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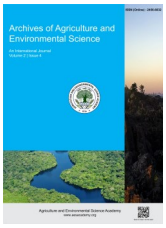

REVIEW ARTICLE

Impact of climate change on the ecosystem of the central Himalayas, Nepal

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ABSTRACT

The threats of climate change are found in both developed and developing countries. Since the impacts of climate change are global, irreversible, and pervasive, it is gaining worldwide attention. High mountains are the first indicators of climate change. However, the idea of what causes climate change effects on multiple ecosystem services remains scattered. This article is meant for information regarding the impacts of climate change on the ecosystem of Nepal. The result shows that climate change causes tree line shifting, change in land cover, extinction of species due to loss of habitat, imbalance in carbon sequestration on the terrestrial ecosystem while eutrophication of water bodies and extinction of endemic fish species was reported from the aquatic ecosystem. Tropical area is considered to be more affected by climate change in terms of Natural disasters and Health impacts. Moreover, different types of ecological modeling can be simulated in the context of Nepal for the prediction and future analysis of the impacts of climate change in the Ecosystem. Therefore, the impact of climate change is crucial and challenging.

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INTRODUCTION

Climate change denotes the alteration in the earth's global or regional climate over an extended period, either due to natural inconsistency or as the consequence of anthropogenic activities (IPCC, 2007). Climate change is caused due to growth of CO_2 and other greenhouse gases exponentially in the atmosphere (Malla, 2009). Major gases that play a vital role in Global warming are water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs). It is a change in the statistical distribution of weather patterns for decades to millions of years and has various impacts on the ecosystem (Figure 1). Scientists have been actively working to understand past and future climate by using observations and theoretical models. Climatic change is a direct driver of ecosystem changes (Mclaughlin *et al.*, 2002). Global warming, a consequence of climate change is the most emerging and challenging issue. Climate changes have affected all forms of life on the earth. Nepal, being an underdeveloped country, the influence of climate change is more serious affecting an enormous population (NAPA, 2010). The contribution of a human being to climate change is through the tremendous emissions of GHGs, aerosols, and changes in land use (Brath *et al.*, 2015). An ecosystem refers to the community of living organisms and interaction (plants, animals, and microorganisms) with each other and also with a non-living component that is controlled by external and internal factors (Paudel *et al.*, 2017; Sharma *et al.*, 2020). In an ecosystem, solar energy, climate, topography, biotic and abiotic components are being interconnected in the network through biogeochemical cycles. Global climate change pattern indorses that there will be significant impacts on ecosystems and their related ecosystem services with serious consequences for the

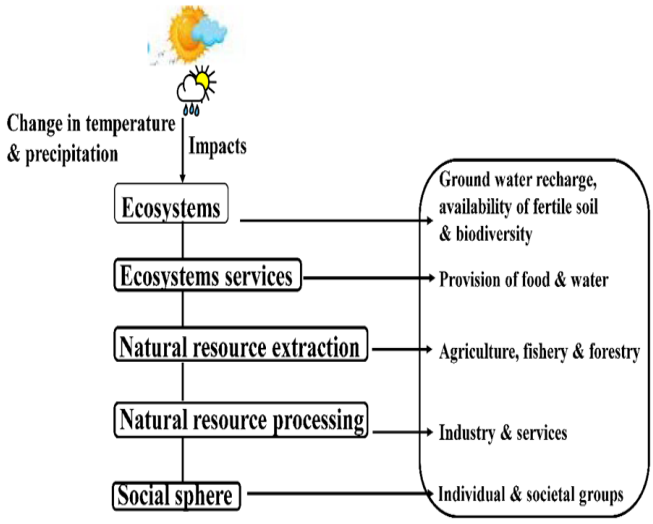

Figure 1. *The overall impact of climate change on the Ecosystem (modified from Adelphi/EURAC 2014).*

