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Climatic Trends and Their Impacts on High-Altitude Ecosystems in Nepal: Implications for Biodiversity and Ecosystem Services

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Abstract

Nepal's high-altitude ecosystems (>3000 m asl) are experiencing unprecedented impacts from climate change, with profound implications for biodiversity conservation and ecosystem services. This systematic review synthesizes evidence from 72 peer-reviewed studies to assess climatic trends and their ecological consequences in the Nepal Himalaya. Temperature records from 1976-2015 reveal significant warming trends, with higher elevations experiencing more pronounced increases (0.045°C y^{-1} for maximum temperatures). Climate projections indicate continued warming of 1.2-4.2°C by the 2080s under RCP8.5 scenarios, with precipitation increases of 11-23% by 2100. These climatic changes are driving cascading ecosystem effects. Glacial retreat has accelerated, with 15% reduction in glacier surface area over five decades and upward snowline shifts of 182 m in the Everest region. Freshwater ecosystems face mounting pressures from altered hydrology and increased glacial lake outburst flood risks. Forest ecosystems exhibit treeline advance (2.61 m y^{-1} for *Abies spectabilis*), phenological shifts, and upslope vegetation migration. Biodiversity impacts include altered species distributions, invasive species expansion, and habitat degradation for endemic species. The convergence of warming temperatures, changing precipitation patterns, and extreme weather events poses significant threats to Nepal's mountain biodiversity hotspots and ecosystem services. These findings present the urgent need for integrated climate adaptation strategies and science-based conservation approaches to safeguard these vulnerable ecosystems. Nepal's mountainous regions serve as both indicators of global climate change and critical refugia requiring immediate conservation attention to maintain ecological integrity.
Keywords: *Temperature, Precipitation, Forests, Water, Biodiversity*

Introduction

The world's biodiversity is cradled and protected by mountains (Rahbek et al., 2019), hosting nearly half of the planet's biodiversity hotspots. They are home to a diverse range of species, including many that are endemic, rare, or threatened. Diversity of species is exceptionally high in mountains and outside of Antarctica that covers 12–30% of Earth's land surface. Himalayan slopes occupy the majority of Nepal's land area creating enormous environmental heterogeneity. The distinct physiographic and topographic features of Nepal harbor a diverse range of western niches for diverse flora and fauna. Stretching approximately 800 km from east to west and 144-240 km from north to south, the Himalaya regions exhibit a remarkable blend of Sino-Japanese characteristics (Stearn, 1960). Located in Southeast Asia, this vast region stretches from the Indo-Gangetic basin to the Himalayan range and the Tibetan plateau. The intricate topography of Nepal is primarily responsible for the presence of a significant amount of plant endemism in the country from a phytogeographical perspective (Schickhoff, 2005). Tiwari et al. (2019) reported that the Nepal Himalaya is home to 312 endemic species of flowering plants.

Concerns regarding the present and potential effects of climate change in the region are heightened by the Himalayan region's delicate terrain, which makes it extremely vulnerable to natural calamities (Cruz, 2007). The mountain climate differs due to its topography complexity, gradient complexity, short-term oscillations, physical parameters as air pressure, oxygen availability (Rahbek et al., 2019).

According to Ghosh (2009) the Himalayan region is recognized as the most striking mountain chain exposed to climatic perturbation. Due to the high elevation and rugged landscape of the area, there is a phenomenon of geographic isolation, restrictions in species distribution, and reduced human influence. Collectively, these factors heighten the system's vulnerability to the effects of climate change (Zomer et al., 2014) and this change in climate are miscellaneous encircling droughts, landslides, flood (Barnett et al., 2005).

Mountain ecosystems posses a direct and indirect ecosystem services to the world population living in and around the high-altitude mountain regions (Liu et al., 2019). Mountain ecosystems provide a diverse array of valuable services, including essential resources such as food and timber, protection from natural hazards, cultural importance, and habitats that support biodiversity (Payne et al., 2017). Mountain ecosystems also play a vital role in supporting services such as nutrient cycling and regulating services, including climate control and natural hazard mitigation (Baral et al., 2017). Forest cover in these areas acts as a buffer zone, effectively mitigating the impact of natural hazards like landslides and avalanches, reducing the risk of flooding, preventing soil erosion, and promoting soil formation processes. Thus, the human beings are also well-benefited by the montane forest as it delivers the ecosystem services (Seidl et al., 2019)

Numerous studies highlight that global climate change has been occurring for an extended period, threatening the stability of societies and the resilience of both natural and managed ecosystems. Because of their isolated positions and marginalized status, Nepal's mountain villages are especially susceptible to the effects of climate change (Macchi et al., 2015). Notably, the mountainous regions of Nepal experience a higher magnitude of warming compared to the lower altitude areas (Shrestha & Aryal, 2011). The vegetation in mountainous regions is especially vulnerable to climate change due to its dependence on the cooler temperature characteristic of higher altitudes (Körner, 2003). Mountains offer a broad range of essential ecosystem services that support the well-being of people worldwide. However, these regions are highly susceptible to various stressors, resulting in global changes that threaten and degrade the ecosystems they sustain. This article aims to assess climatic trends and their impacts on Nepal's high-altitude ecosystems (>3000 m asl), with a particular focus on water resources, forests, and biodiversity.

