Zone C is attributed to the availability, collection, and degradation of natural resources, while the zone has a comparatively better adaptive capacity to withstand climate change. Although this zone reports sufficient availability of natural resources, they are not easily accessible, and those that are accessible are currently degrading due to higher anthropogenic pressures. The lowest vulnerability was reported in Zone A, owing to lower dependency on natural resources and availability of alternatives representing a better adaptive capacity.

4. Conclusions

It is evident that the temperature (maximum and minimum) of the district has increased, and rainfall has decreased in the last few decades. The communities along the altitudinal gradient also accepted and identified the changes in the climate. The greater ability of Zone C communities to identify changes is thought to be due to their geophysical position; they live at a higher altitude, mostly in cold weather condition, and thus can quickly recognize variations in climate such as prolonged summer and variation in temperature range.

Lower natural resource degradation in Zone A is attributed to less reliance on natural resources as well as combatively active law enforcement. The higher altitude and some inaccessible pockets of the mountain limit the reach of forest officials, while at the same time, natural resource alternatives are limited, and communities are also dependent on available resources for sustaining livelihood, so degradation is greater. The forest is a renewable resource, and the degradation could be reduced, and services restored, but biodiversity loss is irreversible. Thus, conservation-centric forest management, with maximized involvement of local communities in collaboration with research or academic institutions and forest departments, is likely to be highly effective. Forests in Uttarakhand are under great pressure (natural and anthropogenic), demanding afforestation programs with site-specific and climate-adapted multi-species initiatives and protective measures for species-rich ecosystems. Community-owned biodiversity hotspots should be more emphasized, such as the *Nagdev*, *Ekeshwer*, and *Tarkeshwer* sacred groves in the study district, and *Taxus baccata* forest of Uttarkashi district; the local community should be made aware of the need for ecological conservation. This approach can promote the sustainable extraction (time, part, quantity, etc.) of forest resources, which is currently one of the major drivers of forest degradation. The larger area covered by a conservation-centric plan in an altitudinal plan may limit the supply of forest produce; additionally, the inclusion of a community-centric forest management plan may contribute to meeting demand. As a result, it is critical to adopt and implement a forest management plan that incorporates conservation and a community-centric approach.

Establishing fodder banks and up-gradating energy consumption patterns (e.g., using improved smokeless stove (chulha), solar cookers, pine bricks, etc.) in Zone B and C could, to a certain extent, reduce dependency on the forest. Agroforestry practices with particular emphasis on fast-growing, demand-oriented tree species in Zone B possess significant potential for reducing the gap between supply and demand and could be an important mitigation strategy. Furthermore, all the zones require upgraded fodder storage techniques (hay and silage), particularly Zone C. The forests of Uttarakhand are also highly vulnerable to forest fires, which are major sources of GHG and, therefore, contributors to reductions in the terrestrial carbon sink. Consequently, there is a need to introduce fire management techniques and innovative monitoring and warning approaches in as little time as possible, which should be included in the policy of the Government of Uttarakhand.

The results revealed that collecting fuelwood and fodder was common in the district. Maximum degradation was recorded in the moderately dense forest of Zone B due to anthropogenic disturbances such as lopping, grazing, fodder, and fuelwood collection. Furthermore, the forest in Zone A and B was dominated by *Pinus roxburghii*, which hinders understory regeneration. The maximum above-ground biomass density in the forest of Zone C was recorded in *Cedrus deodara*. Overall, maximum above-ground biomass density was recorded in the dense forest of Zone C. The variation in biomass at different altitudinal ranges was attributed to forest type, species, age, other environmental factors, and edaphic factors. Therefore, vulnerability reduction strategies should be centered on developing natural capital and tailored to a specific sector and site (i.e., altitude). Development of the natural resource base should be targeted throughout the study district, strengthening alternatives to natural resources prioritized in Zone B.

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References

1. Rasul, G. Food, water, and energy security in South Asia: A nexus perspective from the Hindu Kush Himalayan region. *Environ. Sci. Policy* **2014**, *39*, 35–48. [CrossRef]
2. Badola, R.; Hussain, S.A.; Dobriyal, P.; Barthwal, S. Assessing the effectiveness of policies in sustaining and promoting ecosystem services in the Indian Himalayas. *Int. J. Biodivers. Sci. Ecosyst. Serv. Manag.* **2015**, *11*, 216–224. [CrossRef]
3. Government of Uttarakhand (GoU). *Uttarakhand Action Plan on Climate Change (UAPCC)*; GoU: Dehradun, India, 2014.
4. Hoy, A.; Katel, O.; Thapa, P.; Dendup, N.; Matschullat, J. Climatic changes and their impact on socio-economic sectors in the Bhutan Himalayas: An implementation strategy. *Reg. Environ. Chang.* **2016**, *16*, 1401–1415. [CrossRef]
5. Indian Network for Climate Change Assessment. *Climate Change and India: A 4X4 Assessment a Sectoral and Regional Analysis for 2030s*; Government of India: New Delhi, India, 2010.
6. Chaturvedi, R.K.; Ranjith, G.; Jayaraman, M. Impact of climate change on Indian forests: A dynamic vegetation modeling approach. *Mitig. Adapt. Strateg. Glob. Chang.* **2011**, *16*, 119–142. [CrossRef]
7. Singh, R.B.; Hietala, R. *Livelihood Security in Northwestern Himalaya—Case Studies from Changing Socio-Economic Environments in Himachal Pradesh, India. Advances in Geographical and Environmental Sciences (AGES)*; Springer: Tokyo, Japan, 2014.
8. Jha, S.K. Assessment of Climate Change Vulnerability and Adaptation of Forest-Dependent Communities in Western Himalaya. Ph.D. Thesis, DoF&NR, HNB-GU, Srinagar, India, 2020.