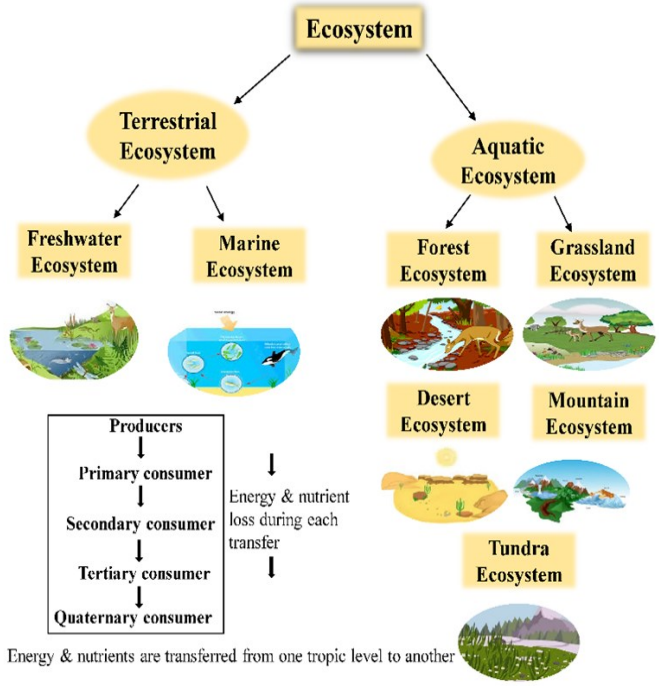

Figure 2. *Types of ecosystems and energy transport.*

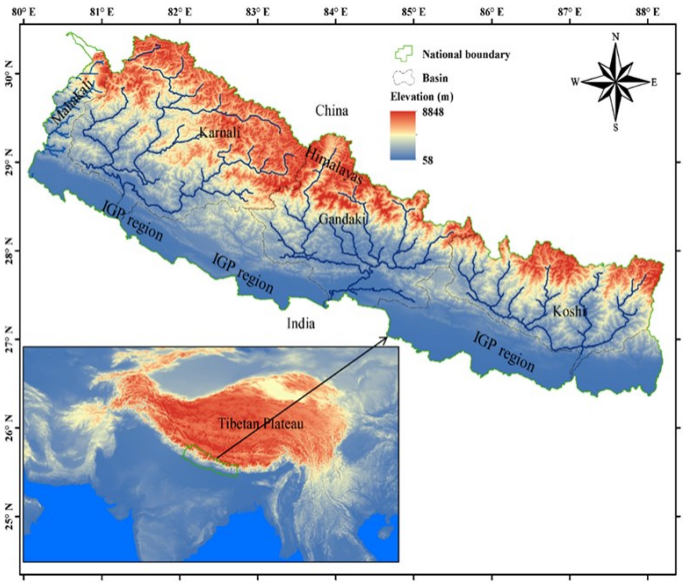

Figure 3. *Map of Nepal showing four major river basins of Nepal.*

livelihoods of people, predominantly in the most economically challenged parts of the world (IPC, 2007; Sharma *et al.*, 2009).

There are two types of ecosystems *viz.*, terrestrial and aquatic ecosystem. The terrestrial ecosystem includes forest, grassland, mountain, alpine, and tundra ecosystem whereas the aquatic ecosystem includes fresh water and marine ecosystem (Figure 2). In all ecosystem types, ecosystem processes are important determinants of the biogeochemical cycle occurring in nature and are profoundly sensitive to climate change (Adhikari *et al.*, 2019a, 2019c; Merisiers, 2016; Paudel *et al.*, 2017). Nepal, a country with high variation in altitude (60-8848m) within a short vertical distance (150- 200 Km, south to North) consists of major ecological zones including 5 ecological belts, 11 bioclimatic Zones,75 vegetation types, and 118 ecosystems with highly diverse life forms (Karki *et al.*, 2015). The variation in bioclimatic zones due to altering altitudes causes high endemism of floral and faunal diversities across the Himalayas. Tropical, subtropical, temperate, sub-alpine, and alpine regions are five major ecological belts in Nepal. The lower elevation characterized by tropical or subtropical climate includes arable lands and natural forest. Warm-temperate zone, cold temperate zone, subalpine and alpine zones are found from south to north along the elevation gradient respectively (Karki *et al.*, 2015).

