

# Climate Change Vulnerability and Adaptive Capacity of Rural Communities in South Central Bhutan: An Integrated Socio-Ecological Assessment

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## Authors

Wangdi<sup>1</sup> (Corresponding author), Sangay Chedup<sup>2</sup>

## Affiliations

<sup>1</sup> Divisional Forest Office, Sarpang, Department of Forests and Park Services, Ministry of Energy and Natural Resources, Royal Government of Bhutan, Thimphu, Bhutan

<sup>2</sup> Divisional Forest Office, Mongar, Department of Forests and Park Services, Ministry of Energy and Natural Resources, Royal Government of Bhutan, Thimphu, Bhutan

## Corresponding author

Name: Wangdi

Email: wangdiues@gmail.com

ORCID: <https://orcid.org/0009-0007-7726-1742>

## Other author

Sangay Chedup

Email: sangaychedup16@gmail.com

ORCID: <https://orcid.org/0009-0008-2018-6435>

## Abstract

*Climate change poses significant threats to mountain communities globally, particularly in the Eastern Himalayas where rural livelihoods depend heavily on climate-sensitive natural resources. This study assessed climate change vulnerability across seven Gewogs (administrative blocks) under Divisional Forest Office Sarpang in south-central Bhutan, using an integrated vulnerability index combining exposure, sensitivity, and adaptive capacity indicators. Through household surveys (n = 620, representing 30% of the target population) and spatial analysis, we quantified vulnerability patterns across agricultural and forest-dependent communities. Results revealed negative vulnerability indices for all Gewogs, indicating that adaptive capacity was insufficient to offset combined exposure and sensitivity. Dekiling Gewog exhibited the highest vulnerability (−0.78) due to elevated exposure (0.47) and sensitivity (0.46) coupled with limited adaptive capacity (0.14), while Samtenling demonstrated the lowest vulnerability (−0.61) with higher adaptive capacity (0.17). Rainfall seasonality and associated landslides emerged as dominant exposure factors, while crop yield decline, water scarcity, and human–wildlife conflict significantly increased sensitivity. Community group membership and basic household facilities were primary adaptive capacity drivers. Forest vulnerability assessment identified southern and eastern edge zones as high-risk areas due to fragmentation, fire susceptibility, and climate sensitivity. These findings provide empirical evidence for targeted adaptation planning, emphasizing the need for integrated landscape-level interventions combining disaster risk reduction, sustainable agriculture, water resource management, and human-wildlife conflict mitigation to enhance community resilience in Himalayan ecosystems.*

## Keywords

*Adaptive capacity, Climate vulnerability, Livelihood resilience, Mountain communities, Socio-ecological systems, Vulnerability index*

## 1. Introduction

Global mean temperature has increased 0.8-1.3°C above pre-industrial levels (1850-1900 baseline), with 2020 recorded as one of the three warmest years at  $1.2 \pm 0.1^\circ\text{C}$  above baseline (IPCC, 2021; WMO, 2021). The IPCC Sixth Assessment Report projects temperature increases of 1.4-4.4°C by century's end, contingent upon substantial greenhouse gas emission reductions (IPCC, 2021). These changes profoundly impact natural and human systems globally, with disproportionate effects on rural communities in least developed countries dependent on climate-sensitive natural resources (Brooks et al., 2005; IPCC, 2018).

The Hindu Kush Himalayan (HKH) region is experiencing accelerated environmental change, with projected temperature increases of 0.3-4.8°C by 2100 (IPCC, 2013; Shrestha & Devkota, 2010). Mountain communities face compounded vulnerabilities from remoteness, unsustainable development practices, and natural resource overexploitation, despite abundant ecosystem services (Gerlitz et al., 2017; Pandey et al., 2017). These vulnerabilities are amplified by limited economic resources and constrained adaptive capacity (Choden et al., 2020).

Bhutan, maintaining 71% forest cover, is globally recognized as a net carbon sink yet remains highly vulnerable to climate impacts (DoFPS, 2016; NECS, 2020). The country faces diverse climate hazards including flash floods, glacial lake outburst floods (GLOFs), landslides, erratic rainfall patterns, and droughts affecting livelihoods and infrastructure (NCHM, 2019; NECS, 2020). Bhutan's agricultural sector, entirely dependent on monsoon precipitation with shortened growing seasons, exhibits particular vulnerability (Chhogyel & Kumar, 2018).

Climate analysis reveals increasing temperature trends in Bhutan, with mean annual temperature rising 0.8°C over 29 years (1976-2005) (NCHM, 2019). Warming trends of 0.5°C occurred from 1985-2002 during non-monsoon seasons, with both maximum and minimum temperatures increasing from 2000-2009 (NBC, 2011; NEC, 2011). Spatial and seasonal temperature variations are substantial (mean=17.58°C, max=34.85°C, min=-11.50°C) (Dorji & Lucero-Prisno III, 2022). Warming accelerates more rapidly at high elevations compared to lowland areas (Shrestha & Devkota, 2010). Future projections indicate temperature increases of 0.8-1.6°C (2021-2050) and 1.6-2.8°C (2070-2100) under RCP 4.5, with higher increases under RCP 8.5 scenarios (NCHM, 2019).

Precipitation patterns show high regional variability, with approximately 70% occurring during monsoon season and 20% during pre-monsoon (NEC, 2016; NECS, 2020). Historical

analysis (1996-2007) indicates marginal rainfall decrease with increased variability (NCHM, 2019). Future projections suggest 10-30% increases in mean annual rainfall under RCP 4.5, with summer rainfall increases of 5-15%, and greater increases under RCP 8.5 scenarios (NCHM, 2019).

Recognizing climate change threats to sustainable development, Bhutan has committed to integrating climate impact assessments into national and local development plans (NECS, 2020). The Climate Change Policy of 2020 prioritizes building resilience as a core objective (NEC, 2020). Vulnerability assessment serves as a critical step in adaptation planning, bridging community-level needs with policy processes and identifying intervention entry points (Burton et al., 2006; Macchi, 2011).

Despite growing recognition of vulnerability assessment importance, limited community-based studies exist for Bhutan (Choden et al., 2020; ICIMOD & RSPN, 2017; UNDP, 2021), typically focusing on national scales or specific protected areas. This study addresses this gap by assessing vulnerability across Gewogs in Sarpang District based on community perception and experience, providing evidence for targeted adaptation planning.

### *1.1 Study Objectives*

The specific objectives of this study were:

- To assess household-level exposure, sensitivity, and adaptive capacity to climate change across Gewogs in DFO Sarpang.
- To evaluate spatial patterns of composite vulnerability using geospatial indicators and multi-criteria analysis.
- To prioritise climate-change adaptation options for agriculture- and forest-dependent communities.

## **2. Materials and Methods**

### *2.1 Conceptual Framework*

This assessment adopts the IPCC (2001) vulnerability framework, defining vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change" (Brooks et al., 2005; IPCC, 2001). Vulnerability is expressed as a function of three components:

$$CV = f(E, S, AC)$$

where CV represents climate vulnerability, E denotes exposure (nature and degree of climate variability exposure), S indicates sensitivity (degree of system response to climatic stimuli, either adverse or beneficial), and AC signifies adaptive capacity (system flexibility to adjust and cope with consequences) (Brooks, 2003; IPCC, 2001; KC et al., 2015). Adaptive capacity exhibits inverse relationship with vulnerability (Sharma & Ravindranath, 2019), with capacity dependent on asset ownership and access (Piya et al., 2016).

This study employed the socio-economic vulnerability approach, analyzing social, political, and economic dimensions associated with individual, community, and societal well-being (Adger, 1999; Choden et al., 2020; UNISDR, 2004).