9. Kumar, P.; Kotlarski, S.; Moseley, C.; Sieck, K.; Frey, H.; Stoffel, M.; Jacob, D. Response of Karakoram-Himalayan glaciers to climate variability and climatic change: A regional climate model assessment. *Geophys. Res. Lett.* **2015**, *42*, 1818–1825. [CrossRef]
10. Li, H.; Xu, C.Y.; Beldring, S.; Tallaksen, L.M.; Jain, S.K. Water resources under climate change in Himalayan Basins. *Water Resour. Manag.* **2016**, *30*, 843–859. [CrossRef]
11. Palazzoli, I.; Maskey, S.; Uhlenbrook, S.; Nana, E.; Bocchiola, D. Impact of prospective climate change on water resources and crop yields in the Indrawati basin, Nepal. *Agric. Syst.* **2015**, *133*, 143–157. [CrossRef]
12. Jethi, R.; Joshi, K.; Chandra, N. Toward climate change and community-based adaptation-mitigation strategies in hill agriculture. In *Conservation Agriculture: An Approach to Combat Climate Change in Indian Himalaya*; Bisht, J.K., Meena, V.S., Mishra, P.K., Pattanayak, A., Eds.; Springer: Singapore, 2016; pp. 185–202.
13. ADB. *Climate Change Adaptation in Himachal Pradesh: Sustainable Strategies for Water Resources*; ADB: Mandaluyong, Philippines, 2010; ISBN 978-92-9092-060-1.
14. Wani, A.M.; Raj, A.J.; Kanwar, M. Impact of climate change on forests of Eastern Himalayas and adaptation strategies for combating it. *Int. J. Agric. For.* **2013**, *3*, 98–104.
15. Lewis, S.L. Tropical forests and the changing earth system. *Philos. Trans. R. Soc. B* **2006**, *361*, 195–210. [CrossRef]
16. IPCC. *Climate Change 2007: Synthesis Report*; Cambridge University Press: Cambridge, UK, 2007. Available online: https://www.ipcc.ch/publications_and_data/ar4/syr/en/mains1.html (accessed on 20 December 2021).
17. Das, H.P. Adaptation strategies required to reduce vulnerability in agriculture and forestry to climate change, climate variability and climate extremes. In *World Meteorological Organization (WMO). Management Strategies in Agriculture and Forestry for Mitigation of Greenhouse Gas Emissions and Adaptation to Climate Variability and Climate Change*; Report of CAgM Working Group. Technical Note No. 202, WMO No. 969; WMO: Geneva, Switzerland, 2004; pp. 41–92.
18. Kala, C.P. Deluge, disaster and development in Uttarakhand Himalayan region of India: Challenges and lessons for disaster management. *Int. J. Disaster Risk Reduct.* **2014**, *8*, 143–152. [CrossRef]
19. Ahmad, A.; Rawat, J.S.; Rai, S.C. An analysis of the himalayan environment and guidelines for its management and ecologically sustainable development. *Environmentalist* **1990**, *10*, 281–298. [CrossRef]
20. Ravindranath, N.H.; Joshi, N.V.; Sukumar, R. Impact of climate change on forests in India. *Curr. Sci.* **2006**, *90*, 354–361.
21. Jadin, I.; Meyfroidt, P.; Lambin, E.F. Forest protection and economic development by offshoring wood extraction: Bhutan's clean development path. *Reg. Environ. Chang.* **2016**, *16*, 401–415. [CrossRef]
22. Jha, S.K.; Jana, P.; Negi, A.K.; Negi, R.S. Livelihood Vulnerability Associated with Forest Fire in Pauri-Garhwal, Western Himalaya. *Open Ecol. J.* **2018**, *11*, 62–74. [CrossRef]
23. Sharma, L.N.; Vetaas, O.R. Does agroforestry conserve trees? A comparison of tree species diversity between farmland and forest in mid-hills of central Himalaya. *Biodivers. Conserv.* **2015**, *24*, 2047–2061. [CrossRef]
24. Bruggeman, D.; Meyfroidt, P.; Lambin, E.F. Forest cover changes in Bhutan: Revisiting the forest transition. *Appl. Geogr.* **2016**, *67*, 49–66. [CrossRef]
25. Upgupta, S.; Sharma, J.; Jayaraman, M.; Kumar, V.; Ravindranath, N.H. Climate change impact and vulnerability assessment of forests in the Indian Western Himalayan region: A case study of Himachal Pradesh, India. *Clim. Risk Manag.* **2015**, *10*, 63–76. [CrossRef]
26. Chakraborty, A.; Joshi, P.K.; Sachdeva, K. Predicting distribution of major forest tree species to potential impacts of climate change in the central Himalayan region. *Ecol. Eng.* **2016**, *97*, 593–609. [CrossRef]

27. Giam, X. Global biodiversity loss from tropical deforestation. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 5775–5777. [CrossRef]
28. Alekhya, V.V.L.; Pujar, G.S.; Jha, C.S.; Dadhwal, V.K. Simulation of vegetation dynamics in Himalaya using dynamic global vegetation model. *Trop. Ecol.* **2015**, *56*, 219–231.
29. Sharma, J.; Ravindranath, N.H. Vulnerability and Risk Assessment: Framework, Methods and Guideline. Indian Institute of Science. 2018. Available online: http://ihcap.in/?media_dl=1519 (accessed on 20 December 2021).