There were few studies carried out on climate change and its impacts on the ecosystem from Nepal's perspective. So, this study is carried out to understand the impact of climate change on the ecosystem of Nepal and review the existing datasets in Nepal concentrating on climate change and the ecosystem. Climate change mainly impacts food, natural hazards regulation, spirituality, water availability and cultural identity, aesthetics, and recreation.

PHYSIOGRAPHY OF NEPAL

Nepal lies between 80°4' and 88°12' East longitude, and from 26°22' to 30°27' North latitude, covering a territory of approximately 147,181 km² that extends roughly 885 km from east to west. It is a land-locked country, surrounded by India to the east, west, and south, and China to the north (UNDP, 2009). Geographically, Nepal consists of the earth's highest mountain peaks in the north and foothills in the Indo-Gangetic plain in the south (Figure 3). The physiographical division of Nepal divides into five sections (Figure 4). Due to the enormous deviation in elevation, the central Himalayas shape extensive bioclimatic zones i.e. tropical, subtropical, temperate, and subalpine to alpine snowcapped mountains (Bhattarai *et al.*, 2004). The central Himalayas, Nepal divided into four major river basins i.e., Koshi River Basin, Gandaki River Basin, Karnali River Basin, and Mahakali River Basin from east to west respectively (Adhikari *et al.*, 2019b) (Figure 3). The climate of the central Himalayas is governed by South Indian Monsoon during summer and westerly during winter. The eastern part is much more influenced by the South Indian monsoon than the central and western parts (Figure 5). The variation of precipitation from east to west is 3600mm/year to 800mm/year respectively. Nearly, 80%

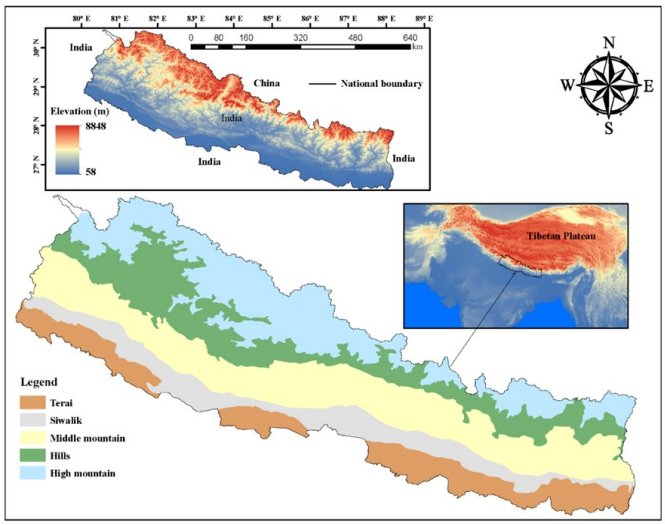

Figure 4. *Physiographical division of Nepal.*

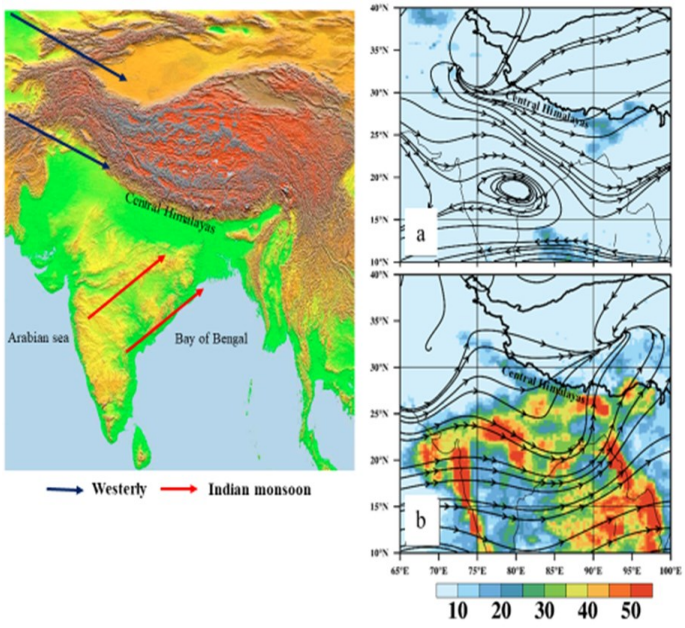

Figure 5. *Circulation of the wind fields calculated by the NCEP FNL Operational Model Global Tropospheric Analysis monthly datasets, with a spatial precision of 2.5° from longitude-latitude grids at 850 hPa, and precipitation (TRMM3B42 7V monthly datasets PP in mm) with the precision of 0.5° across the central Himalayas and adjoining region for the period 2010-2020 (a: FMAM 800 hPa, and b: JJAS 850 hPa) showing the influence of summer monsoon.*