## *2.2 Study Area*

The study focused on Divisional Forest Office (DFO) Sarpang, established in 1959 as Bhutan's second forest division (Figure 1). Located in south-central Bhutan (26.8643°N, 90.2690°E), the division encompasses 1,011.7 km<sup>2</sup> with elevations ranging 153-3,506 m above sea level. Vegetation comprises subtropical, warm broadleaved, and cool broadleaved forests, receiving 3,500-5,500 mm annual precipitation.

DFO Sarpang borders Assam, India to the south, Royal Manas National Park (RMNP) east, Phibsoo Wildlife Sanctuary (PWS) west, and Jigme Singye Wangchuck National Park (JSWNP) north. Biological Corridor 3 (BC-3), connecting these three protected areas, falls within division jurisdiction, encompassing 407.69 km<sup>2</sup> with 84.48% under DFO Sarpang management.

Seven Gewogs outside BC-3 and neighboring protected area boundaries were surveyed: Dekiling, Shompangkha, Chhuzagang, Sherzhong, Gelephu, Gakiling, and Samtenling. Chhudzom and Jigmechoeling Gewogs were excluded as they were covered under BC-3 assessment, while Singye, Umling, and Taraythang are administratively managed by PWS and RMNP.

## *2.3 Climate Characteristics*

Temperature exhibits clear seasonal patterns, gradually rising from February, peaking in August, then declining through December. Maximum temperatures reach 35-36°C during July-August, while minimum temperatures occur in January (9-10°C). Temperature variations between maximum and minimum are greatest February-May, becoming more consistent June-August.

Precipitation demonstrates distinct monsoon patterns, increasing significantly from April and peaking July-August (exceeding 500mm monthly). Rainfall gradually decreases September-December, transitioning to dry season with minimal precipitation January-February. This pattern creates favorable agricultural conditions during monsoon while requiring water management strategies during dry periods.

Vegetation and land-surface variables were derived from MODIS products (MOD13Q1 NDVI, 250-m resolution) for the period 2014–2023. Land-cover information was obtained from the Bhutan Land Cover Map (2019) produced by the National Land Commission Secretariat. Historical climate variables were extracted from the National Centre for Hydrology and Meteorology gridded datasets (1986–2015), while future projections were taken from the CMIP6 multi-model ensemble under SSP2-4.5 and SSP5-8.5 scenarios, downscaled for Bhutan.

#### *2.4 Data Collection and Sampling*

Primary data were collected through household surveys conducted October 2023, sampling 30% of total households residing within division jurisdiction outside BC-3 (n=620 households). Sampling distribution by Gewog: Gakiling (59), Shompangkha (80), Dekiling (153), Samtenling (82), Chhuzagang (107), Gelephu (84), and Serzhong (55).

Indicators and questionnaires were developed referencing previous protected area CVCA surveys, peer-reviewed literature, and available resources. Epicollect5 application (<https://five.epicollect.net>) facilitated digital data collection, eliminating manual entry burden. Fifteen surveyors received training on application usage and questionnaire familiarization before field deployment. Surveys collected demographic information and indicators for exposure, sensitivity, and adaptive capacity over the previous 10-year period.

#### *2.5 Indicator Selection and Description*

The indicator-based method was applied following established vulnerability assessment frameworks (Brooks et al., 2005; Deressa et al., 2008; Hahn et al., 2009; Maiti et al., 2015; Piya et al., 2016). Indicators were finalized through consultation with focal officials and IKI project taskforce members in October 2023.

Exposure indicators (n=7) comprised perceived historical changes in climate variables and extreme event occurrence: temperature extremes, shifts in rainfall seasonality, flash floods, landslides, windstorms, and seasonal droughts.

Sensitivity indicators (n=12) measured livelihood impacts across climate-sensitive sectors (agriculture, water, livestock, forest, health, infrastructure): crop yield changes, pest and disease incidence, invasive weed presence, irrigation and drinking water availability, time spent collecting water, forest composition changes, wildlife population dynamics, pastureland condition, human disease patterns, infrastructure impacts, and disaster-related family member loss.

Adaptive capacity indicators (n=19) were structured around five livelihood assets following sustainable livelihoods framework (Banerjee et al., 2019; Maiti et al., 2015, 2017; Piya et al., 2016):

- Human assets: household head literacy, vocational skills, climate change adaptation awareness
- Social assets: community group membership, productive group participation
- Natural assets: landholding size, crop diversity, forest resource availability, alternative water sources
- Physical assets: house type, communication facility access, distance to essential services
- Financial assets: livelihood diversity, off-farm income proportion, credit access, savings

Each indicator was quantified using measurable parameters scored 0-2 based on community impacts, determined through consultation with focal officials representing respective Gewogs.

### *2.6 Vulnerability Index Calculation*

Latent variables (Exposure, Sensitivity, Adaptive Capacity) were captured using confirmatory factor analysis (CFA) via the lavaan package in R studio. One-factor CFA was employed assuming indicator variables reliably estimate respective latent variables. Observed population covariance matrix  $\Sigma$  formed fundamental CFA components, with model-implied covariance matrix  $\Sigma(\theta)$  defined as:

$$\Sigma(\theta) = Cov(y) = \Lambda\Psi\Lambda' + \Theta\varepsilon$$

where  $\theta$  comprises parameters  $\Lambda$  (loadings),  $\Psi$  (latent variable covariance), and  $\Theta$  (residual error covariance). The marker method fixed each factor variance to one while freely estimating loadings. Model robustness was verified using RMSEA (0.061,  $p < 0.001$ ), indicating satisfactory fit. Predicted latent variable values were normalized using min-max transformation:  $(Value - Min)/(Max - Min)$ .

Vulnerability index was calculated as:

**Vulnerability (V) = Adaptive Capacity (AC) – (Exposure (E) + Sensitivity (S))**

Higher vulnerability index values indicate lower vulnerability. Negative values indicate net negative effect of adaptive capacity relative to exposure and sensitivity (Maiti et al., 2017). This index provides comparative assessment rather than absolute measurement.

All statistical analyses were conducted in R (version 4.3 or later) using the *lavaan* package for confirmatory factor analysis. Model fit was evaluated using the comparative fit index (CFI > 0.90), Tucker–Lewis index (TLI > 0.90), and root mean square error of approximation (RMSEA < 0.08). Standardised factor loadings were used to derive indicator weights, following initial equal weighting to avoid a priori bias, and subsequently refined through analytic hierarchy process (AHP)–based expert scoring.

### *2.7 Forest Vulnerability Assessment*

Desktop GIS analysis assessed forest vulnerability through five-step methodology integrating multiple data sources within GIS framework.

**Climate Sensitivity Index:** Baseline and future climate data (temperature, precipitation) at 10,000 m<sup>2</sup> resolution calculated percentage precipitation change and absolute temperature change between baseline and future scenarios (RCP4.5, RCP8.5 for 2050). Changes were reclassified into vulnerability classes (very low, low, moderate, high, very high) and combined using weighted overlay analysis with equal weights (50% each).

**Productivity Vulnerability Index:** Remotely sensed data including MODIS Enhanced Vegetation Index anomaly (ecosystem stress), MODIS Net Primary Productivity trend (Mann-Kendall analysis), and MODIS Evapotranspiration trend assessed forest productivity vulnerability. Variables were reclassified and integrated using weighted overlay analysis with weights reflecting relative productivity influence.

**Fire Risk Index:** Factors contributing to fire risk included land cover/vegetation type, MODIS Land Surface Temperature (maximum), distance from settlements and roads, elevation, and slope. Variables were reclassified and integrated using weighted overlay analysis.

**Degradation Index:** Forest fragmentation served as key degradation indicator. Land cover data were reclassified into Forest/Non-Forest categories and analyzed using Landscape Fragmentation

Analysis tool with 100m edge width, classifying forest landscape into patch types (patch, edge, perforated, core areas of varying sizes).