30. Kumar, M.; Kumar, R.; Konsam, B.; Sheikh, M.A.; Pandey, R. Above-And Below-Ground Biomass Production in *Pinus roxburghii* Forests along Altitudes in Garhwal Himalaya, India. *Curr. Sci.* **2019**, *116*. [CrossRef]
31. Cutter, S.L.; Finch, C. Temporal and spatial changes in social vulnerability to natural hazards. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 2301–2306. [CrossRef] [PubMed]
32. Eriksen, S.H.; Kelly, P.M. Developing credible vulnerability indicators for climate adaptation policy assessment. *Mitig. Adapt. Strateg. Glob. Chang.* **2007**, *12*, 495–524. [CrossRef]
33. Kaly, U.L.; Briguglio, L.; McLeod, H.; Schmall, S.; Pratt, C.; Pal, R. SOPAC Technical Report. In Proceedings of the Environmental Vulnerability Index (EVI) Think Tank, Pacific Harbour, Fiji, 7–10 September 1999.
34. Lonergan, S.; Gustavson, K.; Carter, B. The index of human insecurity. *AVISO* **2000**, *6*, 1–7.
35. Prescott-Allen, R. *The Well-Being of Nations*; Island Press and International Development Research Centre: Washington, DC, USA, 2001.
36. World Economic Forum. *Environmental Sustainability Index: An Initiative of the Global Leaders for Tomorrow Environment Task Force*; World Economic Forum: Cologny, Switzerland, 2002.
37. Sullivan, C. Calculating a Water Poverty Index. *World Dev.* **2002**, *30*, 1195–1210. [CrossRef]
38. Brooks, N.; Adger, W.N. *Country Level Risk Measures of Climate-Related Natural Disasters and Implications for Adaptation to Climate Change*; Tyndall Centre for Climate Change Research: Norwich, UK, 2003.
39. Adger, W.N.; Brooks, N.; Kelly, M.; Bentham, S.; Eriksen, S. *New Indicators of Vulnerability and Adaptive Capacity*; Technical Report 7; Tyndall Centre for Climate Change Research, University of East Anglia: Norwich, UK, 2004.
40. Vincent, K. *Creating an Index of Social Vulnerability to Climate Change for Africa Tyndall*; Working Paper 56; Centre for Climate Change Research: Norwich, UK, 2004.
41. Adger, W.N.; Vincent, K. Uncertainty in adaptive capacity. *Comptes Rendus Geosci.* **2005**, 399–410. [CrossRef]
42. Esty, D.C.; Levy, M.; Srebotnjak, T.; de-Sherbinin, A. *Environmental Sustainability Index: Benchmarking National Environmental Stewardship*; Yale Center for Environmental Law & Policy: New Haven, CT, USA, 2005.
43. Cardona, O.D. Indicators of Disaster Risk and Risk Management-Program for Latin America and the Caribbean: Summary Report, Inter-American Development Bank, Department of Sustainable Development, Washington. 2005. Available online: http://idea.unalmzl.edu.co (accessed on 17 September 2022).
44. UNISDR. *Living with Risk*; United Nations International Strategy for Disaster Reduction: Geneva, Switzerland, 2004.
45. UNDP. The Human Development Concept. 2008. Available online: http://hdr.undp.org/en/humandev/ (accessed on 7 December 2017).
46. Hahn, M.B.; Riederer, A.M.; Foster, S.O. The Livelihood Vulnerability Index: A pragmatic approach to assessing risks from climate variability and change—A case study in Mozambique. *Glob. Environ. Chang.* **2009**, *19*, 74–88. [CrossRef]
47. Vincent, K.; Cull, T. A Household Social Vulnerability Index (HSVI) for Evaluating Adaptation Projects in Developing Countries. In Proceedings of the PEGNet Conference 2010: Policies to Foster and Sustain Equitable Development in Times of Crises, Midrand, South Africa, 2–3 September 2010.
48. Urothody, A.A.; Larsen, H.O. Measuring climate change vulnerability: A comparison of two indexes. *Banko Jankari* **2010**, *20*, 9–16. [CrossRef]
49. Pandey, R.; Jha, S.K. Climate vulnerability index—Measure of climate change vulnerability to communities: A case of rural Lower Himalaya, India. *Mitig. Adapt. Strateg. Glob. Chang.* **2011**, *17*, 487–506. [CrossRef]
50. Gerlitz, J.Y.; Banerjee, S.; Hoermann, B.; Hunzai, K.; Macchi, M.; Tuladhar, S. *Poverty and Vulnerability Assessment—A Survey Instrument for the Hindu Kush Himalayas*; Report; ICIMOD: Lalitpur, Nepal, 2014.
51. Aryal, S.; Cockfield, G.; Maraseni, T.N. Vulnerability of Himalayan transhumant communities to climate change. *Clim. Chang.* **2014**, *125*, 193–208. [CrossRef]
52. Gerlitz, J.Y.; Macchi, M.; Brooks, N.; Pandey, R.; Banerjee, S.; Jha, S.K. The Multidimensional Livelihood Vulnerability Index—An instrument to measure livelihood vulnerability to change in the Hindu Kush Himalayas. *Clim. Dev.* **2016**, *9*, 124–140. [CrossRef]
53. Pandey, R.; Maithani, N.; Aretano, R.; Zurlini, G.; Archie, K.M.; Gupta, A.K.; Pandey, V.P. Empirical assessment of adaptation to climate change impact of mountainous households: Development and application of Adaptation Capability Index. *J. Mt. Sci.* **2016**, *13*, 1503–1514. [CrossRef]
54. Pandey, R.; Meena, D.; Aretano, R.; Satpathy, S.; Semeraro, T.; Gupta, A.K.; Rawat, S.; Zurlini, G. Socio-ecological vulnerability of smallholders due to climate change in mountains: Agroforestry as an adaptation measure. *Chang. Adapt. Socio-Ecol. Syst.* **2015**, *2*, 26–41. [CrossRef]
55. Shukla, R.; Sachdeva, K.; Joshi, P.K. Inherent vulnerability of agricultural communities in Himalaya: A village-level hotspot analysis in the Uttarakhand state of India. *Appl. Geogr.* **2016**, *74*, 182–198. [CrossRef]
56. Pandey, R.; Jha, S.K.; Alatalo, J.M.; Archie, K.M.; Gupta, A.K. Sustainable livelihood framework-based indicators for assessing climate change vulnerability and adaptation for Himalayan communities. *Ecol. Indic.* **2017**, *79*, 338–346. [CrossRef]

57. Thakur, S.; Negi, V.S.; Pathak, R.; Dhyani, R.; Durgapal, K. Indicator based integrated vulnerability assessment of community forests in Indian west Himalaya. *For. Ecol. Manag.* **2020**, *497*, 117674. [CrossRef]
58. Jha, S.K.; Negi, A.K.; Alatalo, J.M.; Negi, R.S. Socio-ecological Vulnerability and Resilience of Mountain Communities residing in Capital-constrained Environments. *Mitig. Adapt. Strat. Glob. Chang.* **2021**, *26*, 38. [CrossRef]
59. DST. *Climate Vulnerability Assessment for Adaptation Planning in India Using a Common Framework*; Government of India: New Delhi, India, 2020.