Material and Methods

The study is based on a desk review of the published scientific literatures. Literatures were searched in Web of Science, Scopus, and NepJol database using relevant search strings such as 'climate change trends', 'climate change scenarios', 'climate impact ecosystem', 'Nepal Himalaya'. A total of 105 articles were downloaded from the three databases. After removing the duplications, 72 articles were found relevant to this study. The articles were reviewed to understand the trends, scenarios, and impacts of climate change on Nepal's high-altitude

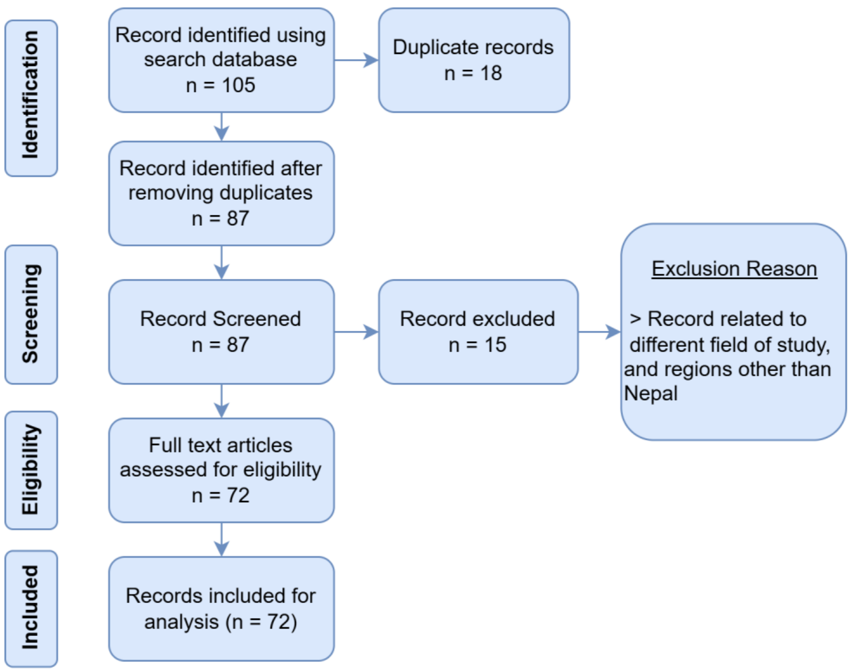

Figure 1: *PRISMA flow diagram illustrating the article selection process for the systematic review.*

ecosystems. The PRISMA flow diagram for the article selection is given in Fig. 1.

Results and Discussion

Climatic trends and variability in Nepal

Annual and seasonal trends of temperature and precipitation

According to Global Climate Risk Index (CRI) index 2021, Nepal is ranked as the 12th most vulnerable country. Over the few decades, the country has been experienced clear trend of increasing temperature (MoFE, 2021). In Nepal, the air temperatures exhibit distinct patterns throughout the year. The highest temperatures, ranging from 36 to 39°C on average, occur in May or early June, while the monsoon season brings more moderate temperatures. During December and January, the mean minimum temperatures fall below -3°C. Notably, the warming trend is more significant in Nepal's high-altitude regions, including the middle mountains and the high Himalayas.

Interestingly, a notable rise in minimum temperatures has been recorded exclusively during the monsoon season on the southern side of the Himalayas. This variation in minimum temperatures on both sides of the Himalayas is closely linked to reduced cloud cover and weakened downward longwave radiation (Yue et al., 2020). The average temperature trends per decade for various seasons were recorded as follows: 0.23°C for the annual average, 0.4°C for winter, 0.2°C for pre-monsoon, 0.3°C for monsoon, and 0.12°C for post-monsoon (Dhital et al., 2023).

In Nepal, about 80% of the annual rainfall occurs during the Indian summer monsoon season, which lasts from June to September (DHM, 2017). The average annual precipitation is approximately 1530 mm, with the heaviest rainfall recorded at elevations around 2000 m. In contrast, the northern regions of the Himalayan peaks experience drier conditions due to their rain shadow effect (DHM, 2015; 2017). During winter and spring, snow and rain are brought by westerly low-pressure weather systems originating from the Mediterranean Sea, with the northwestern part of the country being the most affected. Winter precipitation plays a crucial role in shaping the mass balance of glaciers in western Nepal. The precipitation has been experienced in decreasing order during the period of 1903-1982 and 1962-2002. The similar trend was followed by annual rainfall during 1903-1982, but the increasing trend was observed during the period of 1962-2002 and 1901-2002 (Karki et al., 2017).