**Overall Vulnerability:** Four indices (climate sensitivity, productivity vulnerability, fire risk, degradation) were integrated using weighted overlay analysis with Analytic Hierarchy Process (AHP)-determined weights: Climate Sensitivity Index (50%), Fire Risk Index (20%), Degradation Index (15%), and Productivity Vulnerability Index (15%).

### 3. Results

#### *3.1 Demographic and Socio-Economic Characteristics*

Survey respondents (n=620) had mean age 54 years (range: 22-89). Household leadership distribution: 40% female-headed, 60% male-headed. Overall, 51% of households were headed by literate individuals (formal, non-formal, monastic, or higher education). Gakiling exhibited highest literacy rate (60%), while Serzhong showed lowest (36%). Male-headed households demonstrated higher literacy (47%) compared to female-headed households (34%). Primary education attainment: 112 male-headed versus 33 female-headed households.

Primary income sources: 49% depended on agriculture and livestock, while 61% generated income from off-farm activities (wages, salaries, labor, business, non-wood forest product collection, religious/cultural services).

#### *3.2 Exposure Index*

All seven exposure indicators demonstrated positive contribution ( $p < 0.001$ ) (Table 1). Rainfall Seasonality Impact Types contributed most heavily to overall exposure index, followed by rainfall seasonality and extreme event types. Temperature extremes showed comparatively lower contribution.

Rainfall seasonality impacts (landslides, erosion, flash floods) represent persistent and devastating hazards in Bhutan's steep terrain (Dikshit et al., 2020; NECS, 2020). Third National Communication reported decreasing rainfall trends with high variability (NEC, 2020). Extreme events (earthquakes) contributed minimally to exposure index due to low incidence reports. Gakiling Gewog exhibited highest exposure, while Chhuzagang demonstrated comparatively lower exposure (Figure 2). Dekiling Gewog reported highest percentage of households

perceiving temperature extremes, extreme temperature impacts, extreme events, and rainfall seasonality impacts (Table 2).

### *3.3 Sensitivity Index*

Most sensitivity indicators contributed positively, though water and vector-borne diseases showed negative contribution. Wildlife population was non-significant ( $p>0.05$ ). Crop yield demonstrated highest weightage contribution to sensitivity index (Table 3).

Top sensitivity indicators across all Gewogs: drinking and irrigation water availability, forest composition change and cover loss, crop pests and diseases, and invasive weed species (Figure 3). Human-wildlife conflict (HWC) constituted primary issue affecting crop cultivation and livestock production. Common conflicting species: Asian elephant, wild pig, and macaque (Figure 4).

Chhuzagang exhibited highest sensitivity (index: 0.54), while Gelephu demonstrated least sensitivity (0.45). Subsequently sensitive Gewogs: Gakiling, Serzhong, and Shompangkha (Figure 5). Dekiling reported highest estimated loss from crop damage and livestock depredation (Table 4).

### *3.4 Adaptive Capacity Index*

Social asset indicators (community group membership, membership types) demonstrated comparatively higher contribution to adaptive capacity index (Table 5). Benefits of social group participation include information access and local resource allocation group membership. Model performance remained robust ( $p<0.001$ ) despite some non-significant individual indicators.

Physical Asset indicators: Access to Facilities (Weight: 1.704,  $Z=3.349$ ,  $p=0.001$ ), Access to Household Facilities (Weight: 2.185,  $Z=4.185$ ,  $p<0.001$ ), Road Access and Conditions (Weight: 0.710,  $Z=2.115$ ,  $p=0.034$ ), Communication Medium Types (Weight: 0.917,  $Z=2.953$ ,  $p=0.003$ ). Normalized adaptive capacity scores (0-1 scale) showed limited variation among Gewogs. Gakiling scored highest adaptive capacity; Chhuzagang exhibited lowest adaptive capacity (Figure 6 & 7).

### *3.5 Overall Vulnerability Index*

Overall vulnerability was calculated as:  $Vulnerability = Adaptive\ Capacity - (Exposure + Sensitivity)$ . Gewogs with higher negative vulnerability index scores were more vulnerable (Table 6).

Dekiling emerged as most vulnerable (vulnerability index: -0.78) with lower adaptive capacity but higher exposure and sensitivity. Shompangkha ranked second most vulnerable. Samtenling demonstrated least vulnerability (index: -0.61) with higher adaptive capacity and lower sensitivity and exposure. All Gewogs exhibited negative vulnerability scores, indicating vulnerability to climate change (Figure 8).

### *3.6 Forest Vulnerability Assessment*

Forest vulnerability assessment revealed two vulnerability levels: low and high. The integrated vulnerability map combined four weighted indices: Climate Sensitivity Index (CSI-50%), Fire Risk Index (FRI-20%), Degradation Index (DI-15%), and Productivity Vulnerability Index (PVI-15%).

High vulnerability areas concentrated along southern and eastern Sarpang edges, exhibiting fragmented patterns interspersed with low vulnerability patches, suggesting edge effects from human activity, land use change, and climatic extreme exposure. Isolated high vulnerability patches occurred in central and northern Sarpang, associated with fragmented forest cover or settlement proximity. Majority of Sarpang exhibited low vulnerability, particularly central and western regions with larger, contiguous forest areas (Figure 9).

## **4. Discussion**

### *4.1 Exposure Patterns and Climate Variability*

Exposure analysis revealed rainfall seasonality and associated impacts (landslides, flash floods) as dominant contributors to community exposure. This finding aligns with Bhutan's geomorphological characteristics, where steep mountainous terrain amplifies precipitation-related hazards (Dikshit et al., 2020; NECS, 2020). Landslides cause substantial losses including human casualties (Gyelmo, 2021), infrastructure damage, and agricultural land loss. The Third National Communication reported decreasing rainfall trends with increased variability (NEC, 2020), consistent with regional Himalayan studies documenting erratic rainfall patterns (Lhendup et al., 2011; NBC, 2011).

Temperature extremes contributed moderately to exposure despite observed warming trends in Bhutan (0.8°C increase over 29 years, 1976-2005) (NCHM, 2019). High-elevation areas experience accelerated warming compared to lowlands (Shrestha & Devkota, 2010), potentially

explaining spatial variation in temperature extreme perception among Gewogs. Future projections indicate continued temperature increases (NCHM, 2019), suggesting temperature-related exposure may intensify.

Spatial variation in exposure (Gakiling highest, Chhuzagang lowest) reflects differential hazard exposure patterns influenced by topography, proximity to vulnerable zones, and historical disaster occurrence. Dekiling's high percentage of households perceiving multiple exposure indicators suggests cumulative hazard impact in this Gewog, necessitating prioritized attention in adaptation planning.

#### *4.2 Sensitivity Drivers and Livelihood Impacts*

Crop yield emerged as the dominant sensitivity indicator, reflecting agriculture's climate vulnerability in monsoon-dependent systems (Chhogyel & Kumar, 2018). Annual crop losses from unusual pest and disease outbreaks, erratic rainfall, windstorms, hailstorms, droughts, and flash floods compound agricultural vulnerability (Chhogyel et al., 2020). This finding underscores the urgency for climate-smart agricultural interventions promoting crop diversification, drought-resistant varieties, and improved pest management.

Water scarcity for drinking and irrigation constituted critical sensitivity factors, directly linked to climate change impacts on water resources (NECS, 2020). Mountain communities face particular water vulnerability due to changing precipitation patterns, glacier retreat, and spring discharge variability (Sharma et al., 2021). Integrated water resource management approaches combining rainwater harvesting, efficient irrigation technologies, and watershed conservation are essential adaptation measures.

Human-wildlife conflict emerged as a significant sensitivity driver, with Asian elephant, wild pig, and macaque as primary conflicting species. While HWC drivers are complex, climate change influences conflict dynamics through habitat alteration, resource availability changes, and phenological shifts (Sharma et al., 2021). Systematic reviews of HWC in the Hindu Kush Himalayas identified climate change as a contributing driver, causing plant phenology changes and habitat shifts (Sharma et al., 2021). Climate impacts on resource availability may concentrate wildlife and people in limited spaces, intensifying conflicts (Abrahms, 2021).