60. Jha, S.K.; Negi, A.K.; Alatalo, J.M. Quantification of ecosystem services providing socio-economic benefits to customary owners of natural resources in Pauri, western Himalaya. *Curr. Res. Environ. Sustain.* **2022**, *4*, 100121. [CrossRef]
61. Harley, M.; Horrocks, L.; Hodgson, N. *Climate Change Vulnerability and Adaptation Indicators. European Topic Centre on Air and Climate Change (ETC/ACC) Technical Paper 2008/9*; European Environment Agency: Copenhagen, Denmark, 2008.
62. Sinha, B.; Jha, S.K. *Vulnerability and Capacity Assessment to Climate Change of Malwa-Madhya Pradesh*; Bishen Singh and Mahinder Pal Singh, Publisher and Distributor of Scientific Books: Dehradun, India, 2017.
63. Jha, S.K.; Mishra, S.; Sinha, B.; Alatalo, J.M.; Pandey, R. Rural development program in tribal region: A protocol for adaptation and addressing climate change vulnerability. *J. Rural Stud.* **2017**, *51*, 151–157. [CrossRef]
64. Gabor, T.; Griffith, T.K. The Assessment of Community Vulnerability to Acute Hazardous Materials Incidents. *J. Hazard. Mater.* **1980**, *3*, 323–339. [CrossRef]
65. Timmerman, P. *Vulnerability, Resilience and the Collapse of Society: A Review of Models and Possible Climatic Applications*; Institute for Environmental Studies, University of Toronto: Toronto, Canada, 1981.
66. UNDRO. *Natural Disasters and Vulnerability Analysis*; Office of the United Nations Disaster Relief Co-Ordinator: Geneva, Switzerland, 1982.
67. Susman, P.; O'Keefe, P.; Wisner, B. Global disasters: A radical interpretation. In *Interpretations of Calamity from the Viewpoint of Human Ecology*; Hewitt, K., Ed.; Allen and Unwin: Boston, MA, USA, 1984; pp. 264–283.
68. Pijawaka, K.D.; Radwan, A.E. Transportation of hazardous materials. Risk assessment and hazard management. *Dang. Prop. Int. Mater. Rep.* **1985**, *5*, 2–11.
69. Kates, R.W.; Ausubel, J.H.; Berberian, M. (Eds.) *SCOPE Report on Impact Assessments*; Wiley: Hoboken, NJ, USA, 1985.
70. Bogard, W.C. Bringing social theory to hazards research: Conditions and consequences of the mitigation of environmental hazards. *Sociol. Perspect.* **1988**, *31*, 147–168. [CrossRef]
71. Mitchell, J.K. Hazards research. In *Geography in America*; Gaile, G.L., Willmott, C.J., Eds.; Merill: Colombus, OH, USA, 1989; pp. 410–424.
72. Liverman, D.M. Drought impacts in Mexico: Climate, agriculture, technology, and land tenure in Sonora and Puebla. *Ann. Assoc. Am. Geogr.* **1990**, *80*, 49–72. [CrossRef]
73. Downing, T.E. Vulnerability to hunger in Africa: A climate change perspective. *Glob. Environ. Change* **1991**, *1*, 365–380. [CrossRef]
74. Dow, K. Exploring differences in our common future (s): The meaning of vulnerability to global environmental change. *Geoforum* **1992**, *23*, 417–436. [CrossRef]
75. Smith, K. *Environmental Hazards: Assessing Risk and Reducing Disaster*; Routledge: London, UK, 1992.
76. Alexander, D. *Natural Disasters*; Chapman and Hall: New York, NY, USA, 1993.
77. Cutter, S.L. *Living with Risk*; Edward Arnold: London, UK, 1993.
78. Watts, M.J.; Bohle, H.G. Hunger, famine and the space of vulnerability. *GeoJournal* **1993**, *30*, 117–125. [CrossRef]
79. Blaikie, P.; Cannon, T.; Davis, I.; Wisner, B. *At Risk: Natural Hazards, People's Vulnerability, and Disasters*; Routledge: London, UK, 1994; ISBN 9780415084772.
80. Bohle, H.G.; Downing, T.E.; Watts, M.J. Climate change and social vulnerability. Toward a sociology and geography of food insecurity. *Glob. Environ. Chang.* **1994**, *4*, 37–48. [CrossRef]
81. Dow, K.; Downing, T.E. *Vulnerability Research: Where Things Stand*; National Emergency Training Centre: Emmitsburg, MD, USA, 1995.