Spatial variation of temperature and precipitation

The relatively rapid warming observed in Nepal since the mid-1970s can largely be attributed to significant warming rates in the Himalaya and Middle Mountain regions (Table 1). As a result, the mountainous region of Nepal appears to be amplifying the trend of regional warming, supporting the notion that alpine areas are highly sensitive to climate change. Shrestha et al., 1999 studied the variation of temperature from 1971 to 1994. The study revealed that before 1978, the temperature pattern was either stable or falling across all physiographic regions. In most of the country's region, the mean annual maximum temperature rose from 1997 to 1994. Maximum temperatures have increased in much of the middle ranges and High Himalayan region. Maximum temperatures are rising (albeit more so at higher altitudes), whereas minimum temperatures are falling at high altitudes while rising or positively trending at lower altitudes (Kattel and Yao 2013; Thakuri et al. 2019). A notable increase in near-surface air temperature and diurnal temperature range (DTR) has been observed at varying elevations up to 2566 m during the 1976-2015 period. Over the past four decades, the maximum air temperature exhibited a more significant increase (+0.045°C y^{-1}) compared to the minimum temperature (+0.009°C y^{-1}), resulting in a significant rise in DTR (+0.034°C y^{-1}) (Thakuri et al., 2019). Spatial analysis conducted by Kattel and Yao (2013) also confirms warming trends in most mountainous regions, with maximum temperatures experiencing a greater degree of warming compared to minimum temperatures, which show greater variability with positive, negative, or no change. In terms of maximum temperature, the pattern was inverse, with higher altitudes experiencing greater maximum temperatures and lower altitudes experiencing lower maximum temperatures (DHM 2017; DHM 2015; PAN, 2009; Salerno et al., 2015; Shrestha et al., 1999; Thakuri et al., 2019), signifying that higher altitudes are becoming warmer (Table 1). Over the last four decades, the northern side of the Himalaya has experienced more pronounced warming during night time compared to daytime, whereas the southern side has seen stronger warming during the daytime than at night (Yue et al., 2020).

Dhital et al. (2023) conducted a study on the annual and seasonal warming patterns across various physiographic regions of Nepal. The study found that Nepal's eastern region experienced more pronounced warming compared to the central and western regions, demonstrating greater climatic sensitivity, especially in the Khumbu region, which surrounds Mount Everest. All physiographic zones, namely the Terai, Siwaliks, Lower Hills, and Upper Hills, showed rising temperature trends throughout an altitude gradient, with corresponding rates of 0.15°C, 0.26°C, 0.68°C, and 0.57°C each decade. The average annual and seasonal temperature patterns revealed that the eastern part of the country experienced more warming compared to the central and western regions (Dhital et al., 2023; Thakuri et al., 2019).

In case of precipitation, it is found that the country experienced longer dry periods and reduced post-monsoon rainfall overall (Fig. 2); however, there were different trends in annual and high-intensity rainfall extremes between the eastern and western regions (Karki et al., 2017). The latter showed an increasing pattern while the former exhibited a moderate decrease. In addition, winter precipitation significantly dropped in the western region, suggesting a weakened impact of western disturbances.

Climatic change scenario of Nepal

Several studies have forecast varying degrees of future temperature rise. According to NCVST (2009), it is projected that temperatures will increase by 0.5 to 2.0°C by the 2030s, followed by a rise to 1.7 to 4.1°C by the 2060s, and further increasing to 3.0 to 6.3°C by the 2090s. The IPCC's 2007 report shows that by the 2050s, it is anticipated that the average temperature across the Asian landmass, including the Himalaya, will increase by around 3°C. Furthermore, by the 2080s, the projected temperature rise is expected to reach 5°C. Similarly, there is a projected increase of 10-30% in annual precipitation in this area by the year 2080 (IPCC, 2014). While the projected range of temperature increase may vary, multiple studies concur that temperatures will indeed rise in future (Bajracharya et al., 2018; Dahal et al., 2020; Khadka & Pathak, 2016; Krishnan et al., 2020; Meher et al., 2017). The Ministry of Environment's report (MoE, 2010) also

Table 1: Trends in Nepal's annual and seasonal temperatures (°C y^{-1}) from 1976 to 2015 (Thakuri et al., 2019).

		Terai plain	Siwalik	Middle Mountains	Himalaya	High Himalaya	Lower Stations	Higher Stations	All Nepal
		(T)	(S)	(MM)	(H)	(HH)	(LS)	(HS)	(Nepal)
		100-700 m	700-1500 m	1500 -2000 m	2000-4000 m	4000-8848 m	< 1000 m	>1000 m	70-2566 m
Winter	Tmax	-0.014 *	0.012	0.079 ***	0.064 ***	-	0.005	0.079 ***	0.030 ***
Pre-monsoon	Tmax	0.018	0.029 **	0.078 ***	0.051 ***	-	0.030 **	0.073 ***	0.051 ***
Monsoon	Tmax	0.023 ***	0.030 ***	0.065 ***	0.045 ***	-	0.029 ***	0.063 ***	0.046 ***
Post-monsoon	Tmax	0.014	0.020	0.068 ***	0.064 ***	-	0.024 **	0.069 ***	0.045 ***
Annual	Tmax	0.017 ***	0.028 ***	0.073 ***	0.058 ***	-	0.028 ***	0.072 ***	0.045 ***
	Tmin	0.017 ***	0.010 **	0.006	0.007	-	0.017 ***	-0.002	0.009 *
	Tmean	0.018 ***	0.021 ***	0.035 ***	0.030 ***	-	0.025 ***	0.032 ***	0.027 ***
	DTR	-0.004	0.021 ***	0.068 ***	0.053 ***	-	0.009	0.078 ***	0.034 ***