The Third National Communication proposed HWC management as climate change adaptation option (NEC, 2020), recognizing conflict's role in reducing adaptive capacity and increasing vulnerability (Gupta et al., 2017). Beyond climate, perceived HWC drivers included

human encroachment, decreasing food availability, habitat degradation, increasing conflicting species populations, range shifts, unsupervised grazing, and local deity wrath, indicating multiple interacting factors requiring integrated approaches.

Forest composition changes and invasive weed species represented important sensitivity indicators. Reported negative impacts of forest composition change included forest product scarcity/loss, habitat degradation, HWC, forest pest and disease emergence/increase, and plant and animal range shifts. These findings align with projected climate change impacts on Himalayan forest ecosystems (Ravindranath et al., 2011; Tambe et al., 2011).

### *4.3 Adaptive Capacity Determinants*

Social assets, particularly community group membership and group diversity, contributed most substantially to adaptive capacity. This finding aligns with social capital theory emphasizing collective action, information sharing, and mutual support in building resilience (Piya et al., 2016). Community groups facilitate adaptation through multiple pathways: information access regarding adaptation strategies, collective resource management (community forests), financial support mechanisms (savings groups), and coordinated disaster response. Strengthening community institutions and promoting diverse group participation constitute critical strategies for enhancing adaptive capacity.

Physical assets (basic household facilities, communication access, road access) and financial assets (food self-sufficiency, credit access, savings) demonstrated substantial contributions to adaptive capacity. These findings reflect the sustainable livelihoods framework premise that diverse asset portfolios enhance household resilience (Banerjee et al., 2019; Maiti et al., 2015). Access to basic facilities enables households to better cope with climate shocks, while financial assets provide buffers during stress periods and capital for adaptation investments.

Human assets showed moderate contribution to adaptive capacity. While household head literacy, vocational skills, and climate awareness contribute to adaptation capacity, their relatively lower weights compared to social and physical assets suggest community-level and material resources may be more immediately limiting factors in this context. This finding should not diminish education and awareness importance, as these assets enable effective utilization of other resources and long-term capacity building.

#### *4.4 Composite Vulnerability Patterns*

All Gewogs exhibited negative vulnerability indices, indicating net vulnerability to climate change despite varying degrees. This universal vulnerability reflects Himalayan mountain communities' general susceptibility to climate change (Gerlitz et al., 2017; Pandey et al., 2017) and Bhutan's specific constraints including remoteness, limited economic resources, and climate-sensitive livelihood dependencies (Choden et al., 2020; NECS, 2020).

Dekiling's highest vulnerability (-0.78) resulted from combined high exposure (0.47), moderate-high sensitivity (0.46), and limited adaptive capacity (0.14). This vulnerability profile indicates Dekiling faces substantial climate hazards with significant livelihood impacts and constrained coping capacity, requiring prioritized comprehensive intervention. Shompangkha's second-highest vulnerability similarly reflects elevated exposure and moderate adaptive capacity. Samtenling's relatively lower vulnerability (-0.61) stemmed from higher adaptive capacity (0.17) coupled with lower exposure (0.32) and sensitivity (0.47). This profile suggests Samtenling possesses stronger asset base and coping mechanisms, though remaining vulnerable overall. Understanding factors enabling Samtenling's relatively higher adaptive capacity could inform interventions in more vulnerable Gewogs.

Gakiling presented an interesting case: despite highest exposure (0.53), its substantially higher adaptive capacity (0.36) moderated overall vulnerability (-0.67), demonstrating adaptive capacity's buffering role against exposure and sensitivity. This finding emphasizes adaptive capacity enhancement as critical adaptation strategy even in high-exposure areas.

These findings partially align with nationwide climate vulnerability assessments conducted for National Adaptation Plan formulation (NEC & UNDP, 2021), which identified southern Dzongkhags including Sarpang as high climate risk areas. Tempa's (2022) flood vulnerability assessment for Bhutan ranked Sarpang among more vulnerable districts with higher flood vulnerability index, consistent with this study's exposure findings.

#### *4.5 Forest Vulnerability Patterns and Drivers*

Forest vulnerability assessment revealed concerning patterns with high vulnerability concentrated along southern and eastern edges and in fragmented patches. Edge vulnerability likely reflects multiple interacting factors: increased human-forest interface with associated pressures (grazing, extraction, fire risk), microclimate modifications at forest edges affecting

species composition and ecosystem functioning, and greater exposure to external disturbances including invasive species colonization.

Climate sensitivity contributed 50% to overall forest vulnerability, reflecting temperature and precipitation pattern changes. Climate change impacts on forests include species composition shifts, productivity changes, pest and disease outbreak increases, and phenological disruptions (Ravindranath et al., 2011; Seidl et al., 2011). Future climate projections for Bhutan indicate temperature increases and altered precipitation patterns (NCHM, 2019), likely intensifying forest vulnerability.

Fire risk (20% weight) represents significant threat, particularly in climate change context where temperature increases, altered rainfall patterns, and extreme weather events may increase fire frequency and intensity. Forest fragmentation exacerbates fire risk by creating dry microclimates and increasing ignition sources from human activities. Degradation (15% weight), assessed through fragmentation analysis, highlighted edge effects and patch isolation importance. Central and western Sarpang's large, contiguous forest areas demonstrated lower vulnerability, emphasizing intact forest landscape conservation importance.

#### *4.6 Policy and Planning Implications*

These findings provide evidence base for climate change adaptation planning at multiple scales. At Gewog level, vulnerability profiles enable targeted intervention design reflecting specific exposure, sensitivity, and adaptive capacity characteristics. Dekiling requires comprehensive interventions addressing high exposure (disaster risk reduction, infrastructure resilience), elevated sensitivity (climate-smart agriculture, water security, HWC mitigation), and limited adaptive capacity (asset building across all livelihood categories).

At divisional level, forest vulnerability patterns indicate priorities for forest management and conservation. High vulnerability zones along southern and eastern edges require enhanced protection, restoration of degraded areas, fire management, and buffer zone management. Maintaining connectivity between low vulnerability forest patches supports ecological resilience and biodiversity conservation.

Findings align with and provide local-scale detail for national adaptation priorities identified in National Adaptation Plan and Third National Communication (NEC, 2020; NEC & UNDP, 2021). Priority thematic areas including water, agriculture and livestock, forest and biodiversity, human settlements, health, and disaster risk reduction directly address vulnerabilities identified

in this assessment. The Bhutan REDD+ strategy (DoFPS, 2016) provides additional policy framework for ecosystem-based adaptation.

Bhutan's Climate Change Policy (NEC, 2020) establishes vision for "prosperous, resilient and carbon neutral Bhutan where the pursuit of gross national happiness for the present and future generations is secure under the changing climate." Achieving this vision requires translating national commitments into local action, with vulnerability assessments providing essential evidence for prioritization and resource allocation.

#### *4.7 Study Limitations and Future Research*

Several limitations warrant acknowledgement. The vulnerability assessment is based on cross-sectional household survey data and may therefore be influenced by respondent perception and recall bias, particularly for climate-related impacts experienced over multiple years. The Composite Vulnerability Index is designed to provide a comparative assessment across Gewogs and should be interpreted as relative vulnerability rather than an absolute measure of risk. In addition, the forest vulnerability analysis relies on available spatial datasets and represents conditions at the time of assessment, without capturing temporal changes in forest condition or management interventions. Future research should incorporate longitudinal household surveys, climate and livelihood time-series data, and repeated forest assessments to better understand vulnerability dynamics over time. Integrating qualitative and participatory approaches would further strengthen insights into local adaptation processes and institutional constraints.