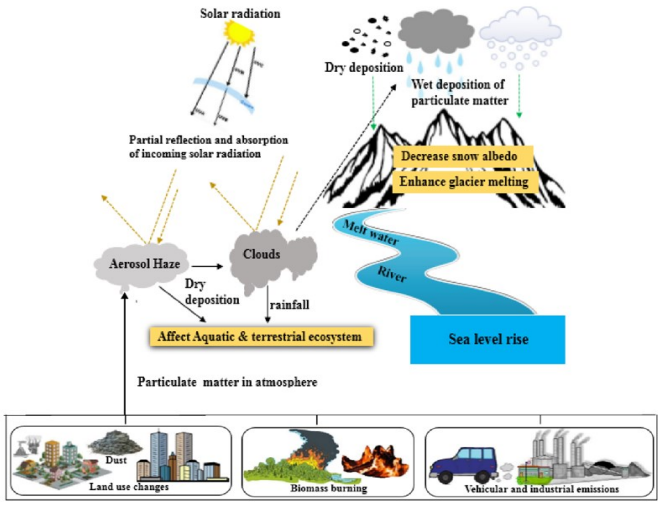

Figure 6. *Regional and long-range transport of pollutants influencing snow albedo.*

of rainfall occurs during the summer monsoon i.e. June to early September (Karki *et al.*, 2015). The steep slope and complex topography of the Central Himalayas are the major obstacles for meteorological observations. Contemporary with a warming climate, most of the Himalayan glaciers have been rapidly melting and shrinking since the 1980s (Bajracharya *et al.*, 2020). The widespread mountain ridge assists as a climatic barrier for moist monsoonal air and serves a sharp decrease in rainfall along with the inner parts of the mountain. With the increase in altitude above 3000 m from sea level, precipitation declines along the central Himalayas. Rate of temperature increase in high altitude by 0.06 °C per year which is a higher value in comparison to a lower elevation (Shrestha *et al.*, 1999). However, due to a large number of meteorological stations in the hilly and Terai region and very few in higher elevation, there is still huge data scarcity about climatic records in Nepal (Tsering *et al.*, 2010).

CLIMATE CHANGE PERSPECTIVE IN NEPAL

Warming of about 0.2 °C per decade for the next two decades is projected in the world. It is also predicted that the temperature will increase by 2.4°C to 6.4 °C by the end of the 21stcentury (IPCC, 2007). Shrestha *et al.* (1999) reported at least 0.6 °C per decade warming in the Himalayas which is already three times higher than the prediction by IPCC for the coming decades. The temperature in the Himalayan region has been identified to be rising more promptly than the global average. The maximum temperature in Nepal amplified at a rate of 0.06 °C per year between 1978 and 1994, with higher rates at higher elevations (Shrestha *et al.*, 1999)s. High-elevation regions are not only prone to rapid warming but also are strongly influenced by regional and long-range transport of pollutants influencing snow albedo (Adhikari *et al.*, 2021; Adhikari *et al.*, 2020; Beniston *et al.*, 1997) (Figure 6). The fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC, 2007) also projected a severe impact of climate change on mountain ecosystems. As compared to the lower elevation, global climate change is found to occur hastily in higher elevations. Higher (about 1 °C per 160 m) than with latitude. Subsequently, the trans-Himalayan region is estimated to experience hasty fluctuation in its ecosystem which will have a large impact on natural phenomenon, livelihood, and vegetation resources. Climate change may sometimes benefit the ecosystem dynamics but has more severe impacts on ecology by altering the natural processes (Figure 7). Some effects of climate change on the ecosystem of Nepal are as follows.

