

Review

The Impact of Climate Change on Biodiversity in Nepal: Current Knowledge, Lacunae, and Opportunities

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Abstract: Nepal has an extreme altitudinal range from 60–8850 m with heterogeneous topography and distinct climatic zones. The country is considered a biodiversity hotspot, with nearly a quarter of the land area located in protected areas. Nepal and the surrounding Himalayan region are particularly vulnerable to climate change because of their abrupt ecological and climatic transitions. Tens of millions of people rely on the region's ecosystem services, and observed and modeled warming trends predict increased climate extremes in the Himalayas. To study the ecological impacts of climate change in Nepal and inform adaptation planning, we review the literature on past, present, and predicted future climatic changes and their impacts on ecological diversity in Nepal. We found few studies focusing on organisms, while research on species and communities was more common. Most studies document or predict species range shifts and changes in community composition. Results of these few investigations highlight major lacunae in research regarding the effects of changing climate on species comprising the Himalayan biota. Further empirical work is needed at all levels of biological organization to build on information regarding direct ecological impacts of climatic changes in the region. Countries face an ever-increasing threat of climate change, and Nepal has strong physiographic, elevational, and climatic gradients that could provide a useful model for studying the effects of climate change on a mountainous, and highly biodiverse, area.

Keywords: biodiversity; ecological impacts; global change; Himalayas; review

1. Introduction

Climate change may exacerbate the effects of other anthropogenic factors that threaten the biota of species-rich countries [1,2]. Range shifts, changes in seasonal phenology, altered species interactions, species selection pressure, and increased extinction risks are some of the key biological impacts observed worldwide due to climate change-induced alterations in temperature and rainfall patterns [3–5]. In the 20th century, destruction of natural habitats was the main driver of biodiversity loss. However, contemporary projections of the primary threats to global biodiversity are increasingly related to climate change [6]. Areas that already have extreme climates are predicted to experience the most severe effects on biodiversity under climate change projections for the year 2100 [7]. Myers et al. [8] identified 25 global biodiversity hotspots based on species richness, endemism, and anthropogenic threat. Of the 16 tropical hotspots, 4 occur in Southeast Asia, and the Indo-Burma hotspot extends westward to include Nepal [9], a least developed country. Biodiversity-rich regions are disproportionately found in developing countries, which are less able to afford mitigation efforts to ameliorate the effects of anthropogenic and climatic change [8].

As one of the world's most important hotspots for biodiversity [10], the study of climate change and monitoring of ecological processes being altered by climatic changes that affect Nepal are relevant. This review focuses on the impacts of climate change on biodiversity in Nepal, with consideration of impacts on the Himalayas and the broader South Asian subcontinent. The region's high elevations and mountainous terrain cause geographic isolation, species range limitations, and decreased anthropogenic impacts that could leave the system highly vulnerable to climate change [11–20]. For these reasons, montane areas are ideal sites for studying the biological impacts of climate change [21].

Species richness and beta diversity are strongly influenced by elevation [22], and Nepal ranges from 60–8850 m above sea level (a.s.l.) along its short north–south axis—the greatest range of any country on Earth. The majority of Nepal's land area is on Himalayan slopes—the entire country is more or less on the side of a mountain—creating tremendous environmental heterogeneity. In addition, the country is a biogeographic crossroads, linking tropical communities in the lowland south with temperate communities in the montane north. The steepness of its slopes leads to rapid species turnover from lowland/Oriental flora and fauna in the south to alpine/Palaearctic biota in the north, making the country one of the world's most unique biodiversity hotspots [10]. The many habitat types found in Nepal occur as narrow bands running more or less in parallel with its southern border, and it is likely that climate-induced shifts in the biota will drastically alter species ranges, species interactions, and ecological processes in Nepal [23].