### **5. Conclusions**

This comprehensive vulnerability assessment of Gewogs under DFO Sarpang jurisdiction reveals universal climate change vulnerability across all assessed administrative units, while identifying significant spatial variation in vulnerability drivers and adaptive capacity. All seven Gewogs exhibited negative vulnerability indices, confirming climate change poses substantial threat to rural livelihoods and natural resource-dependent communities in south-central Bhutan.

Key findings indicate: (1) Dekiling Gewog emerges as most vulnerable due to elevated exposure, moderate-high sensitivity, and limited adaptive capacity, requiring prioritized comprehensive adaptation interventions; (2) Rainfall seasonality impacts, particularly landslides and flash floods, dominate exposure patterns, emphasizing need for disaster risk reduction and

climate-resilient infrastructure; (3) Crop yield vulnerability, water scarcity, and human-wildlife conflict constitute primary sensitivity drivers, necessitating integrated approaches combining climate-smart agriculture, water resource management, and conflict mitigation; (4) Social assets, particularly community group participation, emerge as strongest adaptive capacity determinants, highlighting social capital's critical role in building resilience; (5) Forest vulnerability concentrates along edges and fragmented patches, requiring targeted conservation, restoration, and connectivity enhancement.

These findings provide empirical foundation for evidence-based adaptation planning at multiple scales. Recommended priorities include: Implementation of Gewog-specific adaptation strategies reflecting local vulnerability profiles, with emphasis on most vulnerable Gewogs while strengthening resilience in less vulnerable areas. Integration of disaster risk reduction with climate change adaptation, addressing dominant exposure factors through early warning systems, infrastructure resilience, slope stabilization, and flood management. Promotion of climate-smart agriculture combining crop diversification, drought-resistant varieties, improved pest management, conservation agriculture practices, and climate information services.

Additional priorities encompass strengthening water security through integrated watershed management, rainwater harvesting, efficient irrigation technologies, and alternative water source development. Implementation of comprehensive human-wildlife conflict mitigation strategies including biological barriers, early warning systems, compensation mechanisms, and habitat management. Enhancement of adaptive capacity through community institution strengthening, livelihood diversification support, financial service access, and education and awareness programs. Forest conservation and restoration prioritizing high vulnerability zones, fire management, invasive species control, and ecological connectivity maintenance.

This assessment contributes to growing evidence base on Himalayan mountain community vulnerability to climate change, demonstrating integrated vulnerability assessment utility in informing adaptation planning. The methodology combining household surveys, spatial analysis, and multi-indicator vulnerability indexing provides replicable framework applicable to other Himalayan contexts. Climate change adaptation in Bhutan's mountain communities requires sustained commitment, adequate resources, and coordinated action across sectors and scales.

Regular monitoring and periodic reassessment will be essential to track vulnerability changes, evaluate adaptation effectiveness, and adjust strategies as climate and socio-economic conditions

evolve. Ultimately, building climate resilience in Bhutan's Gewogs supports broader national objectives of sustainable development, carbon neutrality, and gross national happiness under changing climate. By addressing identified vulnerabilities through targeted, evidence-based adaptation, DFO Sarpang can contribute substantially to securing community livelihoods and ecosystem services for present and future generations.

### **Ethical Considerations**

This research was conducted in accordance with the ethical, legal, and administrative requirements of the Royal Government of Bhutan. Household surveys were undertaken with informed consent, and participation was voluntary. No personal identifiers were retained, and all data were anonymised prior to analysis to ensure respondent confidentiality.

### **Data Availability Statement**

The household survey data and derived vulnerability indices supporting this study are available from the corresponding author upon reasonable request, subject to institutional data-sharing requirements. Spatial datasets used for forest vulnerability analysis were obtained from authorised national sources and relevant public climate databases.

### **Declaration of Generative AI**

Generative artificial intelligence tools were used during manuscript preparation exclusively for language editing to enhance clarity and readability. The total contribution of AI-assisted text generation was below the journal's stated 20% threshold. All AI-assisted content was critically reviewed, revised, and validated by the authors, who assume full responsibility for the accuracy, interpretation, and integrity of the manuscript.

### **Credit Author Statement (CRediT)**

**Wangdi:** Conceptualisation; methodology; formal analysis; data curation; visualisation; investigation; writing – original draft; supervision.

**Sangay Chedup:** Data collection; field investigation; validation; writing – review and editing.

### **Conflict of Interest**

The authors declare no conflict of interest.

