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Beyond Climate Reductionism: Environmental Risks and Ecological Entanglements in the Chittagong Hill Tracts of Bangladesh

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Abstract

Although Bangladesh is frequently regarded as 'ground zero' for climate change, the Chittagong Hill Tracts (CHTs) have only recently been acknowledged for their environmental vulnerabilities, especially after the devastating rainfall and landslides of 2017. However, attributing these risks solely to climate change overlooks their entanglement with structural inequalities, extractive development, deforestation, and long-standing marginalization. The study examines how climate variability intersects with broader environmental risks through a mixed-methods approach, integrating 30 years of NASA TRMM_3B42_daily rainfall data with a household survey (n = 400), life stories, focus group discussions, and key informant interviews conducted across all three CHT districts. Findings do not support a singular attribution to climate change. Rather, they reveal compounded vulnerabilities shaped by land degradation, water scarcity, flash flooding, and landslides—often linked to deforestation and neoliberal development interventions. We argue that the CHT exemplifies ecological entanglement, shaped by climate variability and structural inequalities rooted in land governance and Indigenous dispossession. By integrating spatially disaggregated climate data with historically grounded local experiential narratives, this study contributes to climate justice debates through relational, place-based understandings of vulnerability in the Global South.

Keywords: climate reductionism; Bangladesh; environmental onsets; livelihoods; conflict; everyday life; marginality

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Academic Editor: Charles Jones

Received: 16 April 2025
Revised: 23 May 2025
Accepted: 23 June 2025
Published: 30 June 2025

Citation: Nadiruzzaman, M.; Shewly, H.J.; Rashid, M.B.; Mukul, S.A.; Dutta, O. Beyond Climate Reductionism: Environmental Risks and Ecological Entanglements in the Chittagong Hill Tracts of Bangladesh. *Earth* **2025**, *6*, 63. https://doi.org/10.3390/earth6030063

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1. Introduction

In recent years, global temperature records have been repeatedly broken, reflecting a broader trend of accelerating climate instability. In this context, April 2024 was the

hottest month ever recorded in Bangladesh [1] Among the 19 warmest years recorded in the past one and a half centuries, 18 have occurred since the beginning of the 21st century [2]. Global climate shifts are evident in intensified cyclones, irregular precipitation, prolonged droughts, seasonal changes, and many severe weather events worldwide [3]. Bangladesh is situated in a vulnerable region, frequently subjected to numerous extreme events, earning global attention as the 'epicentre of climate change' and 'ground zero' for climate change [4–6]. Bangladesh has received significant research attention for climatic adversities [7]. A growing body of research explores increased soil salinity [8,9], sea level rise [10–12], and urban climate vulnerability [13–15] in Bangladesh. Visibly, the research focus on Bangladesh's climate change is dominantly on coastal areas. However, heavy monsoon downpours in 2017 caused a horrific landslide, mainly in the Rangamati district [16,17], and the climate change impact in CHT came into the discussion. Soon after that, the National Adaptation Plan (2023–2050) identified the CHT as a priority area for climate action. This research strives to contemplate this problem, framing it with a critical climate change lens [6,18].

This region is the most disadvantaged and vulnerable part of Bangladesh across almost all major development indicators [19]. The CHT area, comprising three administrative districts, namely Rangamati, Bandarban, and Khagrachari, is unique from other parts of Bangladesh because of its topography, vegetation, biodiversity, and diverse Indigenous groups and cultures [20]. Over the last four decades, this ecologically critical region has been experiencing violent conflict, militarization, structural deprivation, and the non-implementation of the peace accords [21–24]. Additionally, over the last few decades, it has been a place of controversial land acquisition for tourism, infrastructural development, and internal displacement [25,26]. The impact of climate change can be much more significant for Indigenous communities living in more remote and ecologically fragile zones and relying directly on their immediate environments for subsistence agriculture [27]. Climate change here, therefore, cannot be meaningfully understood in isolation from broader political and structural forces.

Recent research shows that climate adaptation policies often reproduce, rather than redress, structural inequalities [28,29]. Case studies from the Global South demonstrate that climate shocks tend to exacerbate existing injustices rather than constitute isolated crises [30]. Frameworks grounded in climate determinism frequently obscure the roles of governance failure, land dispossession, and socio-economic disparity [31]. Such climate-centric narratives mask the entanglement of environmental risks with political and social marginalization [32,33]. In Bangladesh, many studies uncritically attribute environmental changes solely to climate factors, overlooking the political economy of vulnerability [6,34]. This tendency—commonly termed climate reductionism or climate washing—risks de-politicizing complex socio-ecological crises [6,18,35–37].

In response, this paper develops the concept of ecological entanglement, drawing on political ecology [38] and critical environmental governance [33], to theorize how climate variability and environmental hazards are co-constituted with longstanding patterns of land dispossession, resource extraction, and political marginalization. To do so, this paper investigates three interlinked aspects: (i) prevailing weather variability and climatic trends in the CHT; (ii) how these interact with local livelihoods, biodiversity, and infrastructure; and (iii) how these changes are perceived, experienced, and governed by diverse actors.

Methodologically, we employ a multi-method design that combines satellite-derived rainfall time series (validated with station data and analyzed using MAD/MAPE diagnostics; see Section 3.3 and Supplementary S1), a household survey (n = 400), and extensive qualitative data from interviews, focus groups, and life histories. Fieldwork covered all three CHT districts and included participants of diverse genders, ages, livelihoods, reli-

gions, and languages—capturing the region's socio-cultural heterogeneity (discussed in Section 3.2). Rather than framing the analysis through linear causality, the study triangulates multiple datasets to situate climate signals within an ecologically fragile and politically complex landscape. This study, thus, does not seek to model climate impacts; rather, it aims to uncover how climate-induced hazards are enmeshed within broader socio-ecological and historical entanglements.

In doing so, this paper addresses a critical gap in climate and environmental research: the lack of scientifically and empirically grounded, politically attuned, and geographically specific studies of the CHT. Theoretically, it contributes to contemporary academic scholarship to move beyond climate-only narratives by offering a place-specific, context-sensitive, relational, multi-scalar understanding of vulnerability. It extends climate vulnerability theory by foregrounding ecological entanglement as a framework that links climate with conflict, dispossession, and governance. To deepen this analysis, the following section delineates the conceptual foundations of this study.

2. Understanding Climate Change Beyond the Climate-Reductionism Approach: Towards Ecological Entanglement

Climate change is an undeniable reality with widespread impacts on weather variabilities, precipitation patterns, and the magnitude and frequency of extreme events. But the changes are not identical across the globe. Global climate assessment reports, such as those produced by the IPCC, provide an overview of average changes across the globe. However, that does not proxy the climate change reality of a specific geographic location. Therefore, to assess the climate scenario of a specific geographic location, it is necessary to analyze 30–35 years of meteorological data from that area. Moreover, understanding long-term climate change trends necessitates baseline data from an even earlier historical reference point.

However, despite a growing number of research projects on climate change impacts, not much research refers to local data on climate change; instead, it makes an uncritical connection between the changed condition and climate change [18]. This uncritical space of the imagined interpretation of climate change makes room for climate washing. Such efforts of climate washing are problematic, as they fail to comprehend the complexity of the problem, and this could potentially divert attention and resources to a climate-only solution, which ends up being unsuccessful.