Climate change impacts on terrestrial ecosystem

Landcover change

A study in Mustang uncovered that grassland and forest decreased drastically and barren land is increased dramatically due to climate change (increase in temperature and decrease in precipitation. Both global climate change and anthropogenic

pressure are contributors to the land cover change in the central Himalayas (Aryal *et al*., 2014).

Treeline shifting in the Nepal Himalaya

Aryal *et al*. (2014) reported shifting of treeline towards a higher elevation above its existing range in the Lower Mustang region (observation of the younger *Betula utilis* and *Abies spp*. tree species (<10 years old) as shown in Figure 6. Another study (White and Beissinger, 2008) reported that lower elevation species have expanded to higher elevations resulting in a change in community composition. However, soil types, water resources act as limiting factors in the process of shifting the species towards a higher elevation (Xu *et al*., 2009). If such a mechanism continues rapidly, associated species are highly vulnerable to extinction and the former site needs to be replaced by new species. A related study conducted by (Gaire *et al*., 2014) and revealed the temporal upward shifting of *Abies spectabilis*, 80m higher in between 1850-2012. The average upward movement of the upper distribution limit of *A. spectabilis* at the study sites was calculated to be 2.61 m year^{-1} (1.56– 3.66 m year^{-1}). A recent study (Sigdel *et al*., 2020) also reported the retreating in the Gangapurna and Annapurna III glaciers in the Manang valley, central Nepal resulted in forest advancement over the past 200 years.

Change in plant phenology

Climate change has altered plant phenology in the Himalayas. Decreases in the length of the dry season have altered the timing of leaf flush, flowering, reproduction of Rhododendron, and also the activities of flower-visiting animals which ultimately alters the balance between the ecosystem in the respective area (Xu *et al*., 2009). Shifts in onset and length of growing seasons are also associated with changes in temperature and rainfall patterns and amounts. Local people observed early flowering, sprouting, and fruiting in some plants around the Mustang region, Central Himalayas (Aryal *et al*., 2014).

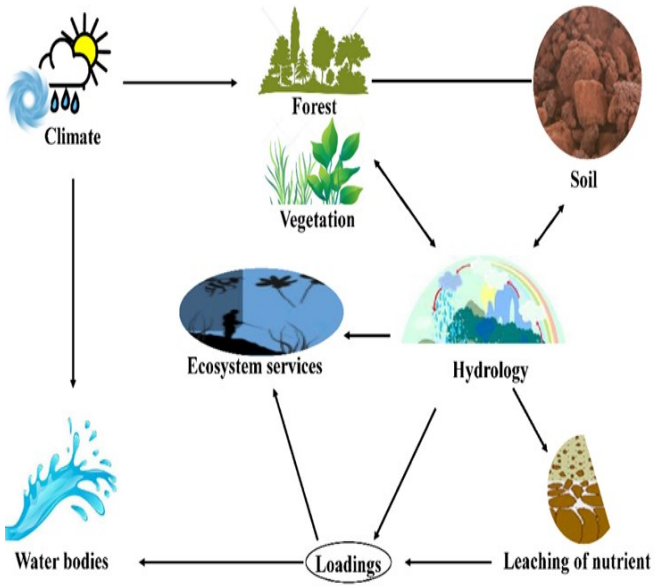

Figure 7. *Mechanism of the impact of climate change in the ecosystem (modified from VACCIA synthesis report, 2011, http://hdl.handle.net/10138/37031).*