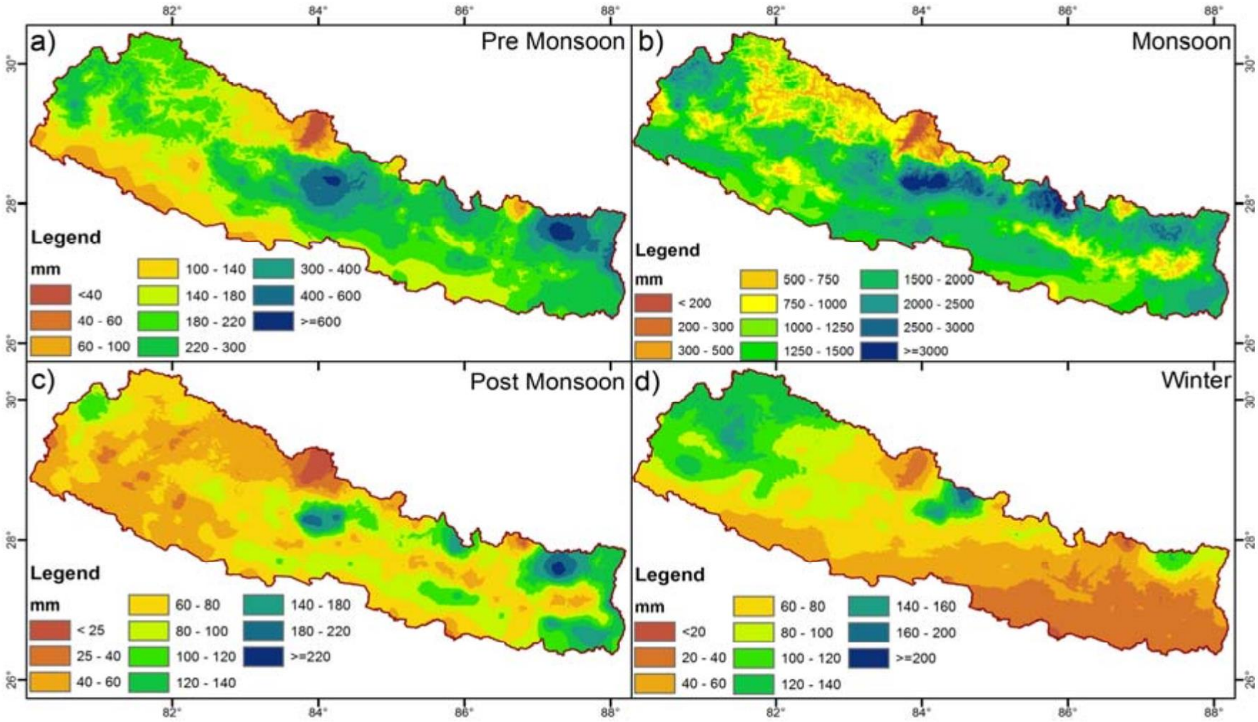

Figure 2: Spatial patterns of average seasonal precipitation (mm) for the periods of 1981-2010, depicting (a) Pre-monsoon, (b) Monsoon, (c) Post-monsoon, and (d) Winter seasons (Karki et al., 2017).

aligns with these findings, indicating a temperature increase of 1.4°C by 2030, 2.8°C by 2070, and 4.8°C by 2090. Furthermore, research indicates that Nepal is expected to experience a more rapid warming compared to the global average. According to the highest emission scenario, RCP8.5, Nepal could see an increase in temperature of 1.2 to 4.2°C by the 2080s, relative to the baseline period of 1986-2005 (WB & ADB, 2021).