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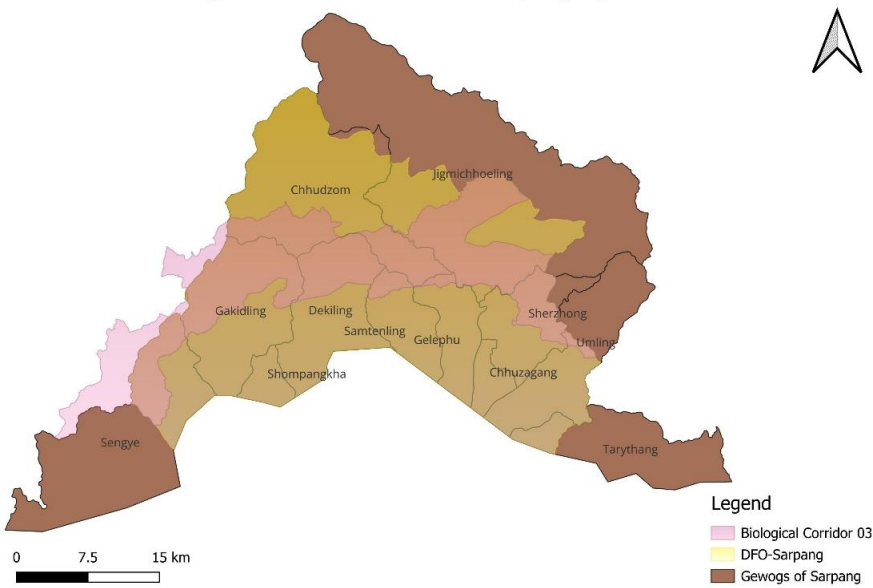
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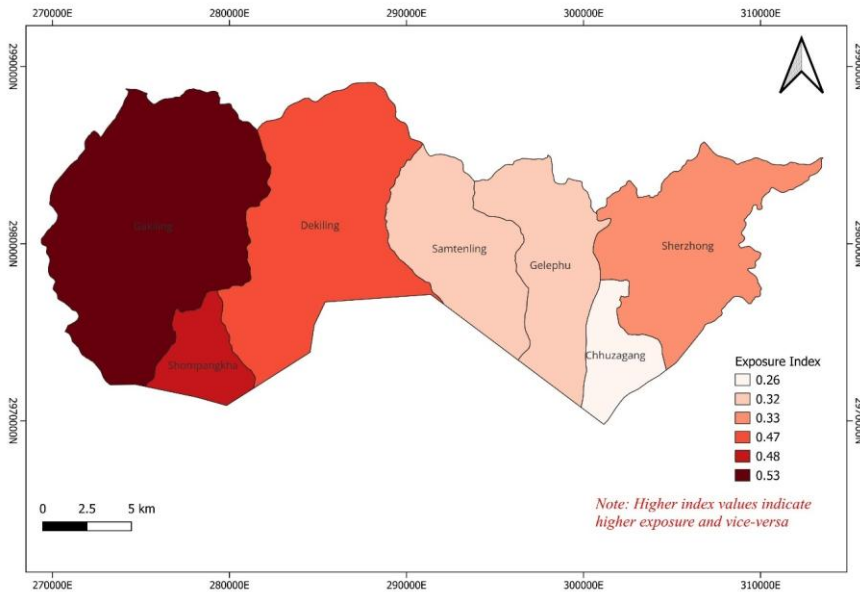
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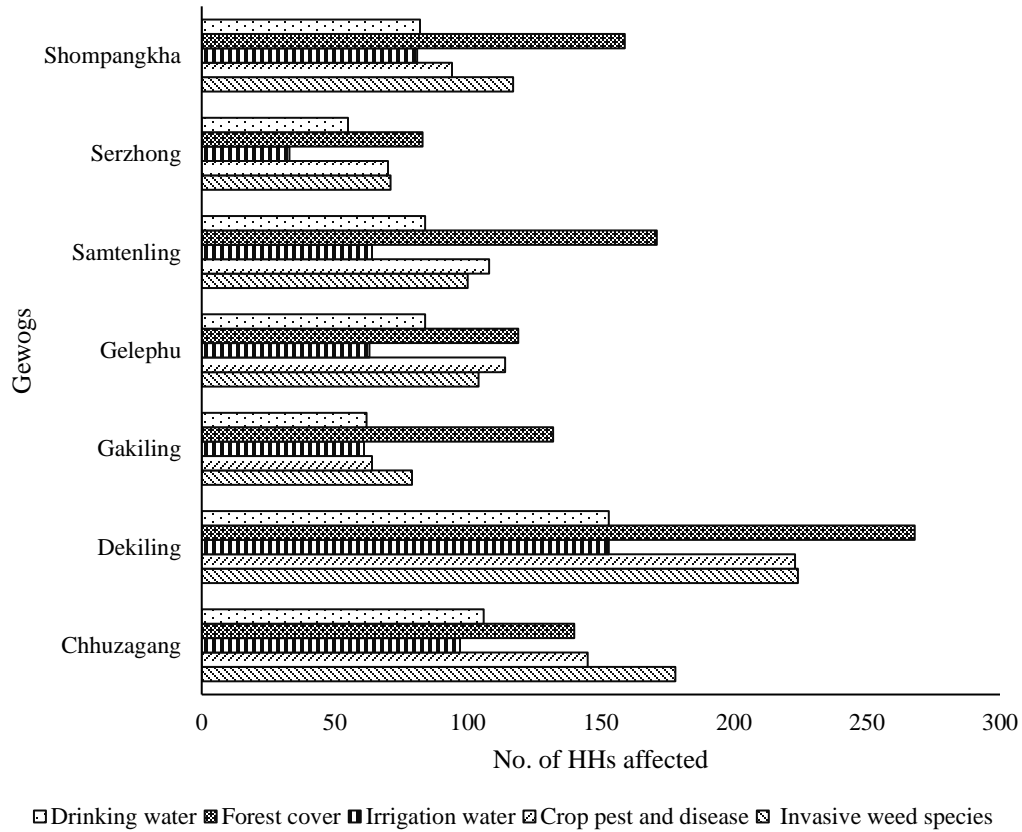
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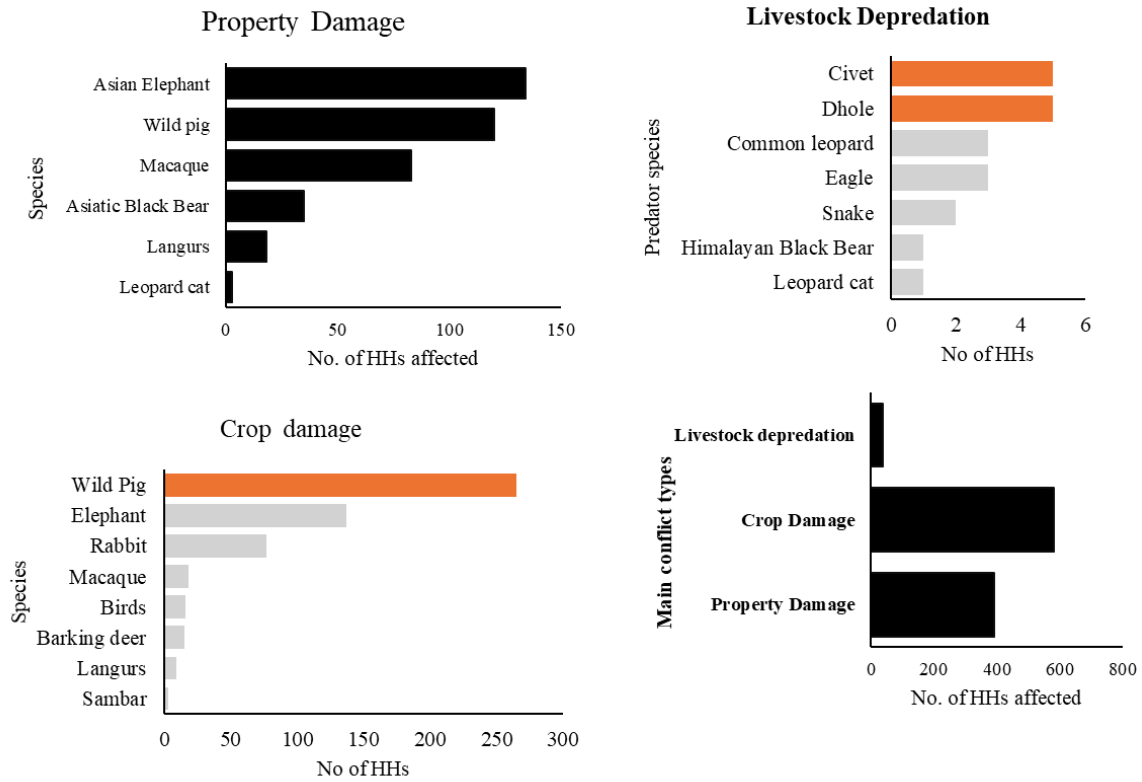
**Figure 1: Location of the study area showing Gewogs within DFO Sarpang, south-central Bhutan.**