Loss of biodiversity and recklessness of wild animals

New alien and invasive species are emerging and their habitat is spreading at a faster rate. The consequence of the migration of the forest towards the higher altitude is a change in their composition, and extinction of species. Species may respond to climate change either by adapting, shifting their range, changing their abundance, or by disappearing (Bhattarai, 2017). Extreme climatic conditions have led to increased incidence of fire & lead to species and habitat loss which leads to the loss of biodiversity, the most significant aspect to show the adverse effect of climate change on the ecosystem. Due to extreme environmental conditions, the migration of birds towards the safe area has been observed. Tropical evergreen forests are the reservoir for many wild animals, reptiles, and birds like One-Horned Rhino, Tiger, Deer, snakes, and birds. Climate changed induced loss of forest area impacts negatively on these wild animals resulting in the extinction of species year by year (Lamsal *et al*., 2017). Snow leopards (already listed as endangered on the IUCN Red List) and Blue Sheep are residents of high altitudes, love snow, and are very sensitive to increasing temperature and previously they were not encountered by humans living in that area. But due to the rapid melting of snow in that area, these organisms are shifted towards the Human settlement areas and creating a problem for local people (Aryal *et al*., 2014). Human-driven habitat reduction and fragmentation gave been observed for decades (IPCC, 2007). In the whole of the country from 1978/79 to 1994/95, forest area has decreased at an annual rate of 1.7 %, whereas forest and shrub together have decreased at an annual rate of 0.5 % (Meen and Chhetri, 2010) all resulting in the loss of habitats of plants and animals. Some species such as *Crocodyluspalustris*, *Kachugakachuga*, and *Gavialis gangeticus* have very poor dispersal capacity and their habitat is Wetland in the Terai region of Nepal. Shrinkage of wetland areas already triggered the extinction of those faunas (Lamsal *et al*., 2017).

Imbalance in carbon sequestration

At normal environmental conditions, the forest is a major component of the carbon cycle as trees can sequester carbon in organic form thus reducing CO_2 emission. It has been estimated that the forest ecosystem can sequester 20-100 times more carbon than that of cropland (Upadhyay *et al*., 2005). Bhattarai *et al*. (2004) reported high uncertainty regarding carbon sequestration in forests of Nepal Emission of CO_2 by anthropogenic activities like land-use change and deforestation and conversion to agricultural land in the Hindu Kush Region resulting in soil erosion, loss of organic carbon in the soil which ultimately alters soil fertility. A high incidence of forest fire also was reported in this region which leads to declining in sequestered carbon. This is mechanism is also proliferating Global Climate Change.

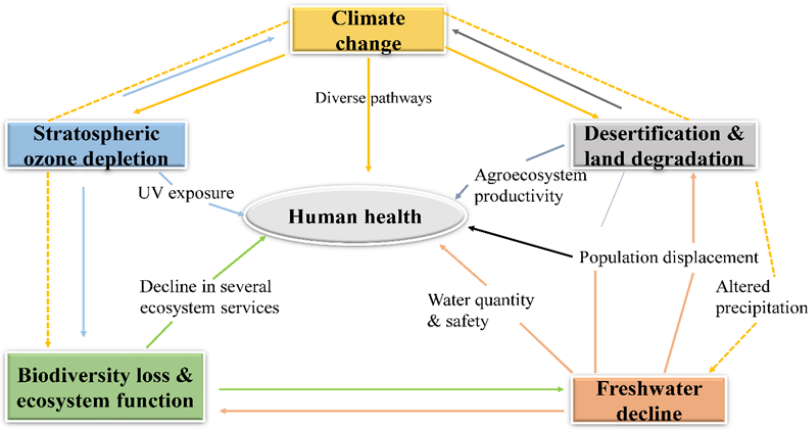

Figure 8. *Impact of climate change on human health (modified from WHO, climate change and human health).*

Impact of climate change in freshwater ecosystem

The aquatic ecosystem includes freshwater ecosystems and marine ecosystems (Adhikari *et al.*, 2019a, 2019b; Paudel *et al.*, 2017; Sharma *et al.*, 2020). Nepal only harbors a freshwater ecosystem as it is a land-locked country and is the most vulnerable type of ecosystem in the world which is very sensitive to climate change. More than half of wetlands in the world are altered although they are biologically rich and play major roles in providing ecosystem services to a greater magnitude (Mooney *et al.*, 2009). Nepal is a rich country in water resources and to date, 10 sites are listed on the wetland. Each of them harbors flora and fauna (Kafle and Savillo, 2009). As glacier fed-river is the source for most of the water bodies in Nepal, the modification in flow regime alters the ecological diversity and function of river systems as well as disrupts sediment flux and thermal regime. A distribution list of 76 indigenous cold-water fish has been observed in Nepal which loves the clean river and cold water and Rara Lake is famous for 3 types of endemic fishes (Lamsal *et al.*, 2017). Some species of fish are already designated as endangered which may be either by the increase in temperature or by the addition of toxic substances and fertilizers from Agricultural land (Kafle and Savillo, 2009).