We explore how climate change will likely affect biodiversity in Nepal, the Himalayas, and the larger South Asian subcontinent. The region's steep elevational gradient influences geographic isolation, species range limits, and creates high beta diversity in a relatively small area [11–20]. For these reasons, montane areas are posited to be ideal for studying biological impacts of climate change [21]. We first summarize physical and ecological aspects of Nepal, including its current climate, future climatic predictions, biodiversity, and threats to biodiversity. We then review existing records of biological impacts of climate change in Nepal, including the Himalayan range and the surrounding South Asian subcontinent. Using the framework outlined in a global climate change review by Scheffers et al. [23], we aggregate available studies into a publication list that identifies the impact of climatic change on ecological processes at different levels of biological organization. We emphasize biodiversity impacts at different levels of biological organization to highlight the types of research that have been conducted and bring attention to observational lacunae.

2. Nepal: Physical and Ecological Overview

With an area of 147,181 km², Nepal is nestled between India to the south and the Tibet Autonomous Region to its north. The heterogeneous topography of Nepal causes distinctive climatic zones that harbor diverse ecosystems that support high species richness and endemism [24–32].

Classification of ecosystem types in Nepal is difficult due to its ecological complexity. Previous attempts to categorize the range of habitat types have identified up to 118 habitat types [32–34]. However, for simplicity, Nepal can be divided into five physiogeographic zones based on elevation: Terai, Siwalik, Middle Mountains, High Mountains, and High Himal. Each zone includes several bioclimatic subzones. Nepal and the surrounding region are increasingly at risk due to climate change, as the subcontinent's economies are highly dependent on the South Asian monsoons [35]. Glacial and snowpack-dependent river basins within the Himalayan plateau have been designated one of the three climate change hotspots of the world. The Himalayas provide one of the world's largest populations with fresh water, which underlines the severe negative impacts that climate change will have on the humanity and biodiversity of this region [36].

2.1. Current Climate

Nepal, spanning the Indo-Gangetic basin to the Himalayan range and the Tibetan plateau, has unique physiographic and topographic features that give rise to its climatic and ecological diversity. The climate ranges from subtropical in the south to Arctic in the north. Most precipitation in Nepal (around 80%) occurs during the Indian summer monsoon (June–September). Mean annual precipitation varies around 1530 mm, with maximum precipitation occurring at 2000 m elevation and dry conditions in the rain shadows north of the Himalayan peaks. Westerly low-pressure weather systems that originate over the Mediterranean Sea bring snow and rain during winter and spring, most significantly in the northwestern part of the country. Winter precipitation plays a major role in the mass balance of glaciers in western Nepal and is important in generating water flows during the winter and spring dry seasons. Air temperatures are highest during May or early June (36–39 °C at the mean maximum range), more moderate during the monsoon, and reach a mean minimum range below –3 °C in December or January. Absolute temperatures vary widely depending on elevation. The Terai region is the warmest part of the country, with high temperatures sometimes exceeding 45 °C [37].

Inhabitants of the South Asian subcontinent are dependent on the monsoon system, which affects industrial development, agricultural, economic, and energy production of the region, and daily life [13,20,35,38]. The intimate dependence of local livelihood on annual rainfall, of which 75% consists of summer monsoon rainfall alone [38], attests to the importance of studying and considering monsoon variability as a consequence of climate change. An example of the regional dependence on the reliability and regularity of its rainfall can be noted in the impact of a drought that occurred in India during July 2002. Just half the normal amount of rain fell, which considerably impacted agricultural production and the economy of India [39].

2.2. Future Climatic Trends

Regional temperature and rainfall patterns are largely driven by elevation contrasts and the orientation of mountain belts [13,40]. A study analyzing maximum temperature trends in the Himalayan region suggested that warming of high altitude regions—particularly in the Middle Mountain zone—largely drives increasing temperatures and variability in rainfall in the High Himalaya [13]. Climate change has accelerated glacier degradation over recent decades, profoundly impacting the Himalayan environment [41]. The analysis of trends in observed temperature and precipitation data in Nepal is limited by the dearth of weather stations, high altitude rain gauges not adapted to measure snowfall [42], and the relatively short period of data collection: about 30–40 years [43,44]. With the limited extent of available ground observations, remote sensing has been useful in resolving spatial and temporal variability in climate variables, especially precipitation [45–48].

The Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR4) projected warming in South Asia of 2–4 °C by the end of the 21st century relative to the end of the 20th century, under the different forcing scenarios explored (A1B, A2, B1) [49]. The most recent Fifth Assessment Report confirms this range for scenarios without immediate strong controls on greenhouse gas emissions (Representative Concentration Pathways (RCPs) 8.5, 6.0, 4.5), though it is

noted that sharp reductions in global emissions beginning before 2020 (RCP 2.6) could keep regional warming below 2 °C [50,51]. In Nepal, warming over the past few decades has been more pronounced at higher altitudes [52], and relatively lower in the Terai, Siwaliks, and Middle mountain regions [13,43]. Precipitation data from Nepal show few consistent trends. One study showed that trends in total monsoon precipitation from 1951–2007 varied among regions of the country, while precipitation generally decreased during the winter season and increased during the pre-monsoon season [53]. Other studies found that droughts in central Nepal have become more intense since the 1980s [54] and from 1981–2012, increases in mean rainfall during the monsoon season were not statistically significant, while rainfall during other seasons had decreased by 1% per year [55]. Precipitation in Nepal is influenced by, or correlated with, several large-scale climatological phenomena, including the El Niño Southern Oscillation [56], the Pacific Quasi-Decadal Oscillation [57], and the Arctic Oscillation [58], which contribute to its interannual and decadal variability and which might also be affected by climate change.

Numerous studies agree that the intensity of temperature extremes will increase [59–70]. Several studies have projected significant increases in mean precipitation and in monsoon variability [38], due to a several anticipated factors, including an increased moisture availability that parallels increases in surface temperature [35] and intensification of the thermal low over northern India [35,38,71–74].

2.3. Agriculture and Agro-Biodiversity

Agriculture constitutes one-third of Nepal's gross domestic product (GDP) and more than half of its exports. Additionally, agriculture is the main source of income for two-thirds of the country's population [75]. Subsistence and mixed farming provide employment for 69% of the population [76]. One-quarter of Nepal's population of 28.5 million [77] lives below the national poverty line [78]. After the devastating earthquake in April 2015, the World Bank estimated that an additional 3% of the population was pushed below the poverty line. One-half to 70% of those people are from rural areas in the central hills and mountain regions of the country [79]. Given the current population demographics of the country, and its dependence on agriculture, the importance of understanding the impact of climate change on the region cannot be overstated. Nepal is rich in agro-biodiversity due to variation in cultivars grown at different elevations. Diversity in agro-ecosystems continuously supplies food, nutrition, fiber, fuel, and services that contribute to livelihoods [80]. Functional and genetic diversity between plant and animal populations that deliver ecosystem services will help humanity adapt to change [81], but severe abiotic changes may necessitate adoption of different crop cultivars.

2.4. Patterns of Species Richness

Nepal's ecological and climatic diversity supports a high species diversity for its relatively small size, it comprises less than 0.1% of Earth's total land cover, and yet current estimates for this small country indicate disproportionately high levels of biodiversity (Table 1). Nepal is home to ~12,000 plant and fungus species, 208 mammals, 867 birds, 123 reptiles, 117 amphibians, 230 fish, 651 butterflies, 3958 moths, and 175 species of spiders [82,83]. In addition to species richness, there are dozens of different habitat types, many of which are found within protected areas [32,83,84]. Nearly one-quarter (23.2%) of Nepal's land area is protected within 12 national parks, 1 wildlife reserve, and 6 conservation areas [85]. The number of national parks has recently increased with the inclusion of Sukhlapanta and Parsa that were previously wildlife reserves (pers. comm. Shrestha B. B.).

Table 1. Taken from the Ministry of Forest and Soil Conservation, Government of Nepal (2014) [83].

Group	Number of Observed Species	% Relative to Known Species Worldwide
Angiosperms	6973	3.2
Gymnosperms	26	5.1
Pteridophytes	534	5.1
Bryophytes	1150	8.2
Lichens	465	2.3
Fungi	1822	2.6
Algae	1001	2.5
Flora total	11,971	-
Mammals	208	5.2
Birds	8673	9.5
Reptiles	123	1.9
Amphibians	117	2.5
Fish	230	1.9
Butterflies	651	3.7
Moths	3958	3.6
Spiders	175	0.4