82. Eakin, H.; Luers, A.L. Assessing the vulnerability of social-environmental systems. *Annu. Rev. Environ. Resour.* **2006**, *31*, 365. [CrossRef]
83. Gilard, O.; Givone, P. Flood risk management: New concepts and methods for objective negotiations. In *Destructive Water: Water-Caused Natural Disasters, Their Abatement and Control*; Leavesley, G.H., Lins, H.F., Nobilis, F., Parker, R.S., Schneider, V.R., van de Ven, F.H.M., Eds.; IAHS Press: Oxfordshire, UK, 1997; pp. 145–155.
84. Comfort, L.; Wisner, B.; Cutter, S.; Pulwarty, R.; Hewitt, K.; OliverSmith, A.; Krimgold, F. Reframing disaster policy: The global evolution of vulnerable communities. *Environ. Hazards* **1999**, *1*, 39–44.
85. Weichselgartner, J.; Bertens, J. Natural disasters: Acts of God, nature or society? On the social relation to natural hazards. In *Risk Analysis II*; Andretta, M.A., Ed.; WIT Press: Southampton, UK, 2000; pp. 3–12.
86. Adger, W.N.; Winkels, A. Vulnerability, poverty, and sustaining well-being. In *Handbook of Sustainable Development*; Atkinson, G., Dietz, S., Neumayer, E., Eds.; Elgar: Cheltenham, UK, 2006.
87. Ciurean, R.L.; Schröter, D.; Glade, T. Conceptual Frameworks of Vulnerability Assessments for Natural Disasters Reduction. In *Approaches to Disaster Management-Examining the Implications of Hazards, Emergencies and Disasters*; Tiefenbacher, J., Ed.; IntechOpen: London, UK, 2013; Chapter 1; pp. 1–32.

88. Wolf, S.; Hinkel, J.; Hallier, M.; Bisaro, A.; Lincke, D.; Ionescu, C.; Klein, R.J. Clarifying vulnerability definitions and assessments using formalisation. *Int. J. Clim. Chang. Strateg. Manag.* **2013**, *5*, 54–70. [CrossRef]
89. IPCC. *Climate Change 2014: Synthesis Report*; Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Core Writing Team, Pachauri, R.K., Meyer, L.A., Eds.; IPCC: Geneva, Switzerland, 2014.
90. Hong, W.; Jiang, R.; Yang, C.; Zhang, F.; Su, M.; Liao, Q. Establishing an ecological vulnerability assessment indicator system for spatial recognition and management of ecologically vulnerable areas in highly urbanized regions: A case study of Shenzhen, China. *Ecol. Indic.* **2016**, *69*, 540–547. [CrossRef]
91. Cutter, S.L. Vulnerability to environmental hazards. *Prog. Hum Geogr.* **1996**, *20*, 529–539. [CrossRef]
92. Weichselgartner, J. Disaster mitigation: The concept of vulnerability revisited. *Disaster Prev. Manag.* **2001**, *10*, 85–95. [CrossRef]
93. Hogan, D.J.; Marandola, E., Jr. Vulnerability and risk: Between Geography and Demography. In Proceedings of the Seminar Making Sense of Vulnerability, Dundee, UK, 10–11 March 2005.
94. Paul, S.K. Vulnerability Concepts and its Application in Various Fields: A Review on Geographical Perspective. *J. Life Earth Sci.* **2013**, *8*, 63–81. [CrossRef]
95. Berrouet, L.M.; Machado, J.; Villegas-Palacio, C. Vulnerability of socio—Ecological systems: A conceptual Framework. *Ecol. Indic.* **2018**, *84*, 632–647. [CrossRef]
96. Holling, C.S. *Adaptive Environmental Assessment and Management*; John Wiley Sons: Hoboken, NJ, USA, 1978.
97. Marcus, S. Towards a Semiotic Approach to Social Indicators. In Proceedings of the International Congress of Logic, Methodology and Philosophy of Science, Salzburg, Austria, 11–16 July 1983.
98. McQueen, D.; Noak, H. Health Promotion Indicators: Current status, issues and problems. *Health Promot.* **1988**, *3*, 117–125, (MWCD). [CrossRef]
99. Tunstall, D. Developing Environmental Indicators: Definitions, framework, and issues. (Draft paper). Background Materials for the World Resources Institute. In *Workshop on Global Environmental Indicators, Washington, D.C. 7–8 December 1992*; World Resources Institute: Washington, DC, USA, 1992.
100. OECD. *Organization for Economic Cooperation and Development Core Set of Indicators for Environmental Performance Reviews*; A Synthesis Report by the Group on the State of the Environment; OECD: Paris, France, 1993.
101. Bakkes, J.A.; Van-den-Born, G.J.; Helder, J.C.; Swart, R.J.; Hope, C.W.; Parker, J.D.E. *An Overview of Environmental Indicators: State of the Art and Perspectives*; Environmental Assessment Sub-Programme; UNEP: Nairobi, Kenya, 1994.
102. Hammond, A.; Adriaanse, A.; Rodenburg, E.; Bryant, D.; Woodward, R. *Environmental Indicators: A Systematic Approach to Measuring and Reporting on Environmental Policy Performance in the Context of Sustainable Development*; World Resources Institute: Washington, DC, USA, 1995.
103. Ott, W.R. *Environmental Indices: Theory and Practice*; Ann Arbor Science: Ann Arbor, MI, USA, 1978.
104. Sen, A.K. *Poverty and Famines: An Essay on Entitlement and Deprivation*; Clarendon: Oxford, UK, 1981.
105. Watson, R.T.; Zinyoera, M.C.; Moss, R.H. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*; Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 1996.
106. IPCC. *The Regional Impact of Climate Change: An Assessment of Vulnerability*; Cambridge University Press: Cambridge, UK, 1997.