Others

Agriculture and food security

In Nepal, more than 80% of the population relies on agriculture as a source of food, employment, and income. More than 70% of Nepal's agriculture is rain-fed. The largest share of total crop production comes from the central region (nearly one third), followed by the eastern and western regions (Regmi, 2007). The agricultural system is highly sensitive to change in temperature, precipitation, natural disasters, and abnormal weather conditions (Karn, 2014). Rice is a major crop of Nepal and its production depends on summer precipitation and rice production is decreased these days due to insufficient precipitation and summer drought (Bhatta *et al.*, 2015), reported the decrease in the paddy and wheat yield due to change in rainfall pattern and increase in winter drought respectively. Increased impacts from various insects' pests and fungal infections triggered by the increase in Temperature were noticed in rice, potato, and millet, thereby reducing total production was also found in Dolakha District. Dahal *et al.* (2016) also presented the temporal and spatial pattern of drought phenomenon on Gandaki River Basin, i.e., the basin with the highest amount precipitation in Nepal, and reported the serious effect of drought on rain-fed agriculture. They detected lesser yield of major crops like Paddy, rice, wheat, maize in drought years as compared to normal years. Generally, beneath a doubled CO_2 scenario predicted for 2100, the rice crop in Nepal is projected to drop by approximately 4.2 % relative to current production levels (Karn, 2014). According to FAO, all people have the right to consume secure food. As domestic food production is declined by abnormal weather conditions like drought, hailstone, and storm, a huge amount of food needs to be imported. In recent times, great food insecurity has been detected in Nepal.

Impact of climate change on human health

Human health is also affected by climate change (Figure 8). Some examples suggest climate change has already resulted in the introduction of infectious diseases into previously unaffected geographic areas in Nepal. Water-borne diseases like typhoid, cholera Diarrhea cases have been increased due to inadequate drinking water especially in summer (May-September). Apart from this, climate change further helps to emerge most of the vector-borne diseases like malaria, kala-azar, dengue, plague, etc. Cardiovascular disease, physiological stress, and malnutrition are also found to be associated with climate change in Nepal (Joshi *et al.*, 2011).

Water-related hazards

Water-associated hazards elicited by global warming and glacier melting are not only being the reason for death and poverty in human civilization but also are being a key driver for the substantial loss of large areas of land along with its respective bio-diversities. Similar events, Glacier lake outburst flood in upstream and flood and landslides in downstream were reported from Eastern part of Nepal i.e. Koshi River Basin which is a direct driver of ecosystem loss (Nepal *et al.*, 2014). Similarly, climate change triggered a loss in drinking water resources already replaced a whole village from its former site to a new place. This course modifies the equilibrium of the existing ecosystem in the shifted area.

Conclusion

Nepal, although contributes very little to Global warming is highly affected by global climate change. The major impact of climate change in Nepal was recounted on the mountain ecosystem and freshwater ecosystems. Treeline shifting, change in land cover, extinction of species due to loss of habitat, imbalance in carbon sequestration were reported on the terrestrial ecosystem while eutrophication of water bodies and extinction of endemic fish species was reported from the aquatic ecosystem. Climate change-induced natural disasters and health impacts especially in Tropic areas were reported. Microbes play a key role in all types of ecosystems balancing the natural phenomenon. However, no studies have been conducted in Nepal related to the impact of climate change on microbes and their role in biogeochemical cycles i.e., carbon, nitrogen, phosphorous, and sulphur cycle. Microbes are changing climate and have been changing climate for decades so they should not be excluded while studying the impact of climate change. Moreover, different types of ecological modeling can be simulated in the context of Nepal for the prediction and future analysis of the impacts of climate change in the ecosystem. Therefore, ecological modeling-based research works should be emphasized in Nepal.

Author contributions

Ganesh Paudel[#] (Contributed equally to this research).
Subash Adhikari[#] (Contributed equally to this research).

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