Studies of biodiversity in the Himalayas have documented similar patterns across plant and animal groups, but point to conflicting underlying processes [86]. A mid-domain effect or unimodal distribution along the altitudinal gradient has been observed in birds in the Indian Himalayas [30], orchids [87], and butterflies in Nepal (pers. comm. Khanal, B.). The highest diversity is typically found in the Mid-Hills across plant and animal groups, which is where nearly one-third of Nepal's forests are found [88]. Although fish diversity in Nepal decreases with altitude, endemic species show a unimodal peak at mid-elevations [89]. Arthropods in the Indian Himalayas show both a unimodal hump, and a decrease in diversity from East to West congruent with changes in climatic factors [90]. Studies on several plant groups and insects showed that this high diversity was associated with in situ diversification caused by habitat fragmentation and climate oscillation resulting from the uplift of the Tibetan plateau and orogenesis of the Himalayas [86], whereas other research indicated that in situ diversification has not produced preponderance of the biota [91]. That the Himalayas are populated primarily by biota dispersed from elsewhere seems further plausible given its relatively low level of endemism.

2.5. Threats to Biodiversity

This rich and unique biodiversity is threatened by multiple anthropogenic and natural factors operating at different spatial scales. Deforestation, biological invasion, pollution, overexploitation, fire, and mining in fragile regions degrade natural ecosystems; while poaching is responsible for the decline of some keystone species [83]. The effect of these factors extends into Nepal's protected areas. Deforestation was a nationwide issue in the past [92,93]. However in recent decades, continued efforts of government agencies, communities, NGOs, and INGOs have improved forest conditions, particularly in hilly and mountain regions. In a forest assessment report from 2015, the government of Nepal reported that 40% of the country was forested [94], up from 29% in 1998 [93]. However, change in forest area varies across landscapes. For example, in the Chitwan-Annapurna Landscape (CHAL) of central Nepal, the forest area remained unchanged (35.5%) between 1990 and 2010 [95], whereas forest area in Nepal's Kailash Sacred Landscape (KSL) declined 9% from 1990 to 2009 [96]. Deforestation is still a major problem in the Siwalik and Terai region. In Koshi Tappu Wildlife Reserve, a Ramsar site in eastern Terai, forest area declined 94% from 1976 to 2010 [97].

Poaching and illegal cross-border trading is another major problem in Nepal, reducing populations of tiger, musk deer, and snow leopard. Unsustainable harvesting of medicinal plants is another contributing factor to biodiversity loss, and in the case of *Cordyceps sinensis* (yarsagumba), leads to

habitat degradation as well. Additionally, invasive plants have recently been recognized as major threats to ecosystems, even within protected areas [98].

3. Methods

We searched articles published between 1990 and April 2017 with Web of Science (webofknowledge.com) and Google Scholar (scholar.google.com) using the search terms “impact” OR “effects” AND “climate/ic change” OR “anthropogenic change” AND “biodiversity”, “species shift”, “community shift” AND “Nepal” OR “Indian subcontinent” OR “South Asian Subcontinent” OR “Himalayas” OR “Himalayan Range”.

Publications on the effects of climatic changes (principally temperature and rainfall) on any form of biodiversity were retained. We further filtered the search results by excluding articles that only discussed predictions of climatic change using climate models without including any form of assessment of impact on a particular species and/or ecosystem. Studies conducted on the importance of shifting climates on food security, crop availability and food production were excluded as they were outside the focus area of this review. Studies on microbe, invertebrate, vertebrate, plant, and crop species were retained.

Our focus was Nepal and we excluded publications that did not pertain to the South Asian subcontinent. We assigned each article a score from 1–3 indicating its relevance: 1 = within Nepal; 2 = within the Himalayan region; 3 = within the Indian subcontinent.

Following the framework of Scheffers et al. [23] for measuring ecological impacts of climate change at a global scale, we scored each article based on the levels of biological organization and associated ecological processes analyzed. The framework identified four levels of organization: organisms, species, populations, and communities. Articles were assigned to each level using the focal ecological process considered and the level of organization to which it relates, such as genetic diversity (organism), range expansion (species), recruitment rates (population), and species composition (community).