107. Handmer, J.W.; Dovers, S.; Downing, T.E. Societal Vulnerability to Climate Change and Variability. *Mitig. Adapt. Strateg. Glob. Chang.* **1999**, *4*, 267–281. [CrossRef]
108. IPCC. Report by Robert Watson, Chair, Intergovernmental Panel on Climate Change, to the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change, The Hague, 20 November 2000. Available online: https://archive.ipcc.ch/graphics/speeches/robert-watson-november-13-2000.pdf (accessed on 10 October 2022).
109. Fussel, H.M. Vulnerability: A generally applicable conceptual framework for climate change research. *Glob. Environ. Chang.* **2007**, *17*, 155–167. [CrossRef]
110. Goulden, M.; Porter, K. *CLICO Conceptual Framework. CLICO Project Deliverable D.1.1 Report*; University of East Anglia: Norwich, UK, 2010.
111. Ebi, K.; Kovats, R.S.; Menne, B. An approach for assessing human health vulnerability and public health interventions to adapt to climate change. *Environ. Health Perspect.* **2006**, *114*, 1930–1934. [CrossRef]
112. Schauser, I.; Otto, S.; Schneiderbauer, S.; Harvey, A.; Hodgson, N.; Robrecht, H.; Morchain, D.; Schrander, J.; Khovanskaia, M.; Celikyilmaz-Aydemir, G.; et al. *Urban Regions: Vulnerabilities, Vulnerability Assessments by Indicators and Adaptation Options for Climate Change Impacts—Scoping Study*; ETC/ACC Technical Paper 2010/12; European Topic Centre on Air and Climate Change: Bilthoven, The Netherlands, 2010.
113. Balica, S. Approaches of Understanding Developments of Vulnerability Indices for Natural Disasters. *Environ. Eng. Manag. J.* **2012**, *11*, 963–974. [CrossRef]
114. Simane, B.; Zaitchik, B.F.; Foltz, J.D. Agroecosystem specific climate vulnerability analysis: Application of the livelihood vulnerability index to a tropical highland region. *Mitig. Adapt. Strateg. Glob. Chang.* **2016**, *21*, 39–65. [CrossRef] [PubMed]
115. Kumar, P.; Geneletti, D.; Nagendra, H. Spatial assessment of climate change vulnerability at city scale: A study in Ban-galore. *India Land Use Pol.* **2016**, *58*, 514–532. [CrossRef]

116. Pandey, R.; Alatalo, J.M.; Thapliyal, K.; Chauhan, S.; Archie, K.M.; Gupta, A.K.; Jha, S.K.; Kumar, M. Climate change vulnerability in urban slum communities: Investigating household adaptation and decision-making capacity in the Indian Himalaya. *Ecol. Indic.* **2018**, *90*, 379–391. [CrossRef]
117. Malone, E.L.; Engle, N.L. Evaluating regional vulnerability to climate change: Purposes and methods. *WIREs Clim. Chang.* **2011**, *2*, 462–474. [CrossRef]
118. Sharma, J.; Chaturvedi, R.K.; Bala, G.; Ravindranath, N.H. Challenges in vulnerability assessment of forests under climate change. *Carbon Manag.* **2013**, *4*, 403–411. [CrossRef]
119. FSI. *State of Forest Report 2019*; Forest Survey of India: Dehradun, India, 2019.
120. Census of India. *Population Census 2011*; Ministry of Home Affairs, Government of India: New Delhi, India, 2011.
121. ISFR. 2021. Available online: https://fsi.nic.in/forest-report-2021-details (accessed on 17 September 2022).
122. Sullivan, C.; Meigh, J. Targeting attention on local vulnerabilities using an integrated index approach: The example of the climate vulnerability index. *Water Sci. Technol.* **2005**, *51*, 69–78. [CrossRef]
123. Solbrig, O.T. *From Genes to Ecosystems: A Research Agenda for Biodiversity*; International Union of Biological Sciences: Paris, France, 1991.
124. Lee, C.-B.; Chun, J.-H. Environmental Drivers of Patterns of Plant Diversity Along a Wide Environmental Gradient in Korean Temperate Forests. *Forests* **2016**, *7*, 19. [CrossRef]
125. Gairola, S.; Rawal, R.S.; Todaria, N.P. Forest vegetation patterns along an altitudinal gradient in sub-alpine zone of West Himalaya, India. *Afr. J. Plant Sci.* **2008**, *2*, 42–48.
126. Rawat, V.S.; Chandra, J. Tree layer vegetational analysis in temperate forest of Uttarakhand. *Nat. Sci.* **2012**, *10*, 167–171.
127. Sharma, E.; Chettri, N.; Tse-ring, K.; Shrestha, A.B.; Jing, F.; Mool, P.; Eriksson, M. *Climate Change Impacts and Vulnerability in the Eastern Himalayas*; International Centre for Integrated Mountain Development: Kathmandu, Nepal, 2009; ISBN1 978-92-9115-134-9 (printed). ISBN2 978-92-9115-136-3 (electronic).
128. Tse-ring, K.; Sharma, E.; Chettri, N.; Shrestha, A. *Climate Change Vulnerability of Mountain Ecosystems in the Eastern Himalayas*; Working Paper; ICIMOD: Lalitpur, Nepal, 2012.
129. Sandhu, H.; Sandhu, S. Poverty, development, and Himalayan ecosystems. *AMBIO* **2014**, *44*, 297–307. [CrossRef]
130. MoEF. *India Second National Communication to the United Nations Framework Convention on Climate Change*; Ministry of Environment and Forests, Government of India: New Delhi, India, 2012.