The consensus among models regarding precipitation projections, and the significance of expected variations, is low for both winter and summer seasons (Solomon et al., 2007). However, in the context of the Nepal Himalaya, the majority of model projections indicate an increase in precipitation in future. Based on a recent projection (MoFE, 2019), it is anticipated that average annual precipitation will likely increase in both the medium-term (2016-2045) and long-term periods (2036-2065). During the medium-term period, average annual precipitation is expected to see a rise of 2-6%, while in the long-term period, it could increase by 8-12%. By the end of 2100, precipitation is expected to experience a further increase of 11-23%. In a study by Kadel et al. (2018) using CMIP5 models, future monsoon precipitation in the central Himalayas was examined. The study consistently showed a substantial increase in seasonal mean precipitation during the middle and late 21st century, regardless of the warming scenarios RCP4.5 and RCP8.5. In contrast, projections from the high-resolution PRECIS model in the Koshi Basin indicated an increase in the frequency and intensity of extreme climate events, such as dry days, consecutive dry days, and extremely wet days, with more significant changes expected in the southern plains compared to the northern mountainous regions. According to future projections, both annual precipitation and river discharge are expected to increase compared to the baseline. However, this increase will not be consistent across all seasons. According to Dahal et al. (2020), the post-monsoon season, which presently has the lowest recorded precipitation, is expected to receive even less rainfall in the future. This projected decrease in precipitation is likely to have a corresponding impact on river discharge, following a similar declining trend.

In the mountain and trans-Himalaya zones, a notable decrease in moderate rainfall days is anticipated (Rajbhandari et al., 2018). Additionally, warm days and nights are anticipated to be more frequent, while colder days and nights are anticipated to be less frequent. In the western region, warmer temperatures, extended monsoon seasons, and occasional rainfall events are expected throughout the year, including during typically dry months. The mountains will suffer major fluctuates in temperature, while the hills and plains are expected to witness the largest differences in precipitation (Dhaubanjar et al., 2020).

The Effects of climate change on high-altitude ecosystems

Mountain ecosystems are closely tied to the climate, and organisms have gradually adjusted to the climate in their specific regions. Climate change, particularly the changes in temperature and precipitation patterns, is to blame for the notable alterations seen in high-elevation areas. These changes serve as a prominent driving force behind the observed shifts in these areas. In different physiographic regions of Nepal, as a consequence of the warming trends, areas experiencing higher rates of warming also faced greater ecological impacts, including changes in water resources, phenology, and more (Fig. 3). In the context of global warming, the negative impacts are more pronounced in the Lower Hills, Upper Hills, and Mountains than in the Terai and Siwaliks (Dhital et al., 2023). The alternation in temperature and precipitation pattern causes retreating the glaciers, change in snow cover (Scherler et al., 2011; Thakuri et al., 2014; Khadka et al., 2020), increasing the number and size of glacial lakes (Khadka et al., 2018), glacial-lake outburst flooding (Khadka et al. 2021; Byers et al. 2019; ICIMOD, 2011), the water towering (Immerzeel et al., 2010), treeline advance (Gaire et al., 2014; Schickhoff, 2005), phenological change (Shrestha et al., 2012) and changed species interactions, greater pressure on species selection, and higher extinction risks (Dillon et al., 2010). Mountain ecosystems are highly vulnerable to changes in temperature and precipitation patterns, and are expected to face significant biotic disruptions in the coming years (Zomer et al., 2014).

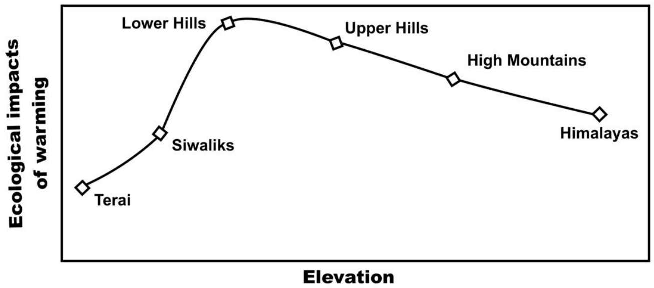

Figure 3: *Possible ecological impact of climate change with altitude (Adapted from Dhital et al., 2023)*

Fresh water ecosystem

The climate change impact on rapid melting of glaciers was observed in high-mountain of Nepal. According to Thakuri et al. (2014), the glaciers in the Mount Everest (Sagarmatha) region have experienced a reduction of 13% in surface area and 6.1 m y^{-1} in glacial length from 1962 to 2011, while the snowline has shifted upward by 182 m. The Himalayan region is seeing the effects of climate