4. Impacts of Climate Change in Nepal

4.1. Results

We identified 63 publications from 38 scholarly journals, 5 conference papers, and 1 book chapter that matched our search specifications. Twenty articles were found on Web of Science and 20 other articles were located with Google Scholar. The remaining articles were added to our database by searching for articles that cited these 40 papers. Of the articles identified in our search, only 13 of the 63 papers provided studies that explored direct effects of climate change on biodiversity and ecological processes. We scored these 13 articles using the Scheffers et al. framework [23] to gauge different biological levels studied in this region, and grouped our findings in that context (Table 2). Five of the papers were scored ‘1’ based on relevance to the study area. These studies were conducted within Nepal. Six of the papers were scored as ‘2’, focusing on study areas within the Himalayan Plateau. One of the papers was scored as ‘3’, which covered an area within the Indian subcontinent. One paper could not be scored from 1–3 and was designated as ‘*’ to indicate that it was a meta-analysis covering the entire world. However for the analysis, we focused on their five population samples that covered area within the Himalayan region.

Table 2. Studies reviewed and their approaches, organized based on Scheffers et al. framework [16].

Biological Organization	No. Articles	Studies	Methods
Organism	0	-	-
Species	8	Song et al. (2004), Gaire et al. (2011), Forrest et al. (2012), Telwala et al. (2013), Ferrarini et al. (2014), Gaire et al. (2014), Shrestha & Bawa (2014), Thapa et al. (2016)	Field surveys, sample collections, statistical analysis, seed dispersal models, species distribution models (current and projected climate scenarios), general circulation models, digital elevation models
Population	4	Gaire et al. (2011), McCain & Colwell (2011), Shrestha et al. (2012), Gaire et al. (2014)	Field surveys, sample collections, statistical analysis, meta-analysis (using published data), species distribution models (current and projected climate scenarios), remote sensing
Community	6	Shrestha et al. (2012), Telwala et al. (2013), Chitale & Behera (2014), Salick et al. (2014), Shah et al. (2014), Thapa et al. (2016)	Field surveys, sample collections, social surveys, statistical analysis, species distribution models (current and projected climate scenarios), general circulation models, digital elevation models, remote sensing

Nearly two-thirds (8/13) of the publications studied species level effects, evaluating changes in distribution of biodiversity in the region as a response to climate change. Several studies [4,15,99,100] used habitat suitability and species distribution models inferred with the general-purpose machine-learning method MaxEnt [101]. Other studies [18,52,102,103] implemented correlative analyses and spatial simulation models to assess the impact of climatic factors, such as temperature and precipitation, on species distributions or range limits of the focal taxa. All species-level studies in our review reported a significant change in the distribution and/or range limits of their respective focal taxa (Table 3).

About one-third (4/13) of the sources studied climate impacts at the population level. One publication [104] was a meta-analysis using species elevational ranges from global datasets. This study predicted local population extirpation risks under varying climate scenarios to evaluate the effects of climate change on biodiversity at a global scale. We included the paper in our review, as five of the montane vertebrate populations included in the study were found in Nepal.

Gaire et al. [52,102] examined growth of alpine tree species in the Himalayan region that are strongly limited by low temperatures. They recorded growth and regeneration changes in response to climatic changes, in addition to observing a shift in tree line position and range limits at the species level. Shrestha et al. [105] documented the effects of temperature and precipitation change on phenological parameters of vegetation systems in 13 different ecoregions within the Himalayan plateau. This study used remote sensing and meteorological station data to report earlier onset of the growing season, coupled with climatic changes over two decades. These three studies are among the only publications documenting population level changes in tree line dynamics of the region (i.e., tree growth, recruitment rates, variation in onset and duration of growing season, and senescence). Reliable, long-term meteorological records are required to calibrate field-collected tree ring data, which are integral to studying tree line dynamics [52]. The paucity of these data limit dendroclimatic research in this region.