131. Jha, S.K.; Negi, A.K.; Alatalo, J.M.; Negi, R.S.; Patasaraiya, M.K. Assessment of climate change pattern in the Pauri Garhwal of the Western Himalayan Region: Based on climate parameters and perceptions of forest-dependent communities. *Environ. Monit. Assess.* **2020**, *192*, 632. [CrossRef] [PubMed]
132. Shrestha, A.B.; Devkota, L.P. Climate change in the Eastern Himalayas: Observed trends and model projections. In *Climate Change Impact and Vulnerability in the Eastern Himalayas—Technical Report 1*; ICIMOD: Kathmandu, India, 2010.
133. Shrestha, U.B.; Gautam, S.; Bawa, K.S. Widespread climate change in the Himalayas and associated changes in local ecosystems. *PLoS ONE* **2012**, *7*, e36741. [CrossRef] [PubMed]
134. Sharma, E. Chapter 2 Climate Change and its Impacts in the Hindu Kush-Himalayas: An Introduction. In *Climate Change Modeling for Local Adaptation in The Hindu Kush-Himalayan Region (Community, Environment and Disaster Risk Management, Vol. 11)*; Lamadrid, A., Kelman, I., Eds.; Emerald Group Publishing Limited: Bingley, UK, 2012; pp. 17–32. [CrossRef]
135. Nepal, S.; Shrestha, A.B. Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: A review of the literature. *Int. J. Water Resour. Dev.* **2015**, *31*, 201–218. [CrossRef]
136. ICIMOD. *The Hindu Kush Himalaya Assessment*; ICIMOD: Kathmandu, Nepal, 2019. [CrossRef]
137. World Bank. *Turn Down the Heat: Why a 4 °C Warmer World Must Be Avoided*; World Bank: Washington, DC, USA, 2012.
138. Goswami, B.N.; Venugopal, V.; Sengupta, D.; Madhusoodanan, M.S.; Xavier, P.K. Increasing trend of extreme rain events over India in a warming environment. *Science* **2006**, *314*, 1442–1445. [CrossRef]
139. Xu, J.; Grumbine, R.E.; Shrestha, A.B.; Eriksson, M.; Yang, X.; Wang, Y.; Wilkes, A. The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. *Conserv. Biol.* **2009**, *23*, 520–530. [CrossRef]
140. Rao, C.A.R.; Raju, B.M.K.; Rao, A.V.M.S.; Rao, K.V.; Rao, V.U.M.; Ramachandran, K.; Nagasri, K.; Dupdal, R.; Samuel, J.; Shankar, K.R.; et al. Climate change in Uttarakhand: Projections, Vulnerability and Farmers' Perceptions. *J. Agrometeorol.* **2018**, *20*, 37–41.
141. Gaire, N.P.; Koirala, M.; Bhuju, D.R.; Carrer, M. Site- and species specific treeline responses to climatic variability in eastern Nepal Himalaya. *Dendrochronologia* **2017**, *41*, 44–56. [CrossRef]
142. Bajpai, O.; Pandey, J.; Chaudhary, L.B. Periodicity of different phenophases in selected trees from Himalayan Terai of India. *Agrofor. Syst.* **2016**, *91*, 1–12. [CrossRef]
143. Amano, T.; Smithers, R.J.; Sparks, T.H.; Sutherland, W.J.A. 250-year index of first flowering dates and its response to temperature changes. *Proc. R. Soc.* **2010**, *277*, 2451–2457. [CrossRef]
144. Locatelli, B. Ecosystem Services and Climate Change. In *Routledge Handbook of Ecosystem Services*; Potschin, M., Haines-Young, R., Fish, R., Turner, R.K., Eds.; Routledge: London, UK; New York, NY, USA, 2016; pp. 481–490. ISBN 978-1-138-02508-0. Available online: https://www.routledge.com/products/9781138025080 (accessed on 20 December 2021).
145. Hussain, A. *Impact of Forest Fire on Vegetation Composition and Nutrient Status in Oak Dominated Forest in Garhwal Himalaya*; HNB-Garhwal (A Central) University: Srinagar, India, 2018.

146. Maikhuri, R.; Nautiyal, S.; Rao, K.; Saxena, K. Conservation policy—People conflicts: A case study from Nanda Devi Biosphere Reserve (a World Heritage Site), India. *For. Policy Econ.* **2001**, *2*, 355–365. [CrossRef]
147. Davidar, P.; Sahoo, S.; Mammen, P.C.; Acharya, P.; Puyravaud, J.P.; Arjunan, M.; Garrigues, J.P.; Roessingh, K. Assessing the extent and causes of forest degradation in india: Where do we stand? *Biol. Conserv.* **2010**, *43*, 37–44. [CrossRef]
148. Shank, R.E.; Noorie, E.N. Microclimate vegetation in a small valley in eastern Tennessee. *Ecology* **1950**, *11*, 531–539.
149. Levine, J.S.; Bobbe, T.; Ray, N.; Singh, A. *Wildland Fires and the Environment: A Global Synthesis*; UN Environment Program UNEP/DEIAEW/TR.99-1, Geneva 46; UNEP: Nairobi, Kenya, 1999.
150. Rajesh, S.; Jain, S.; Sharma, P.; Bahuguna, R. Assessment of inherent vulnerability of rural communities to environmental hazards in Kimsar region of Uttarakhand, India. *Environ. Dev.* **2014**, *12*, 16–36. [CrossRef]
151. Connor, R. *The United Nations World Water Development Report 2015: Water for a Sustainable World*; UNESCO Publishing: Paris, France, 2015; Volume 1.
152. Tambe, S.; Arrawatia, M.L.; Bhutia, N.T.; Swaroop, B. Rapid, cost effective and high-resolution assessment of the climate-related vulnerability of rural communities of Sikkim Himalaya, India. *Curr. Sci.* **2011**, *101*, 165–173.
153. Rawat, P.K.; Tiwari, P.C.; Pant, C.C. Climate change accelerating hydrological hazards and risks in Himalaya: A case study through remote sensing and GIS modelling. *Int. J. Geomat. Geosci.* **2011**, *1*, 687–699.