In conflict-affected, ecologically fragile regions like the CHT, environmental risks emerge from complex socio-ecological processes. We propose ecological entanglement as a critical framework to interrogate how hydro-climatic variability is inseparably intertwined with land dispossession, militarized governance, and extractive development. We conceptualize ecological entanglement as the recursive, relational, and co-constitutive interplay among above mentioned aspects. It is not merely a summation of environmental stressors and social inequities, but a framework that captures the dynamic, historically sedimented entwinement of environmental processes with power-laden social structures. Building on the insights of political ecology [38], which foregrounds the distributional injustices and power asymmetries embedded in environmental change, and critical environmental governance [33], which emphasizes the performative and contested nature of environmental authority, this concept transcends linear, deterministic, or mono-causal framings of ecological crisis. From intersectional climate justice [28,39], it takes the recognition that climate impacts are unevenly distributed along lines of ethnicity, gender, and territoriality, and extends this by examining how vulnerability is shaped through everyday negotiations of exclusion and structural marginality.

The ecological entanglement framework is operationalized through three interlinked dimensions:

(a) Climate change science combining meteorological data and people's experiences with climatic changes: Various attributions to climate change are used in contemporary research to show variability and future changes. Researchers often use local oral history/farmers' perceptions as a proxy for climate data [40–42] or the time series analysis of meteorological data and these data are compared with local perceptions [43]. IPCC climate projections [44,45] are increasingly used in research and decision-making processes. In this context, scholars have observed substantial discrepancies in slow climate variability at a regional scale and call for continued research on temporal and spatial structures of climate variability [46–48]. At regional scales, observational uncertainties do not simulate precipitation [49]. Additionally, there is low confidence in projections of changes in monsoons (rainfall, circulation) and regional-scale precipitation because there is little consensus in climate models regarding the signs of future changes in monsoons [50,51]. Therefore, comparing the alignment of projections with the accumulating observational data is essential. We argue that the attribution to climate change requires meteorological data assessments (in places where weather data is available) to comprehend the local and regional-scale impact precisely, which can be compared or linked with local perceptions of climate change. For instance, meteorological data in the CHT do not indicate significant temperature changes, yet local people report feeling increased heat. Qualitative inquiry supports this perception, revealing that deforestation and changing work patterns have increased exposure to direct sunlight. Similarly, although the volume of heavy rainfall has not risen, flash floods and landslides are becoming more frequent in this region. This connects to people's observational knowledge on land use change-induced soil erosion, surface runoff management, deforestation, unplanned development, and so on.

(b) Interplay of climatic and non-climatic factors that culminate in hazards: We contend that clarity between the climate change element and the underlying non-climatic conditions is essential for understanding the problem better and identifying options to address the issue [18]. In line with the growing literature challenging the naturalistic and linear understanding of insecurities [52–55], we consider it crucial to pursue a critical exploration of the broad spectrum of intersecting factors. For all disasters, there are many more factors at play than climate change alone; therefore, caution is required to avoid the conflation of the causes of extreme weather events and associated crises [6,56]. Such perspectives have also informed interdisciplinary campaigns like #NoNaturalDisasters (active since 2018), initiated by scholars and practitioners across the social and environmental sciences, which challenge the framing of disasters as 'natural' and instead highlight the socio-political conditions that render hazards disastrous.

To understand climate change attribution and evidence, we need to investigate climate change onsets (i.e., drought, flood, etc.), underlying conditions (i.e., knowledge and skills, economic condition, cooperation, ethnic tension, conflict, etc.), potential impacts and the complexity of the systems. In a region that has experienced low-intensity conflict, it is necessary to check whether climate change drives the deterioration of order and the restoration of (in)security. Unlike conventional vulnerability studies that isolate climate stressors as primary causal factors, ecological entanglement captures the recursive interactions between anthropogenic interventions (deforestation, infrastructure expansion, agrarian transitions) and hydro-climatic processes (rainfall variability, temperature shifts, and landslides).

(c) Construction of vulnerabilities: The impacts of climate change are uneven across the country or regions. Also, within a similar geographical setting, it affects different groups of people differently. In most cases, poor and marginal groups are the victims of the most brutal effects of environmental onsets [53,54]. Long-term livelihood sustainability is not

possible if socio-ecological conditions are degraded, institutions fail to adapt, competing interests are ignored, and ethical and political concerns are not built into decision-making [39].

In this connection, ecological entanglement offers a critical lens to understand vulnerability not as a fixed or technocratically solvable condition, but as a relational and historically embedded process shaped by the interplay of ecological disruption and political–economic power. While some of these issues have been explored previously, this study adds to the scholarship by integrating multiple dimensions and offering fresh insights into how climate change, environmental degradation, and development intersect in the under-researched context of the CHTs. In doing so, it advances a more nuanced, context-specific analysis of climate vulnerability—an urgent task in the face of the crisis's multicausal nature.

While ecological entanglement builds upon key insights from political ecology and critical environmental governance, it departs from these frameworks by offering an explicitly recursive and multi-scalar analysis of environmental risks in frontier zones. Unlike vulnerability frameworks such as the pressure-and-release (PAR) [55] or exposure–sensitivity–adaptive capacity triads used in IPCC reports, ecological entanglement foregrounds the historically rooted power relations, dispossession, and military-development regimes. In this sense, it complements—but also advances beyond—dominant climate-risk models by embedding biophysical processes within structures of political violence, land control, and epistemic marginalization. This approach thus demands a more situated ethics of environmental inquiry—one attentive to place, power, and history.

3. Materials and Methods

3.1. The Study Area

Located in the southeastern corner of Bangladesh, this region is geographically encircled by India to the north and east and Myanmar to the southeast (Figure 1). The region is characterized by hilly terrain, with elevations ranging from 450 to 1060 m, and features numerous valleys and cliffs. The CHT covers 12% of Bangladesh's total land area and contain nearly 40% of the country's evergreen to semi-evergreen forests [57]. Forests span approximately 1,105,353 hectares, accounting for over 80% of the region's land area [58].

The CHT forests are categorized into three groups: unclassified, reserved, and community forests [57]. The unclassified forests, primarily characterized by exposed hilly terrain, encompass 64% of the total forested area, whereas reserved forests, which encompass medium and dense forest types, account for the remaining 36% and are under the exclusive jurisdiction of the Bangladesh Forest Department (BFD). In addition to state-owned forests, the community-owned forests, commonly called the Village Common Forests (VCFs), span approximately 12,530 hectares [59].

This region is inhabited by 11–13 diverse Indigenous groups, constituting 55.77% of Bangladesh's total Indigenous population [60,61]. Recent data reveal that the CHT's overall population is 1,842,815, with 920,217 individuals (49.94%) belonging to various Indigenous groups, while 50.06% are Bengalis [61]. Historically, this region was a distinct geopolitical entity with its own social and political system, operating independently of colonial administration. This autonomy was reinforced by the 1935 Government of India Act, designating the CHT as a 'totally excluded area,' which prohibited Bengalis from the adjacent plain districts from purchasing land or establishing permanent residence in the region [23].