Changes in species distributions and range limits predicted or recorded in this region beget the question of how species interactions (predation and competition) may change within shifting ecotones, whether new interactions will emerge, and how these changes will affect existing species [106,107]. These species-level effects may manifest community-level changes such as species composition and productivity. Nearly half (6/13) of the studies refer to ecological impacts at the community

level. However, none of these articles documented changes in interspecific interactions in Nepal or the South Asian subcontinent as a response to climate change. Several of the studies evaluated changes in species composition within their respective study areas [18,19,21,100,108]. Shrestha and colleagues [105] documented regional changes in phenology that directly complement research on patterns of productivity as a response to temperature and precipitation. Research on how climate change affects interspecific interactions on the South Asian subcontinent is scarce relative to other regions of the world [109]. This may be because documenting interactions requires prolonged observation, because it is difficult to link changes directly to climate, or because there is a dearth of community ecologists in the region. Even though no studies directly observe climatic effects on biotic interactions, some results infer increased competition and vulnerability of endemic, alpine species as lower elevation species ranges move northward [21].

No studies occurred at an organism level, which would involve genetic, physiological, or morphological research on individual species. A likely theme in such studies would examine climate-induced selection and adaptation promoting range shifts. One example of a potential organism level study can be derived from the predicted range expansion of the Himalayan endemic Chinese Caterpillar Fungus (*Ophiocordyceps sinensis*) under future climate scenarios [99]. These predictions were linked to the existing relationship between temperature and physiology of the fungus, hence it can be expected that there would be organismal level change in this species that can be individually examined. Similarly, studies recording and predicting shifts in alpine tree line dynamics [52,102] may assume potential physiological changes occurring at an organismal level, such as temperature-driven responses in this case. However, the lack of any published research investigating the effects of climate change on organisms in this region suggests a need for more research on the autecology of Nepal's flora and fauna.

Table 3. Summary of key findings from the 13 studies used in this review, with corresponding level(s) of biological organization, reference, focal taxa and relevance score for each study.

Biological Organization	Reference	Focal Taxa, Relevance Score (RS)	Key Findings
Species	Song et al. (2004) [15]	6 Alpine tree species (<i>Abies spectabilis</i> , <i>Picea likiangensis</i> , <i>Pinus densata</i> , <i>Larix griffithiana</i> , <i>Quercus aquifolioides</i> , <i>Betula utilis</i>) RS: 2	(1) Range of <i>A. spectabilis</i> , <i>P. likiangensis</i> , <i>Pinus densata</i> , <i>L. Griffithiana</i> , and <i>Q. aquifolioides</i> projected to extend northwards and westwards under the future climate scenarios; (2) <i>B. utilis</i> range projected to shift northwards and shrink in overall distribution under future climate scenarios; (3) Significant difference in 7 alpine species distributions under current climate conditions versus future scenarios
Species, Population	Gaire et al. (2011) [102]	Himalayan fir (<i>Abies spectabilis</i>) RS: 1	(1) High <i>A. spectabilis</i> recruitment rates in recent decades; (2) Lower average age along as altitude increases; (3) Growth rate exhibits a negative response to temperature (particularly March–May season); (4) Tree line is predicted to extend northwards due to future climate change
Species	Forrest et al. (2012) [2]	Snow leopard (<i>Panthera uncia</i>) RS: 2	(1) Predicted loss of 30% snow leopard habitat in the Himalayas mainly along southern distribution range due to projected shrinking of alpine zones
Species, Community	Telwala et al. (2013) [18]	Endemic alpine plants RS: 2	(1) 90% of endemic plants studied in Sikkim Himalayas have experienced temperature driven elevational range shifts; (2) Increased species richness in the upper alpine zone due to upper range extensions; (3) Species from the lower alpine zone exhibited the largest range shifts

Table 3. Cont.