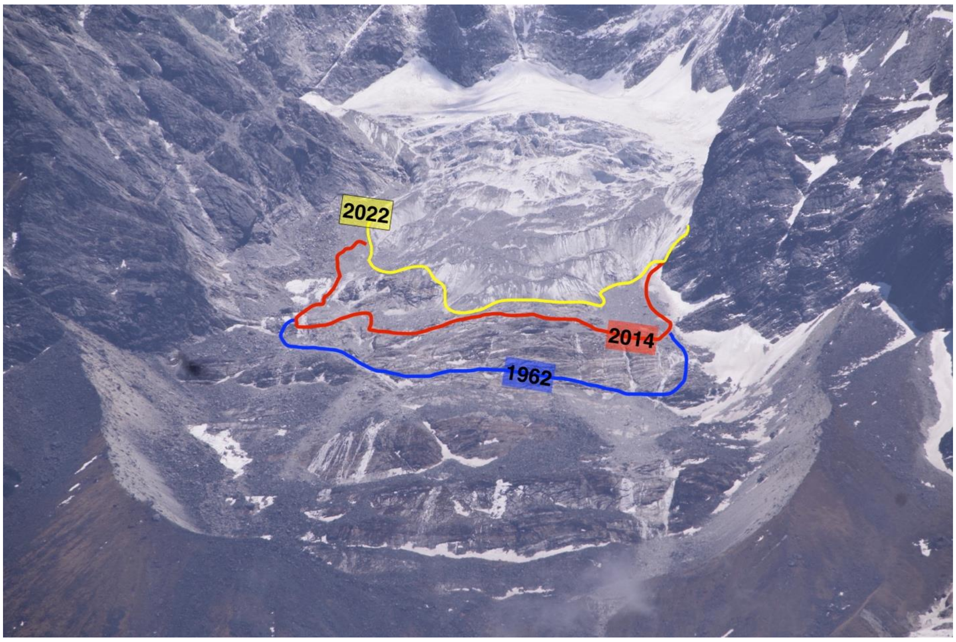

Figure 4: Photo of a glacier located on the north-west slope of Mount Thamserku (in front of Syangboche), taken in 2022, showing the glacier extend in 1962 (from satellite imagery) and 2014 (photo). The photo clearly marks the glacier ice loss (Photo credit: Sudeep Thakuri, 2022).

change, with many glaciers retreating more quickly (Fig. 4 & 6) than those in other mountain ranges (Thakuri et al., 2014; Bajracharya et al., 2023; Shrestha et al., 2017), thereby increasing the extent of glacier lakes and increasing glacier lake outburst floods risks (Fig. 5a and 5b). Studies showed that there has been a significant upward shift in the permanent snowline (Thakuri et al. 2014; Khadka et al. 2020). In the last fifty years, the Nepal Himalaya has experienced an overall loss of about 15% of its glacier surface area.

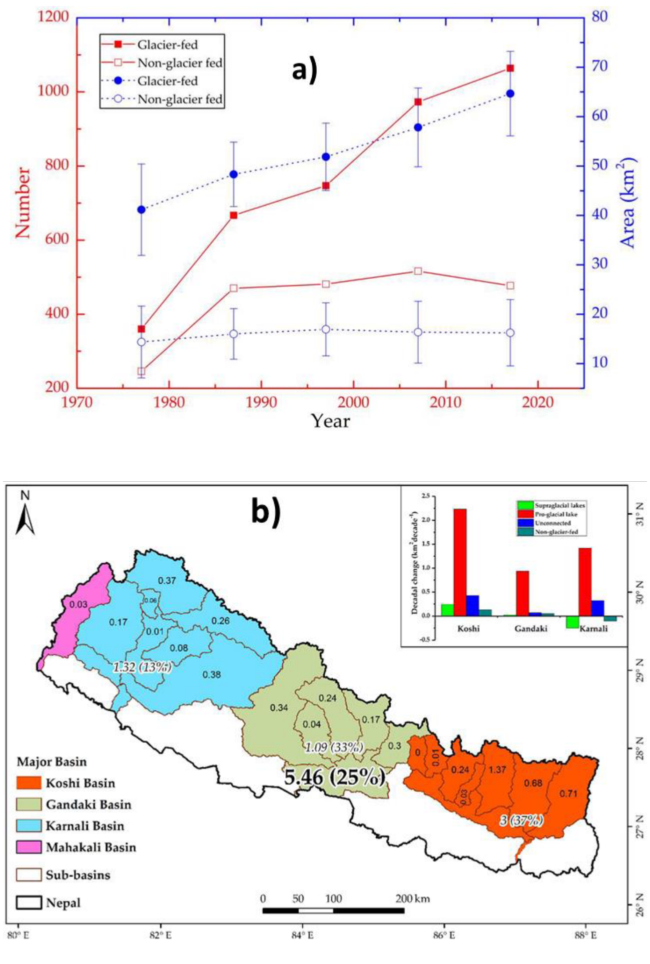

Figure 5: Status of glacier lakes in Nepal. a) Changes in the number and surface area of glacier-fed and non-glacier-fed lakes and b) Expansion of glacial lakes from 1987 to 2017 (km^2 $decade^{-1}$) in various sub-basins of Nepal (Khadka et al., 2018).

Paudel & Andersen (2011) found a reduction in the volume of annual snowfall and alterations in the seasonal snowfall patterns in the Trans-Himalayan Region of Nepal, based on MODIS data. These changes were linked to ongoing climate change and its associated variability. Alterations in the cryosphere can lead to hydro-ecological impacts, such as the drying up of springs and lakes. These changes can have major implications for water availability and food production, potentially leading to water stress. As a result, the costs associated with water collection and storage may increase (Manandhar et al., 2012). Climate change has affected the upstream snow and ice reserves in the Hindu Kush Himalaya (Shrestha & Aryal 2011). A study conducted in the Khumbu (Everest) Himalaya revealed that the lower limit of permafrost has experienced an elevation rise of 100-300 m between 1973 and 1991, followed by a period of stability at least until 2004 (Fukui et al., 2007; Chauhan et al., 2017). The retreat of glaciers, decreased snowfall, and faster snowmelt driven by rising temperatures have contributed to the degradation of habitats for alpine medicinal plants such as *Neopicrorhiza scrophulariiflora* (Shrestha & Jha, 2009) and *Ophiocordyceps sinensis* (Shrestha & Bawa, 2015).