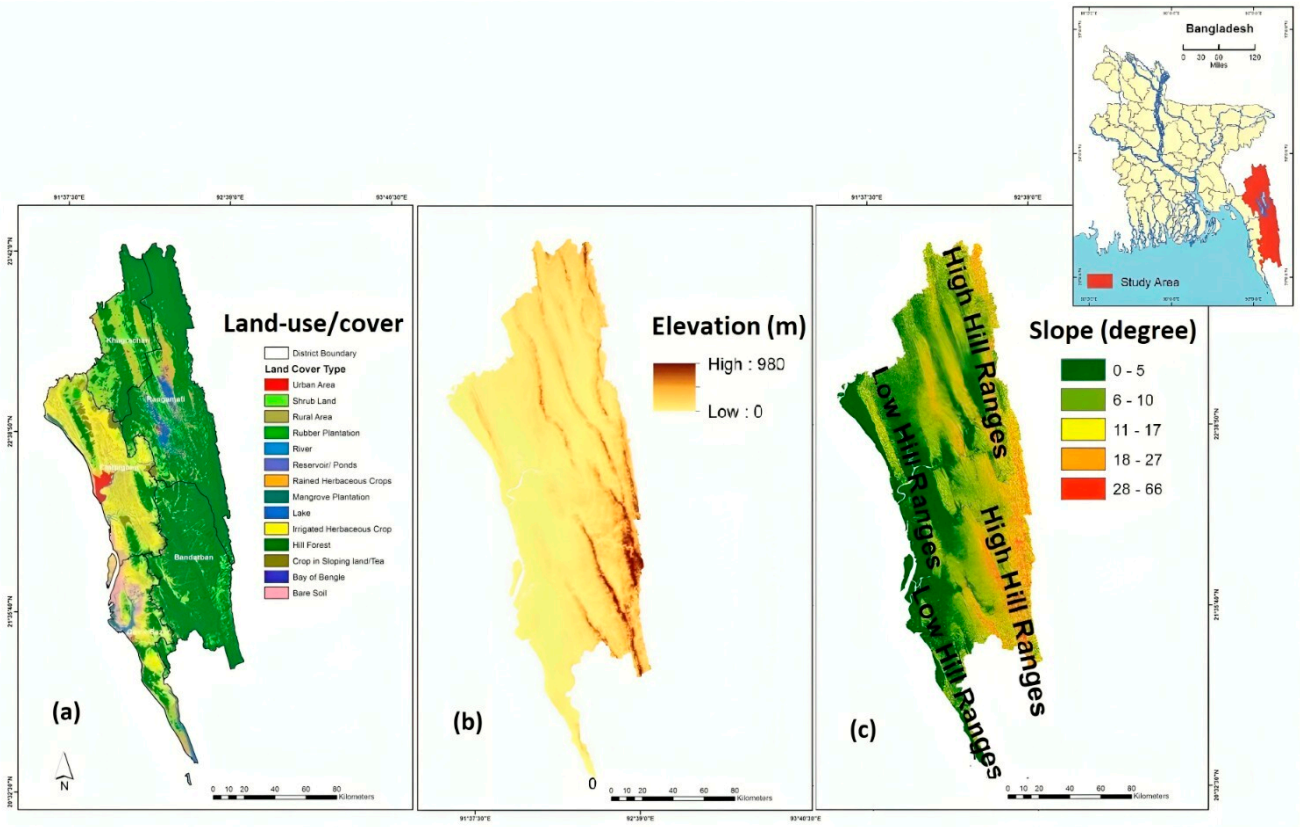

Figure 1. Map and location of the Chittagong Hill Tracts in Bangladesh with (**a**) dominant land use, (**b**) elevation, and (**c**) slope gradient.

The post-colonial states of Pakistan and, subsequently, Bangladesh sought control over the CHT's Indigenous territories through military, bureaucratic, political, demographic, and economic measures, leading to low-intensity conflicts and extensive displacement [23,24]. For example, the construction of the Kaptai dam in the 1960s submerged 40% of the region's arable land, displacing numerous Indigenous families, many of whom migrated to neighboring India and Burma. Despite a peace agreement in 1997, three critical political factors—the government's transmigration policy, ongoing militarization, and non-implementation of the CHT accord—have caused political instability among the Indigenous communities [25,62,63]. Past and current development projects, alongside increasing land grabbing in the name of the expansion of the tourism industry, have displaced local populations and adversely impacted the local ecosystem [64,65].

3.2. Field Data and Techniques

This paper is primarily based on questionnaire surveys, focus group discussions, interviews, observations, and casual discussions to gain insight into the local population's daily challenges. The questionnaire survey was conducted in January and February 2020. This was followed by focus group discussions and key informant interviews in 2021 and 2022. Additional follow-up observations, interviews, and informal discussions took place in December 2024 and January 2025. Data enumerators for the survey were from local ethnic groups, possessing in-depth knowledge of local cultural sensitivities, extensive social research experience, and fluency in local languages and dialects. The authors also built local networks during the field survey, which they later relied on during follow-up visits in subsequent years. These connections helped them cross-check and verify their understanding of the issues. In terms of data collection, this study aimed to encompass a diverse representation of ethnic groups (69% Chakma, 12% Mro, 11% Bengali, 8% Marma)

and various livelihoods (including agriculture, labor, livestock, poultry, fruit gardening, non-agricultural work, and more). This research also aimed to achieve extensive geographical coverage and engage diverse stakeholders, including local elites, elected representatives, government officials, and development agencies.

We calculated a sample size of 384 for a population of 1,586,141 [66], accounting for a 5% margin of error, a 95% confidence level, and a 50% response distribution. We then conducted surveys with 400 households to gather people's perspectives, knowledge, and experiences regarding climate change in their local contexts. In the survey, 68% of the informants were male and 32% female. The majority (49%) of respondents were between 28 and 42 years old, while 28% were aged 43 to 57. We conducted 21 interviews with personnel from public institutions and development organizations, held 6 FGDs involving 48 participants (approximately 6–8 members per group), and carried out 18 key informant interviews with community members. FGDs explored local views on the causes of changes, community practices, values, and beliefs. Interviews focused on agricultural practices, biodiversity, changes in employment and livelihoods, vulnerability, and coping strategies.

In developing the questionnaire, interview protocols, and FGD schedules, we engaged in a comprehensive review of the existing literature, alongside a critical reflection on our extensive experience in the development sector, spanning over a decade. Our methodological framework underwent scrutiny and approval by an independent review body, after which we conducted a pilot field test wherein data enumerators assumed primary roles under the direct observation of the research lead. This initial stage allowed all team members to observe interview techniques employed by others, document their observations, and subsequently discuss insights within the group. Based on feedback from this field test, the data collection instruments were refined for enhanced rigor and applicability. Random spot-checks were implemented during the data collection phase to ensure procedural consistency. Furthermore, daily debriefing sessions facilitated a collaborative environment where enumerators discussed encountered challenges, posed inquiries, and collectively devised standardized solutions. Upon completion of the data collection process, a comprehensive consistency check was conducted on each questionnaire to ensure data integrity.

3.3. Climatic Data and Techniques

One of the major challenges in developing climatic models is the availability and reliability of data from historically unchartered areas like the CHT. The region's only half-century-old weather station is located in the Rangamati valley. In that kind of undulating terrain, rainfall can vary significantly over short distances due to two key effects: the orographic effect and the precipitation shadow effect. Therefore, we had to rely on alternative data sources, which are representative of spatial variability and validated with existing weather station data.

Two of the major satellite-based widely recognized data sources used in the region are the Tropical Rainfall Measurement Mission (TRMM) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANNs). We collected precipitation and temperature data from both ground-based sources (for example, BMD's weather station at Rangamati) and both TRMM and PERSIANN satellite-based sources, covering 20 years from 1998 to 2019 on a grid-wise basis. However, satellite data are less reliable for capturing temperature variations in regions with diverse topographies. As a result, the climate forecasts and patterns presented in this study heavily rely on rainfall data.

Hassan et al. [67] analyzed daily PERSIANN and TRMM data and compared them with observed rainfall data. They found that while the spatial distribution of satellite-derived rainfall reasonably matched the observed data, there were differences in the

rainfall amounts. Chang, Cheung, and McAneney [68] studied TRMM rainfall estimates for ten typhoons that made landfall over Taiwan between 2007 and 2010. By comparing the TRMM data with radar reflectivity maps, they found that the overall rainband structures within the tropical cyclones were well captured by TRMM, both over ocean and land.