154. Kanagawa, M.; Nakata, T. Analysis of the energy access improvement and its socio-economic impacts in rural areas of developing countries. *Ecol. Econ.* **2007**, *62*, 319–332. [CrossRef]
155. Bhatt, B.P.; Sachan, M.S. Firewood consumption along an altitudinal gradient in mountain villages of India. *Biomass Bioenergy* **2004**, *27*, 69–75. [CrossRef]
156. Sharma, C.M.; Gairola, S.; Baduni, N.P.; Ghildiyal, S.K.; Suyal, S. Variation in carbon stocks on different slope aspects in seven major forest types of temperate region of Garhwal Himalaya, India. *J. Biosci.* **2011**, *36*, 701–708. [CrossRef]
157. Saxena, A.K.; Singh, J.S. A phytosociological analysis of woody species in forest communities of a part of Kumaun Himalaya. *Vegetation* **1982**, *50*, 3–22. [CrossRef]
158. Gairola, S.; Sharma, C.M.; Ghildiyal, S.K.; Suyal, S. Live tree biomass and carbon variation along an altitudinal gradient in moist temperate valley slopes of the Garhwal Himalaya (India). *Curr. Sci.* **2011**, *100*, 1862–1870.
159. Pandey, P.K. Quantitative vegetation analysis as per aspect and altitude, and regeneration behaviour of tree species in Garhwal Himalayan forest. *Annu. For.* **2001**, *9*, 39–52.
160. Rana, B.S. Biomass and net Primary Productivity in Different Brest Ecosystems Alony ah Attitudinal lradient in Kumaun Himataya. Ph.D. Thesis, Kumaun University, Naini Tal, India, 1985.
161. Chaturvedi, O.P.; Singh, J.S. The structure and function of pine forest in central Himalayan I: Dry matter dynamics. *Ann. Bot.* **1986**, *60*, 237–252. [CrossRef]
162. Chaturvedi, O.P. Biomass Structure, Productivity and Nutrient Cycling in *Pinus roxburghii* Forest. Ph.D. Thesis, Kumaun University, Naini Tal, India, 1983.
163. Kumar, M.; Savita; Singh, H.; Pandey, R.; Singh, M.P.; Ravindranath, N.H.; Kalra, N. Assessing vulnerability of forest ecosystem in the Indian Western Himalayan region using trends of net primary productivity. *Biodivers. Conserv.* **2019**, *28*, 2163–2182. [CrossRef]
164. Haripriya, G.S. Estimates of biomass in Indian forester. *Biome. Bioenerg.* **2000**, *19*, 245–258. [CrossRef]
165. Sundriyal, R.C.; Sharma, E.; Rai, L.K.; Rai, S.C. Tree structure, regeneration and woody biomass removal in a sub-tropical forest of Mamlay watershed in the Sikkim Himalaya. *Plant Ecol.* **1994**, *113*, 53–63. [CrossRef]
166. Sharma, C.M.; Baduni, N.P.; Gairola, S.; Ghildiyal, S.K.; Suyal, S. Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India. *For Ecol Manag.* **2010**, *260*, 2170–2179. [CrossRef]
167. Singh, S.P.; Adhikari, B.S.; Zobel, D.B. Biomass productivity, leaf longevity and forest structure in the Central Himalaya. *Ecol. Monogr.* **1994**, *64*, 401–421. [CrossRef]
168. Semwal, D.P.; Uniyal, P.L.; Bhatt, A.B. Structure Composition and Dominance—Diversity Relations in Three Forest Types of a Part of Kedarnath Wildlife Sanctuary, Central Himalaya. *India Not. Sci. Biol.* **2010**, *2*, 128–132.
169. Raturi, G.P. Forest Community Structure along an Altitudinal Gradient of District Rudraprayag of Garhwal Himalaya, India. *Ecol.* **2012**, *2*, 76–84. [CrossRef]
170. Kumar, A.; Ram, J. Anthropogenic disturbances and plant biodiversity in forest of Uttaranchal, Central Himalaya. *Biodivers. Conserv.* **2005**, *14*, 309–331. [CrossRef]
171. Pandey, J.C. Vegetation analysis in a mixed Oak-Conifer forest of Central Himalaya. *Ind J. For.* **2003**, *26*, 66–74.
172. Sanjeev, G.M.; Sankhayan, P.L. Phytosociological analysis of Arnigad micro-watershed in Mussorie hills of Garhwal Himalayas. *Indian For.* **2006**, *132*, 19–29.
173. Dhar, U.; Rawal, R.S.; Samant, S.S. Structural diversity and representativeness of forest vegetation in a protected area of Kumaun Himalaya, India: Implications for conservation. *Biodivers. Conserv.* **1997**, *6*, 1045–1062. [CrossRef]
174. Singh, J.S.; Singh, S.P. Forest vegetation of the Himalaya. *Bot. Rev.* **1987**, *53*, 80–192. [CrossRef]
175. Rawat, V.S.; Chandhok, A. Phytosociological Analysis and Distribution Patterns of Tree Species: A case study from Govind Pashu Vihar, National Park, Uttarakhand. *N. Y. Sci. J.* **2009**, *2*, 58–63.

176. Sagar, R.; Raghubanshi, A.S.; Singh, J.S. Tree species composition, dispersion and diversity along a disturbance gradient in a dry tropical forest region of India. *For. Ecol. Manag.* **2003**, *186*, 61–71. [CrossRef]
177. Srivastava, K.; Tewari, A.; Shah, S.; Tewari, B. Species composition and regeneration pattern along a transect perpendicular to a river course in foot hill Deciduous tropical forest of Kumaun. *Indian J. For.* **2008**, *1*, 7–12. [CrossRef]