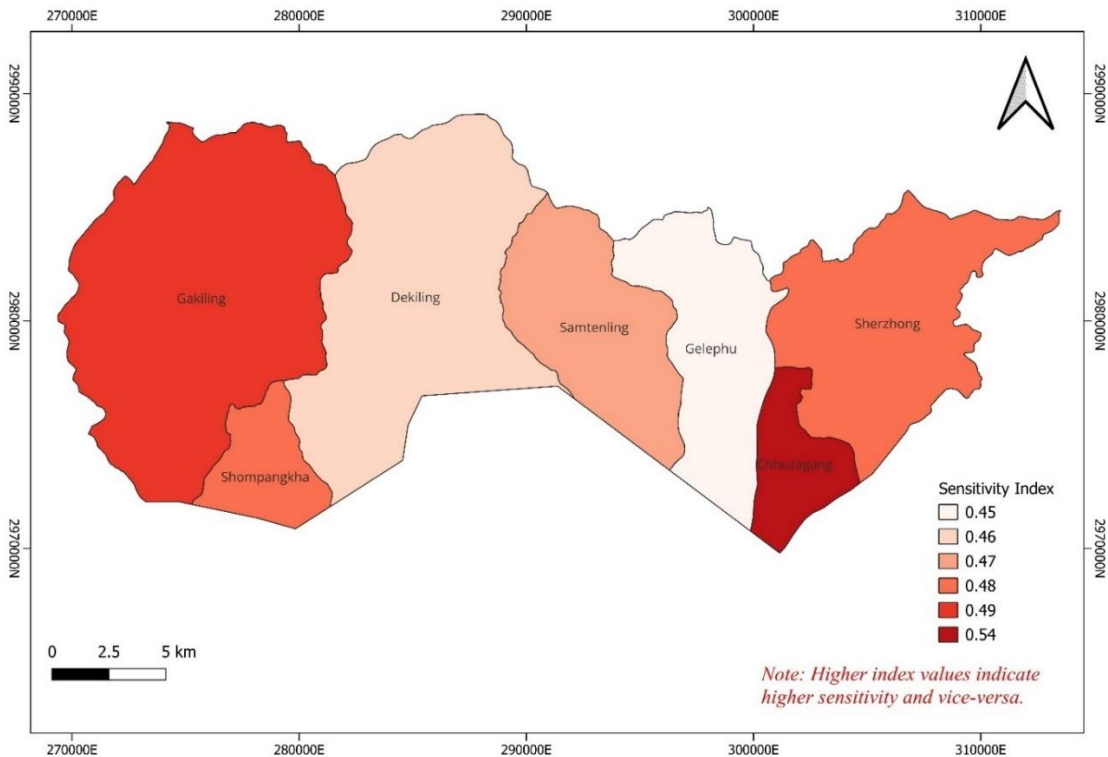
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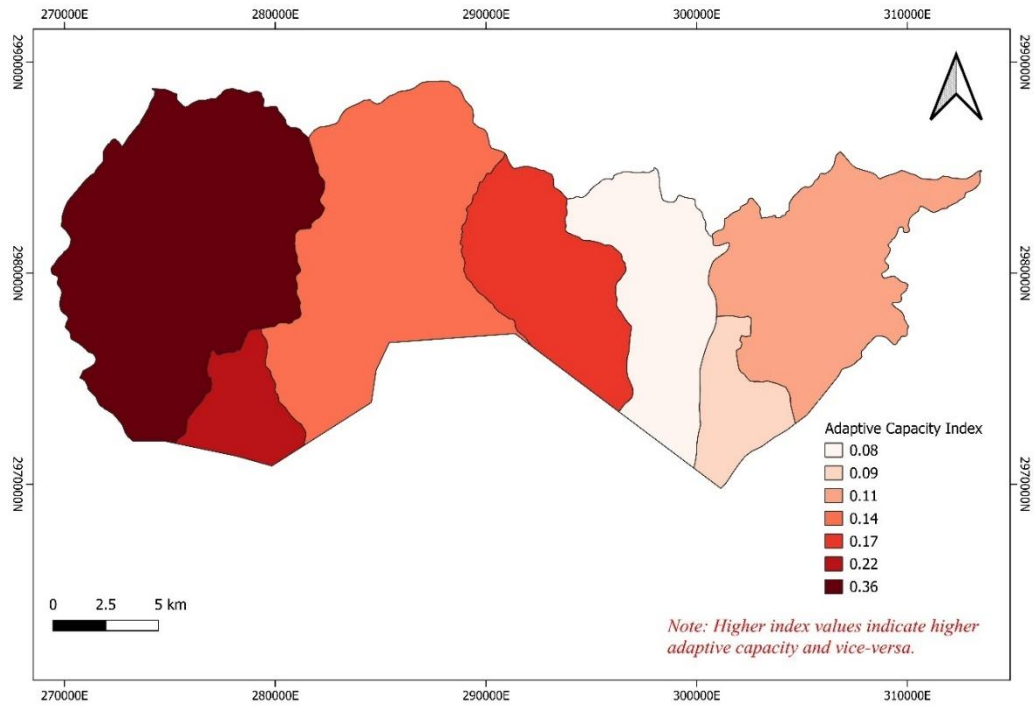
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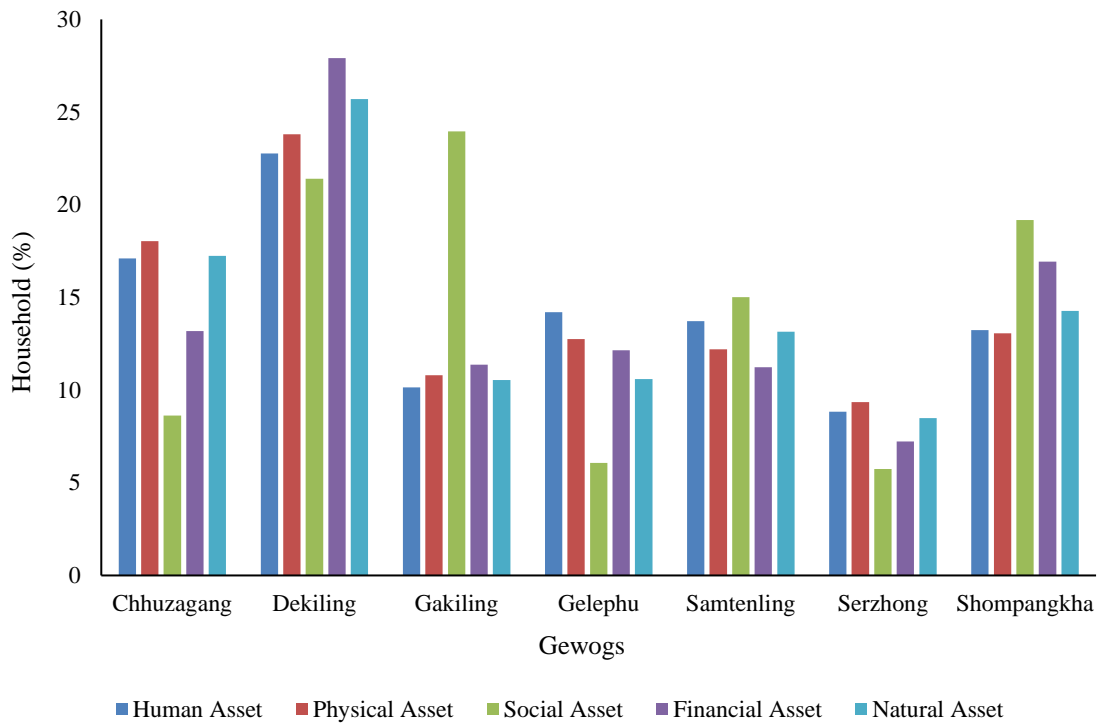
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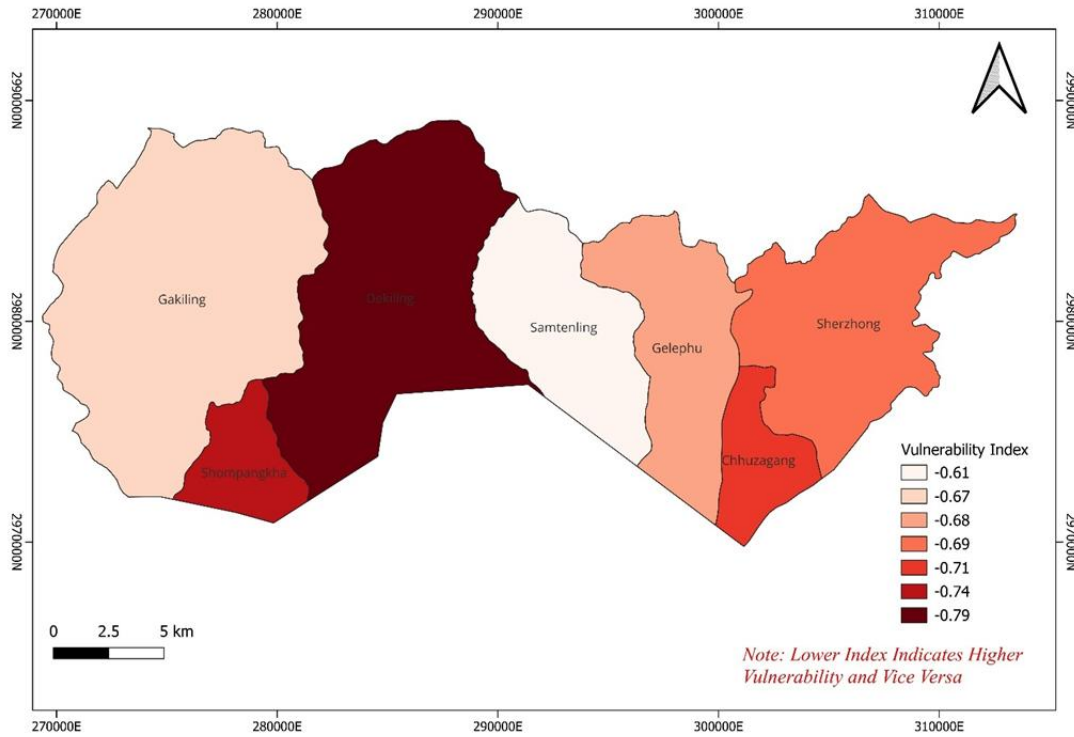
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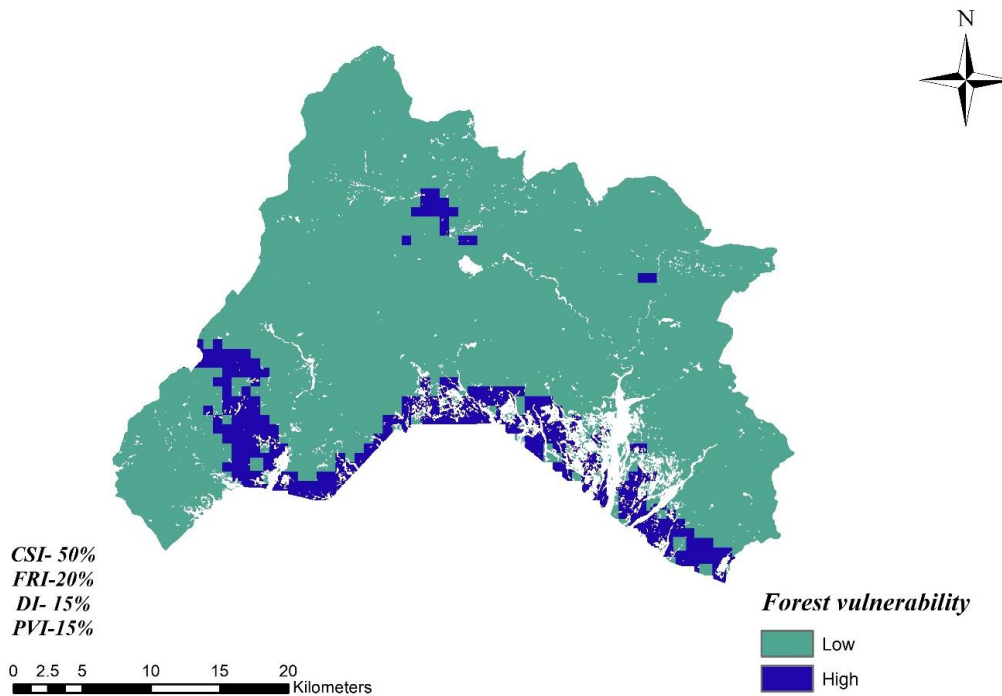
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**Figure 9: Spatial distribution of forest vulnerability to climate change across Gewogs in DFO Sarpang, Bhutan.**