We compared the daily satellite-based rainfall estimates (both PERSIANN and TRMM data) and the rain-gauge data at Rangamati at the point-based station locations scale, covering 20 years from 1998 to 2019. The best performance is observed with TRMM data ($r = 0.63$), but PERSIANN showed a poor correlation with the rain-gauge data ($r = 0.54$) (please see details in the Supplementary S1). The loss of more localized convective rainfall is possible regarding the type of comparison. Therefore, it could be expected that differences occur between rain-gauge and satellite data.

Islam, Das, and Uyeda [69] explained that in monthly, seasonal, and annual scales, TRMM estimated rainfalls follow the similar distribution of historical patterns obtained from the rain-gauge data and the correlation coefficient of rainfalls between TRMM and rain-gauge data is obtained about 0.71. Since the correlation of TRMM is better than PERSIANN data, we estimated TRMM-derived rainfall for Bandarban and Khagrachari using observed data from Rangamati—where a BMD station is located—as a reference point for approximating rainfall in these mountainous regions [70].

3.4. Combining Field Data with Climate Data in Analysis

The above outlines the limitations of available climatic data and underscores why relying on a single station in a vast and topographically complex region is inadequate for robust climate change attribution. It also provides a strong basis to argue that labeling the CHT as a 'climate change hotspot' risks becoming yet another climate reductionist move [6]—one that obscures the broader drivers of environmental degradation that cumulatively lead to ecological stress. Therefore, though TRMM data are available from 1998 to 2019, we used this to obtain maximum precision in estimation. Thus, alongside observed changes in climatic data, we sought to understand how people experienced and responded to those changes within a continuously evolving context—particularly through life-history interviews with elderly individuals. Local oral history is a well-established proxy in climate research, offering critical insights that complement quantitative records [18]. In this study, such oral accounts helped supplement information on temperature and other meteorological variables.

The analysis of climate change trends in this region involved two key steps: (i) Time series plots, correlograms, and unit tests (like the Augmented Dickey–Fuller test) were applied to evaluate the stationarity of seasonal data for rainfall, temperature, sunshine hours, humidity, and wind pressure in each district. (ii) Trend analysis was carried out using linear, quadratic, and exponential models, with model selection guided by the Mean Absolute Deviation (MAD) and Mean Absolute Percentage Error (MAPE), for the stationary climatic variables. While we incorporate statistical diagnostics for climatic variability, the central analytical emphasis lies in contextualizing these trends through triangulated social data—foregrounding lived experience and institutional structures shaping vulnerability. Questionnaire survey data were coded, edited for consistency, computerized, and then collated, synthesized, and analyzed. Data were categorized by gender, age, location, learning background, and other social, economic, and cultural categories. Quantitative data were recorded numerically, while some qualitative data were converted using semantic differential or Likert scales. Informants' qualitative opinions obtained from semi-structured interviews, FGDs, and informal queries were transcribed, coded, and analyzed.

4. Results

4.1. Climate Change Projection for CHT

This section presents district-wise rainfall and dry spell patterns across the CHT to ground the analysis in observable climatic trends. These projections provide the meteorological backdrop against socio-environmental vulnerabilities. Bangladesh experiences four distinct seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). Analyzing data on intense precipitation between 1988 and 2017 reveals a decrease in the frequency of precipitation events ($\geq$89 mm) in all three districts. The highest documented rainfall occurred on 12 June 2017 in Rangamati (343 mm/24 h), on 9 June 2018 in Bandarban (170 mm/24 h), and on 12 June 2018 in Khagrachari (148 mm/24 h).

In Bandarban, the analysis of monsoon data (dry spells of $\geq$3 and $\geq$4 days without precipitation) demonstrates a notable trend of rising drying conditions during the 1998–2017 period (Figure 2). One of the major reasons for declining precipitation trends could be rising temperatures that increase the carrying capacity of moisture in the air. Ref. [71] analyze the BMD weather stations' data from 1980 to 2024 and suggest that across all the stations, there is a rising trend of temperature rise. As we see in Figure 2, in the monsoon season, the frequency of dry spells lasting over three days decreased in June, July, and September. However, a rise was noted in August, with recorded data from 2001 to 2017. The dry spell continuing over four days during the monsoon season denoted a consistent annual trend in June and September (2002–2016). However, the trajectory displayed an annual increase in July and August (2003–2015). The yearly decrease was observed in winter for more than 1 and 2 days of wet spells. In contrast, Khagrachari's monsoon data (dry spells $\geq$ 3) show a pattern of declining temperatures from 1998 to 2017, indicating that the dry periods lasted less than three days. This research also found that during the monsoon season (June–September), dry spells lasting three or more days either declined or stayed unchanged each year. Monsoon dry spells of $\geq$4 days demonstrated a yearly declining pattern in June and July. In August, the frequency of dry spells rose each year, while in September, the pattern remained unchanged. A yearly decline was recorded in winter (December–February) for wet spells of at least one day ($\geq$1), while wet spells lasting two or more days exhibited a rising trend. Monsoon data in Rangamati (dry spells $\geq$ 3 and $\geq$4) show a declining pattern in temperature from 1981 to 2016, meaning the dry periods lasted fewer than three days. This research also found that during the monsoon season (June–September), the dry spell of $\geq$3 days decreased each year except in June. Monsoon dry spells of four or more days indicated a yearly rising pattern in June and July. In August, the dry spell stayed constant from 1983 to 2004. In September, the four-day dry spell decreased each year. During winter (December–February), a yearly decline was noted for wet spells lasting at least one day, while wet spells of two or more days showed an annual increase. In December and January, wet spells lasting at least one day increased each year, whereas in February, there was no annual increase in wet spells.