Figure 6. Lower-Barun Glacial Lake (4450 m asl) is one of the rapidly expanding glacial lakes since its formation in early 1970s (Photo credit: Sudeep Thakuri, 2020)

Changes in precipitation patterns, with some areas experiencing more frequent and severe droughts, while others experience increased flooding are clear evidence of climate warming. These changes in water availability have a significant impact on freshwater ecosystems, altering hydrology and affecting the abundance and distribution of aquatic species (Bhattarai & Pant, 2016). Rising temperatures can also affect freshwater ecosystems, with warmer water temperatures affecting the growth, reproduction, and survival of aquatic species. In particular, some cold-water species, such as trout, are especially susceptible to these changes. Climate change can also impact water quality, with increased temperatures and changes in precipitation patterns leading to altered nutrient and sediment loads, as well as changes in pH levels. These changes can impact the quality of aquatic habitat, and may have knock-on effects on the overall health of freshwater ecosystems (Adhikari & Neupane, 2019). Climate change is intensifying the frequency and severity of extreme weather events, such as floods, landslides, and avalanches (Sudmeier-Rieux et al., 2012; Thakuri et al., 2020; Wijaya et al., 2023). These events can have significant impacts on freshwater ecosystems. For instance, major floods can modify channel morphology and sediment deposition, which may result in changes to habitats and the abundance of aquatic species (Giri et al., 2018).

This scenario of climate change impacts illustrates the vulnerability of Nepal's freshwater ecosystems to climate change and highlights the need for effective management strategies and adaptive measures to minimize these impacts and ensure the long-term sustainability of these crucial systems. Multiple studies have emphasized the importance of sustainable water resource management, such as wetland restoration and the adoption of integrated water resource management, to address the challenges posed by climate change.

Forest and biodiversity

Forest cover

Climate change is causing changes in forest cover in Nepal, with some forests shifting to higher elevations, while others are being replaced by non-forest vegetation (Chaudhary et al., 2017). Forest cover declined by 1.4% y^{-1} from 1995 to 2010, due to factors such as deforestation, forest degradation, and climate change (GoN, 2016). Yet, in recent years forest area has been increasing significantly.

Phenology

Changes in temperature and precipitation have affected the phenology of plants. Multiple studies have provided evidence that increasing temperatures lead to alterations in plant phenology (Scheffers et al., 2016). The timing of flowering in plants is significantly influenced by the onset and retreat of snowfall, as noted by Inouye & Wielgolaski (2003) and Kudo & Suzuki (1999). For example, the early flowering patterns observed in *Aconitum heterophyllum* may be attributed to warmer winter conditions, as evidenced by an average advancement of flowering time by 19-27 days with a 1°C increase in mean winter temperature.

In a study conducted by Lamsal et al. (2017), it was discovered that the flowering time of *Rhododendro*n *arboreum* in the central sub-alpine middle mountains of Nepal advanced by 2-3 weeks, whereas in the western sub-alpine middle mountains, it was delayed by 3-6 weeks. Additionally, the researchers noted an upslope migration of various species, such as *Betula utilis*, *Juniperus indica*, *Rhododendro*n sp., *Berberis* sp., and *Alnus nepalensis*, in the central and western sub-alpine middle mountains.

Phenological changes in three specialized perennial herbaceous alpine flora due to rising temperatures. They observed a delay in flowering time for *Roscoea alpina* and *Roscoea capitata* by 8-30 days, while *R. purpurea* exhibited early flowering by 22 days (Mohandass et al. (2015).

Invasion

Climate change is promoting the spread of non-native species in Nepal, which are negatively affecting native species and ecosystems. One example is the rapid spread of the invasive weed *Mikania micrantha*, which is diminishing the biodiversity of forest ecosystems (Sharma et al., 2018). According to Shrestha et al. (2015), the expansion of invasive species in the high-altitude regions of Nepal is anticipated due to the increasing climatic suitability. The study suggests that *Parthenium hysterophorus* would experience significant growth in the high-altitude areas if the temperature rises by +3°C. Additionally, Rangwala & Miller (2012) discovered that future warming is projected to intensify with altitude, leading to the upward movement and colonization of the invasive species *Ageratina adenophora* in the temperate and sub-alpine forests of the mid-hills and middle mountains in central Nepal. This invasion poses a significant threat to the habitat of endangered fauna such as *Ailurus fulgens* and *Moschus chrysogaster*. Moreover, Bourdôt et al. (2012) predicted that *Nassella neesiana*, a weed typically found in temperate grasslands, could spread to Nepal and disrupt pasture and grassland biodiversity by outcompeting native plants in middle mountain ecosystems.