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**Table 1: Weights and statistical significance of indicators contributing to exposure.**

Exposure Indicator	Weight	St. Err	Z-Value	Sig. (P-Value)
Extreme Temperature	1.000	0.00	0.00	0.000
Extreme Temperature Impact Types	3.050	0.199	15.324	0.000
Rainfall Seasonality	4.057	0.246	16.483	0.000
Rainfall Seasonality Impact Types	6.845	0.416	16.439	0.000
Extreme Events	2.377	0.161	14.798	0.000
Extreme Event Types	3.111	0.208	4.966	0.000

**Table 2: Number and percentage of respondents reporting unfavourable changes or increases in exposure indicators.**

Gewogs	Extreme Temperature (%)	Extreme temperature impact types (%)	Extreme events (%)	Extreme events impact types (%)	Rainfall seasonality (%)	Rainfall seasonality impact types (%)
Chhuzagang	108 (17.7)	98 (16.64)	108 (17.12)	65 (16.37)	108 (17.2)	44 (11.73)
Dekiling	153 (24.3)	143 (24.48)	153 (24.25)	90 (22.67)	153 (24.32)	100 (26.67)

Gakiling	62 (9.86)	58 (9.85)	62 (9.83)	49 (12.34)	62 (9.86)	52 (13.87)
Gelephu	85 (13.51)	80 (13.58)	86 (13.63)	52 (13.1)	84 (13.35)	46 (12.27)
Samtenling	84 (13.35)	79 (13.41)	84 (13.31)	56 (14.11)	84 (13.35)	47 (12.53)
Serzhong	55 (8.74)	50 (8.49)	56 (8.87)	34 (8.56)	56 (8.9)	29 (7.73)

**Table 3: Weights and significance of indicators on Sensitivity.**

Sensitivity Indicator	Weight	St. Err	Z-Value	Sig. (P-Value)
Crop Yield	1.000			
Pest and Diseases	2.724	0.322	8.459	0.000
Invasive Weeds	6.259	0.732	8.548	0.000
Invasive weeds Occurrence	6.081	0.706	8.612	0.000
Drinking Water	0.599	0.101	5.929	0.000
Irrigation Water	0.382	0.081	4.713	0.000
Forest Cover	0.945	0.164	5.770	0.000
Forest Composition	0.943	0.169	5.593	0.000
Wildlife Population	0.023	0.098	0.237	0.812
Vector Borne Diseases	-0.475	0.105	-4.521	0.000
Water Borne Diseases	-0.634	0.111	-5.721	0.000
Family Fatality	0.120	0.026	4.671	0.000
Pastureland	0.348	0.082	4.273	0.000
Infrastructure Impacts	0.930	0.129	7.196	0.000

**Table 4: Estimated financial losses due to livestock depredation and crop damage across Gewogs in DFO Sarpang.**

Gewogs	Estimated loss - livestock depredation (Nu)	Estimated loss - crop damage (Nu)
Chhuzagang	1,174,400	1,366,375
Dekiling	2,162,200	1,930,500
Gakiling	1,336,400	729,000
Gelephu	1,282,800	1,390,750
Samtenling	1,253,000	1,391,500
Serzhong	916,200	861,000

Shompangkha	888,800	772,875
<b>Grand Total</b>	<b>9,013,800</b>	<b>8,442,000</b>

**Table 5: Weights and statistical significance of indicators contributing to adaptive capacity.**

<b>Adaptive Capacity Indicator</b>	<b>Weight</b>	<b>St. Err</b>	<b>Z-Value</b>	<b>Sig. (P-Value)</b>
Human Asset				
Literacy of Household Head	1.000			
Vocational Skills	2.776	0.679	4.087	0.000
Gender of Household Head	0.503	0.239	2.106	0.035
Climate Awareness	0.432	0.140	3.088	0.002
Waste Awareness	1.788	0.572	3.125	0.002
Social Asset				
Community Group Membership	15.974	3.645	4.382	0.000
Community Group Membership Types	20.746	4.745	4.372	0.000
Natural Asset				
Forest Status	0.036	0.366	0.098	0.922
Wetland Status	-0.383	0.313	-1.224	0.221
Forest Produce Type	2.413	0.631	3.826	0.000
Landholding	0.952	0.254	3.749	0.000
Water Availability	1.756	0.522	3.365	0.001
Alternative Water Sources	1.693	0.442	3.833	0.000
Financial Asset				
Food Self-Sufficiency	1.919	0.516	3.717	0.000
Credit Access	2.127	0.532	3.999	0.000
Savings	1.218	0.331	3.675	0.000

**Table 6: Exposure, sensitivity, adaptive capacity, and vulnerability index scores of the Gewogs.**

<b>Gewog</b>	<b>Vulnerability</b>	<b>Exposure</b>	<b>Sensitivity</b>	<b>Adaptive capacity</b>
Chhuzagang	-0.71	0.26	0.54	0.09
Dekiling	-0.78	0.47	0.46	0.14
Gakiling	-0.67	0.53	0.49	0.36
Gelephu	-0.68	0.32	0.45	0.08
Samtenling	-0.61	0.32	0.47	0.17
Serzhong	-0.69	0.33	0.48	0.11
Shompangkha	-0.74	0.48	0.48	0.22