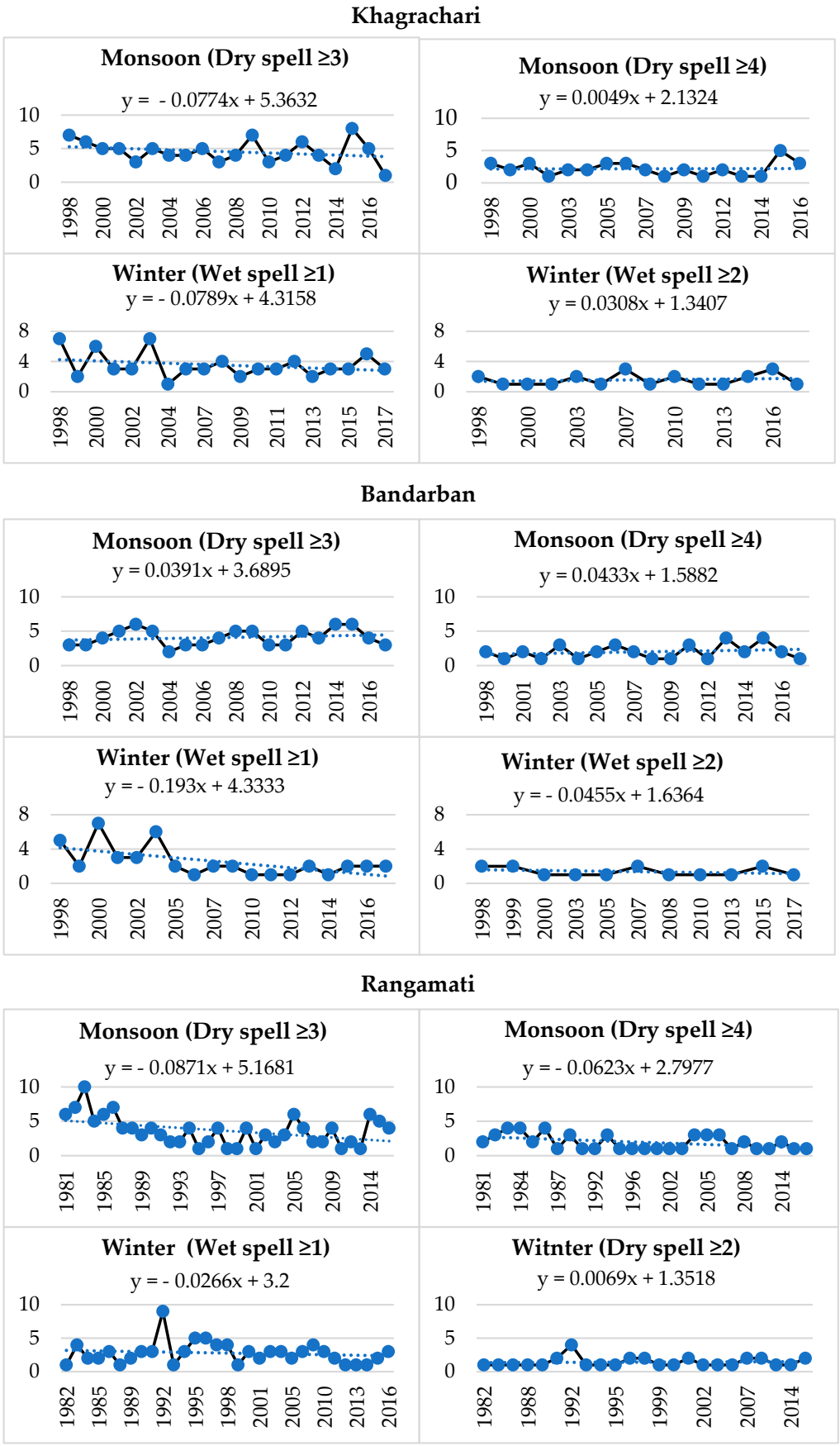

Figure 2. Climate change projection for CHT, Bangladesh (x-axis: year, y-axis: frequency).

4.2. Local Perceptions of Environmental Change in CHT

While climate data provide one layer of analysis, understanding vulnerability in the CHT requires attending to lived experience. This section examines how local communities perceive environmental changes, revealing how climate variability is entangled with perceptions of deforestation, industrialization, and declining ecosystem services. In the household survey, focus groups, and life-history interviews, people were asked about the local weather and surrounding environment in connection to their life and livelihoods; if they had sensed any change in the weather pattern and local environment, people were asked about what triggers that change, how that affects their everyday life, and what they do in response. There was a unanimous response about spotting changes. Over half of the informants responded that they knew about climate change (male 67% and female 33%). Almost all respondents (around 99%) noted noticeable shifts in the weather system in recent years. They perceived climate change based on variations in temperature, rainfall, and weather patterns. Unanimously, they attributed these changes to human activities, pollution, and broader environmental transformations (Table 1). One of the key changes they highlighted is a general increase in temperature across all seasons, significantly impacting their farming practices. About half of the informants across field sites have recognized feel-like temperature as the key indicator of environmental change.

Table 1. Public perception of causes and consequences of environmental stress (n = 400).

District	Upazila	Causes (%)		Consequences (%)			
		Destroying Forest	Industry	Rising Heat	Scarcity of Water Sources	Decreasing Rain	Soil Erosion
Bandarban	Bandarban Sadar	100	0	48	24	19	9
	Lama	100	0	50	20	20	10
Khagrachari	Khagrachari Sadar	100	0	94	3	3	0
	Lakkhichori	93	7	83	17	0	0
Rangamati	Rangamati Sadar	91	9	66	34	0	0
	Naniarchar	95	5	0	66	34	0

Deforestation was identified by 90–100% of informants across all study sites as the primary driver of environmental change. In certain areas of Rangamati and Khagrachari, where industrialization's effects are noticeable, this was also highlighted as a contributing factor. Respondents described their experiences of these changes, emphasizing increased heat and water shortages, especially during the dry season. Interviews and conversations with residents in all field sites revealed that winters have become shorter in recent years, meteorological patterns are shifting across seasons, temperatures are rising, and thunderstorms are occurring more frequently than before.

4.3. Impact of Changed Rainfall and Temperature on Agriculture, Poultry, and Livestock

As climate and ecological conditions shift, their impacts cascade through agricultural and food systems. This section explores how altered rainfall and temperature patterns intersect with structural land degradation, market fluctuations, and livelihood uncertainty—underscoring the co-constitution of ecological and economic stressors. The primary crops in the CHT include rice, ginger, turmeric, mango, and jackfruit, along with secondary crops like pumpkin, cucumber, chili, pineapple, banana, and pomelo [72]. Survey data show that environmental hazards like storms, soil erosion, landslides, floods, excessive rainfall, and rising temperatures significantly impact agriculture (Figure 3). However, over three-quarters of respondents were unaware of upcoming disasters. Additionally, 85% of informants reported a sharp decline in crop prices due to environmental stresses,

with the most severe effects in Khagrachari Sadar (99%) and the least in Rangamati Sadar (49%), directly affecting their income. Beyond income loss, changing rainfall patterns have increased irrigation costs and worsened water scarcity, particularly during crop seasons. Local farmers noted that even slight fluctuations in temperature and rainfall affect agricultural yields and the local economy. In Rangamati, farmers are increasingly forced to buy climate-resilient seeds and fertilizers at higher prices due to land degradation and rising production costs. Therefore, reliance on hybrid seeds, pesticides, and chemical fertilizers has grown, often contaminating water sources and harming aquatic ecosystems.

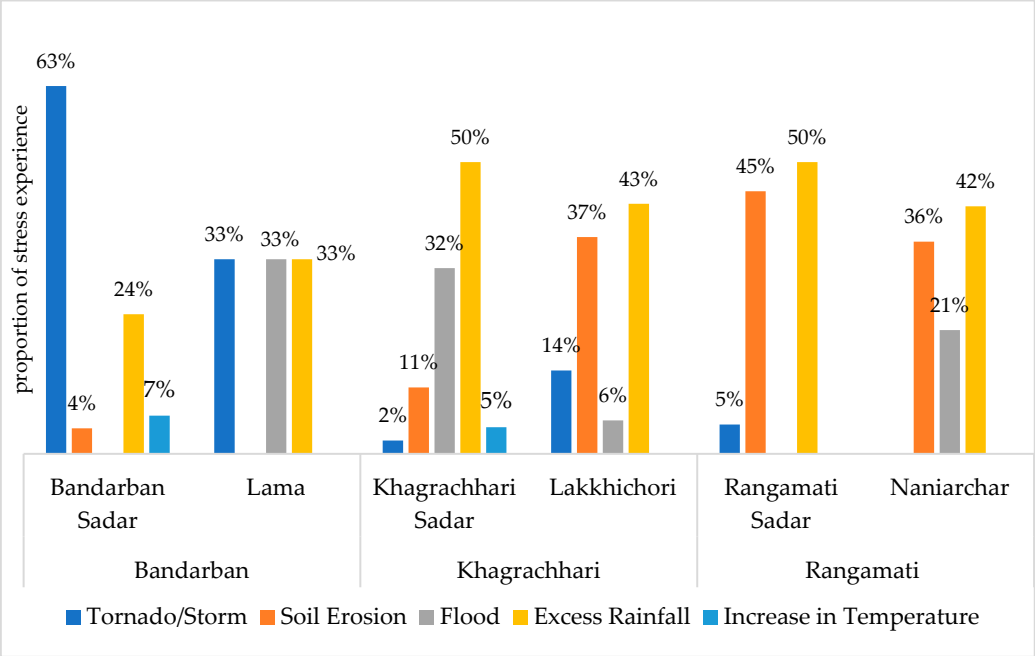

Figure 3. People's experience of environmental stress in the last 10 years.