Vegetation shifting

The tree line shifting has been evident in the Nepal Himalaya (Fig. 7). Gupta (2010) conducted a study in the Gorkha, Mustang, and Manang areas of the western Himalayan belt of Nepal and predicted that a temperature increases of 1°C would lead to an upward shifting of the tree line by approximately 150 m. Similarly, Suwal (2010) studied the upward shift of the tree line of *Abies spectabilis* in the Manaslu region of central Nepal. The research found that the tree line had moved higher in the Manaslu Conservation Area due to climate change, reaching an altitude of 3841 m by 2007, with a shift rate of 34.29 m per decade.

In a study by Gaire et al. (2014) across Nepal, which focused on tree ring analysis, an upward shift was observed in the tree line of *Abies spectabilis* at a rate of 2.61 m y^{-1} since 1850 AD was observed. However, the upper distribution limit of *Betula utilis* remained relatively stable in recent decades. Chhetri and Cairns (2015) also observed the migration of the alpine tree *Abies spectabilis* upslope at a rate ranging from 0.17 to 2.6 m y^{-1} in central Nepal. Pauli (1994) calculated that for every 100 m increase in elevation, a temperature rises of 0.5°C could theoretically result in an 8-10 m shift in vegetation belts per decade. Furthermore, Chettri et al. (2009) estimated that, considering the current rate of warming in the eastern Himalaya, which is expected to increase with altitude, the altitudinal shift of species such as *Abies spectabilis* and *Betula utilis* could range from 20-80 m per decade as they move to higher altitudes.

Figure 7: High-altitude vegetation that are migrating upward in Barun valley (Photo credit: Sudeep Thakuri, 2020).

Species distribution and composition

Climate change is impacting wildlife in Nepal, as changes in temperature and precipitation patterns influence the distribution, abundance, and behavior of various species. For instance, certain bird species are moving their breeding ranges to higher elevations, while some mammals are adjusting their activity patterns to evade high temperatures (Subedi et al., 2017). Gautam et al. (2018) assessed the impacts of climate change on the distribution of three bird species in the Langtang National Park and found alterations in the geographical distribution of these bird species due to climate change, with some populations declining and others expanding their range. Ale et al. (2019) assessed the impacts of climate change on snow leopard populations in Nepal. The study found that climate change is affecting the snow leopard's habitat, as warming temperatures are causing glaciers to melt and snow cover to diminish. This is leading to changes in prey populations, which in turn is affecting snow leopard survival. These studies provide evidence that climate change is exerting notable effects on the wildlife in Nepal, causing changes in their distribution, behavior, and ultimately their survival. These impacts have significant implications for the overall ecological balance of Nepal's natural systems and the well-being of local communities that depend on these ecosystems for their livelihoods and cultural heritage.

Forest fire risk

Climate change is increasing the risk of forest fires in Nepal, due to factors such as warmer temperatures, drier conditions, and more frequent droughts. Forest fires can have significant impacts on forest ecosystems, including loss of biodiversity, carbon emissions, and soil erosion (GoN, 2016). A study on the wildfire risk in Chitwan-Annapurna Landscape showed that increasing temperatures, decreasing precipitation, and changes in wind patterns are contributing to an elevated risk of forest fires in the region (Sharma et al., 2018). Climate change is contributing to an increased risk of forest fires in Nepal, with implications for both the ecological and human systems. Effective forest management practices and strategies to implement measures to reduce the effects on forest ecosystems will be essential due to climate change in addressing this risk and promoting the sustainability of Nepal's natural systems.

Conclusion

Nepal is witnessing profound effects of climate change on its environment, economy, and society. Rising temperatures have led to glacier melt, changes in precipitation patterns, and a higher frequency and intensity of climate and water-related disasters, along with a loss of biodiversity. This has resulted in droughts, floods, landslides, and other natural disasters that have affected the agricultural sector, energy production, and infrastructure development. In addition, the emergence of invasive species as a consequence of climate change has brought detrimental effects on biodiversity and forest ecosystems. This situation is particularly critical in Nepal's mountainous regions, which hold significant natural resources and cultural significance. As a result, it is essential for the government to adopt proactive measures and implement effective strategies to mitigate and adapt to climate change. These efforts are vital to reducing the negative effects on Nepal's environment, economy, and society.

The climatic trends observed in Nepal's high-altitude ecosystems are reshaping biodiversity patterns and threatening vital ecosystem services. Rising temperatures, altered precipitation, and shifting seasons are accelerating the vulnerability of these fragile environments, with significant implications for both local communities and global biodiversity. Immediate, science-based interventions and adaptive conservation strategies are crucial to mitigate these impacts. Moreover, integrating climate resilience into policy and development planning, alongside continued research and monitoring, is essential for safeguarding the ecological integrity of these high-altitude ecosystems. Preserving these regions is not only vital for Nepal, but for the broader health of the planet.

Conflict of Interest

The authors state that there are no conflicts of interest related to this publication.

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