4.4. Increased Environmental Stresses and Water Scarcity

Water scarcity emerges as a key manifestation of ecological entanglement. Here, we analyze how changes in water availability reflect the combined pressures of deforestation, infrastructure expansion, and shifting hydro-climatic patterns, complicating simplistic attributions to climate change alone. Of the informants, 57% feel that water sources have shifted over the past decade. They attribute this change primarily to two factors: 47% point to the increased use of tube wells for water collection, while 37% cite the reduction in forested areas. Additional factors mentioned during interviews and discussions include rock extraction, rising temperatures, and intense rainfall. Excessive water extraction from the same tube wells has led to a drop in water levels. Among the informants, 40% depend on shallow tube wells for drinking water, while 24% use deep tube wells, and 18% rely on springs. Smaller water sources, including ponds, rivers, rainwater harvesting, waterfalls, and supplied water, are also used. Most water sources (85%) are located within 0–1 km, while the remaining 15% are situated between 1 and 2 km away. Half of the informants link deforestation to water scarcity, while the rest mention factors like rising temperatures (29%), falling water tables (14%), and rock extraction (7%) as contributing causes.

Our survey data show that more than half of the informants faced water shortages during extreme events, with Bandarban Sadar and Lakhhichori being particularly affected. Water scarcity intensifies during environmental stresses, especially flash floods, which are the main contributors to shortages, along with landslides and cyclones. Flash floods were especially severe in Lama, affecting 89% of the population. Cyclones and landslides had a major impact on Khagrachari Sadar (44%) and Naniarchar (58%). Over half of the

participants (55%) reported having to travel to nearby villages to collect water in response to the shortage. To cope, they took measures like digging new springs and boiling water for drinking. In Khagrachari Sadar, 84% of individuals are forced to fetch water from surrounding villages, with women being the primary individuals involved in this task.

4.5. Changes in Biodiversity

Biodiversity loss in the CHT reveals the cumulative effects of forest degradation, commercial monocultures, and shifting rainfall regimes. Here, we document community accounts of species disappearance, situating ecological decline within broader political–economic transformations in land use. The CHT are renowned for their magnificent biodiversity, distinctive landscape, vast forest reserves, rich cultural heritage, and stunning natural beauty. Discussions during interviews and household surveys consistently emphasized the following cyclic impacts. For example, an anonymous headman highlights the following:

'Over the past several decades, the population in the CHT has significantly increased, resulting in expanded and intensified land use patterns in the hill forests, accompanied by increased deforestation and commercial forestation activities. Consequently, the overall ecosystem and biodiversity in the CHT have been significantly affected'.

Informants were asked about their views on local biodiversity loss, and their overwhelming responses pointed to deforestation (Figure 4).

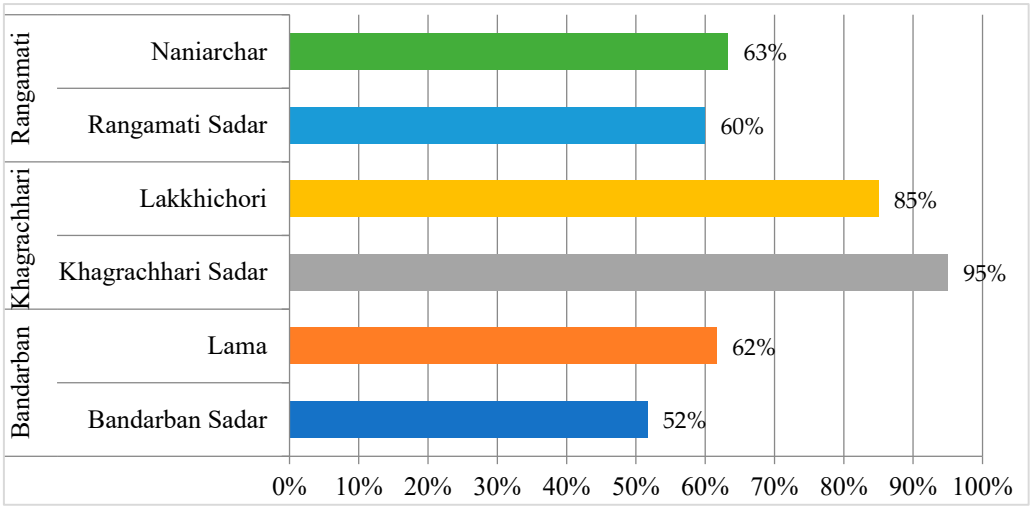

Figure 4. Ratio of locals identified deforestation as the leading cause of biodiversity loss in CHT.

Plant species such as Garjan, Chapalish, Jarul, and Koroi are experiencing severe decline in Khagrachari Sadar and Lakkhichori. In Rangamati Sadar and Naniarchar, Garjan and Chapalish are also facing rapid reductions. Local communities have identified Garjan as the most at-risk species in the CHT. However, these observations tend to focus on the more prominent species seen throughout the community's lifetime, often overlooking smaller shrubs, vines, and other lesser-known plants that, although not immediately noticeable, play a vital environmental role and are gradually disappearing.

The disappearance of the species mentioned above indicates a loss for those dependent on them for sustenance and shelter within their canopy. Informants (78%) also acknowledge the adverse impact on wildlife in the CHT. Species documented during interviews include fox, bear, and deer in Bandarban Sadar and Lama; bear, deer, and wild pig in Khagrachari Sadar; deer and Moorhen in Lakkhichori; fox, deer, and monkey in Rangamati Sadar; and fox, deer, and pig in Naniarchar.

4.6. Impact on Income, Livelihood, and Economy

Livelihoods in the CHT are highly sensitive to cascading environmental risks. This section links ecological disruption—deforestation, water scarcity, and biodiversity loss—with income instability, infrastructural breakdown, and economic precarity, highlighting the material consequences of ecological entanglement. Extreme environmental events significantly impact infrastructure, particularly in the Khagrachari region, where roads, culverts, and bridges suffer extensive damage. These disruptions result in agricultural losses, interrupted communication, halted economic activities, and declining soil fertility, all of which pose serious challenges to local communities. These factors have a considerable impact on people's livelihoods, with only 26% of respondents feeling that their current means of living can sufficiently adjust to these changes. Moreover, 71% of respondents recognized that extreme events harm local infrastructure, including roads, culverts, and bridges. This damage has led to business losses varying between 22% and 94% across different regions, with the most significant losses seen in the Bandarban and Khagrachari districts. Additionally, 15% of those surveyed indicated a desire to switch professions due to increasing environmental pressures, with 76% of them opting for physically demanding work, whether in agriculture or other industries, regardless of gender (Figure 5).

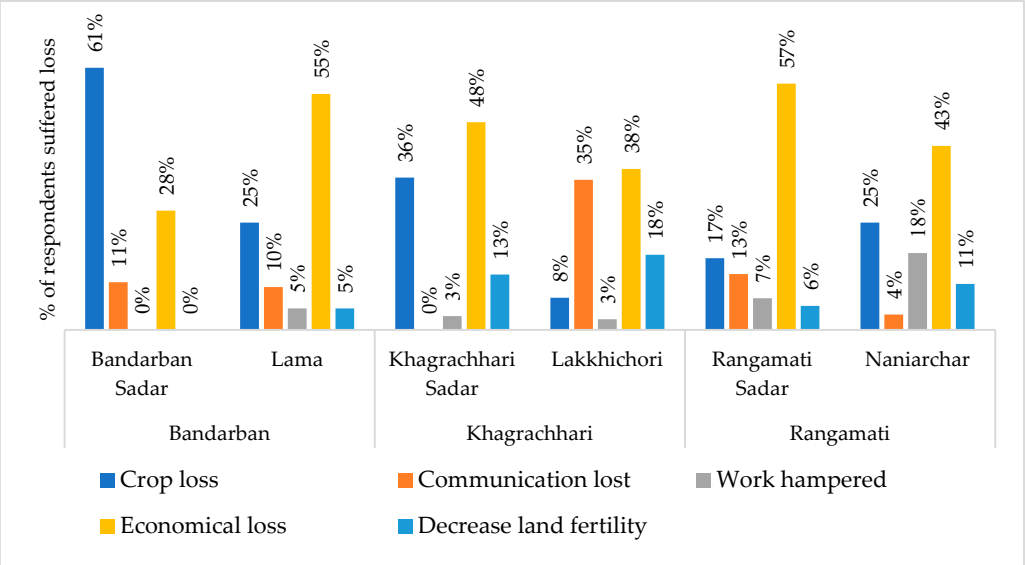

Figure 5. Ratio of affected informants who suffered environmental stress-induced material losses.

The destruction of local infrastructure disrupts transportation and agricultural trade, resulting in reduced earnings. This infrastructure damage primarily led to business declines in Khagrachari and limited access to essential services like healthcare and education. The most significant challenge was the decline in crop yields and widespread livestock fatalities throughout the area.

5. Discussion

5.1. Understanding Climate Change in the Context of CHT

The meteorological data indicate a decrease in the rate of heavy precipitation (>89 mm) throughout the region, which has been detailed in the results section. The duration of monsoon dry spells (>3 and >4 consecutive full dry days) is increasing in Bandarban, while marginally declining in Rangamati and Khagrachari. These patterns suggest that Bandarban may face more frequent dry monsoons, intensifying stress on crop production, vegetation cover, and water availability. In contrast, Rangamati and Khagrachari might experience milder fluctuations in monsoon behavior. Regarding wet spells (>1 day) in

winter, Bandarban shows a decrease, while Rangamati and Khagrachari exhibit an increase. While integrating meteorological data with local experiences does not confirm a direct link between climate change and its immediate impacts on the well-being and livelihoods of CHT residents, it also does not rule out the possibility of future climate-driven effects. Extreme hydro-climatic events such as intense precipitation and severe storms remain a concern. Emerging climate events such as landslides, floods, and hurricanes in the CHT are closely linked to underlying factors, including extensive infrastructure development, changes in land use and cover, and the degradation of forests and biodiversity. These combined factors have significantly affected the overall environmental conditions, aligning with the weather variations and other adverse climate impacts experienced by CHT residents over time.

The CHT have just recently been in Bangladesh's national disaster hotspots. Lately, flash floods and landslides have dominated disaster reports. On 13 June 2017, continuous rainfall and massive landslides ravaged the hill districts of Rangamati, Bandarban, and Khagrachari, claiming 152 lives [73]. Hundreds of sustained injuries and approximately fifteen-thousand families were severely affected, losing most of their possessions. Landslides devastated farmland, ruined harvests, and severely damaged infrastructure, including roads and power systems. This recent event has been consistently echoed in the accounts of the informants. The same amount of pouring twenty years ago and now would have very different effects due to significant alterations in the CHT's landscape and land utilization over time. For instance, looking at the data for the heaviest rainfall, Rangamati witnessed similarly heavy rainfall in 1998, 1999, 2004, and 2017, with each event surpassing 300 mm. However, there has been a significant increase in landslides in recent years. Geology, land use, and land cover change were categorical variables for the 2017 landslide, which was triggered by excessive rain [16,17]. Abedin et al. [17] reveal two important causal relations in their study; the largest landslide occurred in a rubber garden where natural forests were cleared to plant rubber trees. Landslide occurrence had an inverse relationship with distance to the road network; most of the landslides (96.29%) occurred within a 2 km distance to the road. These scientific research findings also match the local voices in our study. Sifat et al. [16] warn that the large number of landslides has made the slope unstable, thereby increasing the possibility of slope failure in the area more than before, in which Rangamati Sadar is the highest-risk zone. The increasing frequency of flash floods and landslides should not be seen merely as "natural hazards," but as symptoms of ecological entanglement, emerging from the convergence of development-induced deforestation, landscape instability, biodiversity loss, and climatic shifts.

Deforestation was a central cause for all measures in the research participants' accounts. Forest loss—identified by 90–100% of respondents as the primary driver of environmental change—cannot be understood outside its political–economic context. The process of forest degradation began during the British colonial period and has accelerated in recent times by the privatization of forest land for the promotion of sedentary agriculture, horticulture, and rubber plantation; the construction of a hydraulic dam on the Karnafuli River; the settlement of lowland Bengali people; militarized governance; and the constant conflict between Indigenous people and the Forest Department [21,63,74,75]. Despite governmental restrictions on access to reserved forests, the region continues to experience a concerning rate of forest loss. For instance, between 2000 and 2015, the extent of forest cover in the CHT diminished by 8% [76]. Furthermore, government-led restoration initiatives have shown limited concern for ecological functionality, biodiversity preservation, and environmental sustainability [57]. The annual forest destruction rate in Bandarban Sadar Upazila is 17.92% [77]. Thus, over the decades, colonial and postcolonial state interventions have altered the region's socio-ecological fabric. This historical narrative of land transformation,

deforestation, soil erosion, intense rainfall, flash floods, and landslides is interconnected. An all-encompassing perspective is required to grasp the interrelation of development, hazards, and climate variability. While flash floods and landslides in the CHTs are mostly related to man-made soil erosion and deforestation, the frequency and severity of such disasters are likely to increase sharply because of climate change-induced precipitation increases [78].

In this light, climate change is an amplifier of socio-ecological processes that were already set in motion by historically rooted and structurally embedded forms of extraction. Neoliberal development agendas—marked by commercial land leasing, plantation economies, and tourism infrastructure—have restructured local ecologies while intensifying risks for Indigenous communities [26]. These processes are not only environmental but also political, revealing how ecological degradation is entangled with patterns of militarization, land dispossession, and uneven development.

5.2. Complex Governance and Power Dynamics in CHT

The socio-ecological vulnerabilities outlined above are inseparable from the region's complex governance structure. The CHT remain governed through overlapping de jure and de facto controls, where militarization, nominal decentralization, and parallel systems of authority limit community agency and environmental accountability.

The region has been militarized for over forty years, despite the 1997 peace treaty aimed at ending this military presence. The military not only oversees security through camps and checkpoints but also develops roads and operates tourist sites. Viewpoints are increasingly constructed within ecologically sensitive reserved forests—such as the Kurukpata viewpoint in the Matamuhuri Reserve Forest—undermining both the legal protections and the ecological integrity of these conservation zones. These governance arrangements do not operate in isolation from the broader development paradigm. In 2020, a planned five-star hotel on the Indigenous Mro area in Bandarban faced strong resistance, prompting a joint communication from UN human rights experts [79], after which Marriott withdrew. The project was quietly postponed without official disclosure. In the CHT, neoliberal development operates not only through market-driven projects but also through militarized commercial land control and ethnic exclusion, enabling land commodification and infrastructure expansion. It is thus structurally entwined with political governance, reinforcing Indigenous marginalization and environmental vulnerability.

The CHT's governance structure comprises three overlapping systems [80]. First, it follows Bangladesh's national administrative hierarchy: Union Parishads, Upazila Parishads, and District Administrations. Second, a parallel Indigenous system—formalized during British rule—includes karbaris (village managers), headmen (mouza level), and rajas (Circle Chiefs). Third, the 1997 CHT accord established a semi-autonomous governance framework, including the CHT Regional Council and three Hill District Councils. While many provisions of the accord remain unimplemented, it formally recognizes the Indigenous system and grants the councils responsibilities for development and law and order [80]. Customary leaders, including karbaris, retain a strong influence in rural areas. In practice, however, decision-making—especially over land and resources—is often influenced by the District Administration and military, whose involvement, as noted in interviews, sometimes overrides Indigenous institutions [81,82]. This layered structure—combining formal, traditional, and militarized authorities—generates administrative incoherence, legal ambiguity, and jurisdictional conflict, especially around land governance, conservation, and development.

Relations between military forces and Indigenous communities remain strained, with differing narratives surrounding the causes of the tension and military actions in the

region, particularly their involvement in tourism and land dispossession. Armed factions with varying demands, including autonomy within Bangladesh, remain active in remote forest areas. While the military blames them for insecurity, the Army is also accused of enabling such groups to justify its continued presence and control [23]. All these factors create a complex governance environment where power dynamics vary across the region. Effective engagements on environmental and climate change issues require a nuanced understanding of local contexts, careful management of intergroup relations, and long-term, community-based involvement in navigating through various official and unofficial governance hurdles.

Across multiple empirical domains—rainfall trends, deforestation, biodiversity loss, livelihood precarity, and governance fragmentation—our analysis reveals a pattern of entanglement, where climate variability both emerges from and amplifies structural dispossession. While this research shows that military and political activities exacerbate environmental risks, a deeper analysis of how such socio-political factors may directly influence climate change is beyond the scope of this study. The interplay—where climate variability both emerges from and amplifies structural dispossession—remains an important area for future research.

6. Conclusions, Recommendations, and Future Research Directions

This study demonstrates that environmental and livelihood vulnerabilities in the Chittagong Hill Tracts (CHT) cannot be attributed solely to climate change. Rather, they emerge from interlocking socio-ecological pressures, including deforestation, infrastructural expansion, and structural marginalization. Climate variability acts as an aggravating force within a historically embedded system of ecological degradation, uneven development, and contested land relations. Empirically, the intensification of water scarcity, reliance on climate-resilient seeds, and agricultural distress illustrates how hydro-climatic events intersect with extractive land use and fragmented governance, producing forward-looking and deeply uneven risks.

Theoretically, this paper advances ecological entanglement as a framework to move beyond climate reductionism and technocratic adaptation paradigms. Rather than departing from existing socio-ecological and vulnerability frameworks, it extends and deepens them by foregrounding the political–economic dimensions of climate risk—showing vulnerability as a historically constituted, relational process rooted in militarized development, colonial legacies, and Indigenous dispossession. This theoretical move advances climate scholarship toward a more politicized, place-based, and justice-oriented understanding of socio-ecological risk, particularly within postcolonial frontier zones. Moreover, ecological entanglement enriches political ecology by highlighting the recursive interplay between environmental risks, militarized infrastructures, and structural marginalization.

By integrating meteorological data with local knowledge, this study provides a nuanced understanding of climate variability in the region and its cascading effects on livelihoods, biodiversity, and social dynamics. In doing so, it enriches contemporary debates of intersectional vulnerabilities [39,56]. This enables a situated reading of climate signals within a deeply contested socio-political terrain, where knowledge production itself is entangled with histories of marginalization.

The findings emphasize that adaptation strategies must be context-sensitive, acknowledging the interplay between climate-induced hazards and anthropogenic transformations in the landscape. Despite national commitments articulated in frameworks such as the CHT accord, the Bangladesh Climate Change Strategy and Action Plan (BCCSAP), and Disaster Risk Reduction (DRR) strategies, practical implementation remains fragmented, top-down, and often blind to local governance realities. Non-implementation is not merely

a logistical shortcoming but reflects deeper power asymmetries, institutional inertia, and the marginalization of both Indigenous voices and ecological concerns.

This study recommends four interlinked and actionable directions: first, to institutionalize accountable land and forest governance by legally recognizing Indigenous-led community forest management systems and treating nature as both co-governing presence and a right-bearing entity rather than a resource to be extracted; second, to establish participatory environmental oversight councils that can monitor and regulate development and tourism activities with an eye toward ecological limits and community accountability; third, to foster the integration of Indigenous and scientific knowledge systems in climate-risk planning and communication, enabling plural epistemologies to inform adaptation strategies; finally, effective climate adaptation planning requires confronting the gap between formal policy commitments and on-the-ground governance realities by fostering inclusive, locally grounded processes that support Indigenous stewardship and recognize ecosystems as relational and regenerative. These proposals are grounded in empirical evidence and community narratives, but they also signal broader structural tensions that national adaptation policies have yet to confront.

Finally, this research provides a framework for future studies on climate change in the CHT by illustrating how environmental risks must be understood in their localized socio-ecological contexts. Ecological entanglement emerges not only as a conceptual critique of climate reductionism but also as a transferable analytic for examining socio-ecological vulnerability across other frontiers or conflict-affected zones globally. This synthesis of climatology, lived experience, and structural analysis opens new directions for place-based, justice-oriented environmental research in the Global South and beyond. It calls for sustained interdisciplinary research that bridges climate science with political and socio-economic analysis, advancing adaptation as both a socio-political and ecological practice—one that ensures justice for both communities and the ecologies they inhabit.

End Note: The term 'indigenous' refers to the population covered by the United Nations' definition of 'indigenous people'. The term has a political connotation for material reasons. The government of Bangladesh uses an umbrella term, 'ethnic minorities,' which allows it to neoliberalize Indigenous peoples' land without worrying much about any international legal remedy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/earth6030063/s1, Supplementary S1: Trend Analysis of Rainfall and Temperature at Rangamati, Bandarban and Khagrachari.

Author Contributions: Conceptualization, M.N. and H.J.S.; methodology, M.N., M.B.R. and H.J.S.; software, M.B.R.; validation, M.N., O.D. and H.J.S.; formal analysis, M.N., M.B.R. and H.J.S.; investigation, M.N., M.B.R., S.A.M., O.D. and H.J.S.; data curation, O.D.; writing—original draft preparation, H.J.S. and M.N.; writing—review and editing, H.J.S., M.N., M.B.R., S.A.M. and O.D.; visualization, M.B.R. and S.A.M.; supervision, M.N.; project administration, M.N.; funding acquisition, M.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The authors are indebted to all the informants for being so open and kind. We are grateful for the comments, reflections, and feedback received from experts and development practitioners at various knowledge-sharing events. Part of this research was funded by the Excellence Cluster 'CLICCS—Climate, Climate Change, and Society' (EXC 2037, Project 390683824), supported by the Deutsche Forschungsgemeinschaft (DFG) at the Center for Earth System Research and Sustainability (CEN), Universität Hamburg. Additional fieldwork funding was provided by the Amsterdam

Institute for Social Science Research (AISSR), University of Amsterdam (Political Tree project).We are deeply grateful to the three anonymous reviewers for their insightful comments, to the editor and Editor-in-Chief for their generous editorial support, and to Earth for its administrative assistance and for inviting our APC-weaved submission.

Conflicts of Interest: The authors declare no conflicts of interest.

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