Biological Organization	Reference	Focal Taxa, Relevance Score (RS)	Key Findings
Species, Population	Gaire et al. (2014) [52]	Himalayan fir and Himalayan birch (<i>Abies spectabilis</i> and <i>Betula utilis</i>) RS: 2	(1) Increased current plant density in Central Himalayas; (2) Current upper range limit of <i>B. utilis</i> observed to be unchanged in recent decades; (3) Growth of <i>B. utilis</i> mainly limited by moisture stress during the pre-monsoon season; (4) High <i>A. spectabilis</i> recruitment rates in recent decades and lower average age, most affected by maximum and minimum temperatures; (5) <i>A. spectabilis</i> regeneration occurring above existing tree line
Species	Ferrarini et al. (2014) [103]	2 Alpine plants (<i>Anaphalis xylorhiza</i> and <i>Leontopodium monocephalum</i>) RS: 1	(1) Predicted species distributions models found to be smaller than potential distributions of Himalayan plant species; (2) Use of potential distributions for predicting species range under future climate scenarios carries a high risk of overestimation
Species	Shrestha & Bawa (2014) [99]	Chinese caterpillar fungus (<i>Ophiocordyceps sinensis</i>) RS: 1	(1) Projected expansion of suitable habitat for <i>Ophiocordyceps sinensis</i> under future climate scenarios; (2) Complete habitat loss predicted for some future climate scenarios in Taplejung and Humla districts; (3) Possible range expansion into two new districts of Dolpa and Pachthar under future climate scenarios
Species, Community	Thapa et al. (2016) [100]	Forest/Vegetation systems RS: 1	(1) Projection of lower- and mid-montane forests show higher vulnerability than upper montane and subalpine forests (providing macrorefugia); (2) Subalpine scrub vegetation projected to shift range northwards; (3) Lower and mid-montane forests predicted to become smaller patches of microrefugia, and may provide important “climate corridors” for species forced to shift northwards
Population	McCain & Colwell (2011) [104]	16,848 vertebrate species * <i>Global study incorporating 5 data sets from Himalayan region</i>	(1) Population extirpation risk predicted to peak at minimum precipitation levels; (2) Salamanders and frog species are predicted to be most vulnerable to local population extirpation risk under global future precipitation scenarios
Population, Community	Shrestha et al. (2012) [105]	Vegetation systems RS: 1	(1) Early average onset of growing season and increased length of growing season observed for Himalayas; (2) Late end of growing season observed in Western Himalayas, with mixed patterns in central and eastern Himalayas (overall longer growing season in western region)
Community	Chitale & Behera (2014) [108]	Forest/Vegetation systems RS: 3	(1) Dominance of <i>Shorea robusta</i> observed in Katarniaghat wildlife sanctuary along the Himalayan foothills; (2) Increased range of grasslands observed over three decades in Katarniaghat Wildlife Sanctuary
Community	Salick et al. (2014) [21]	Alpine plant species RS: 2	(1) Higher number of overall plant taxa and endemic species found at the lowest subalpine-lower alpine ecotone in the eastern Himalayas
Community	Shah et al. (2014) [19]	78 Benthic invertebrate species RS: 2	(1) Altitude is significant related to variation in benthic invertebrate community assemblage in Central Himalayas; (2) 79% of indicator taxa studied exhibited a negative response to increasing altitude; (3) 90% predicted decrease in suitable habitat for <i>Epiophlebia laidlawi</i> and northward elevation shift in range projected under future climate scenarios

4.2. Discussion and Conclusions

The dearth of published studies on ecological impacts of climate change in Nepal and the surrounding Himalayan region, despite their economic and ecological importance, identifies a

critical lacuna and need for further work. Many studies have analyzed meteorological data from the South Asian subcontinent [110–117], studied historic patterns of temperature and precipitation, documented variability in monsoons [118], and predicted future climate scenarios. Given access to the appropriate technology, climate data, including rainfall and temperature, are relatively easy to measure in comparison with more time consuming, but critical, biological observations that require on-the-ground fieldwork and aptitude in identifying species. This disparity is reflected in the literature. Climatological papers are more numerous than studies of climate change effects on biodiversity globally [104], but this disparity is even more pronounced for South Asia.

Of the 63 articles identified by our literature search, only 13 (15%) documented biological effects of climate change in this region, though we might have missed some studies, particularly if they are published in the gray literature [119]. The studies reviewed here constitute a baseline for research on biodiversity impacts due to climate change in Nepal and the surrounding region. The small canon of papers we found suggests the need for more research on organisms and species documenting where they live and how they interact with their biotic and abiotic environment in the topographically complex Himalayan region. These baseline data are needed to understand and predict forthcoming climate change-induced alterations of Nepal's ecology. Of the studies available, most focus on predicting range shifts and changes in species distributions of plants given future climate scenarios. These studies evaluated impacts of climate change on species and communities, but, more focused studies [18] on populations and individual organisms are needed to link the biota to its environment. For example, studies on the physiological thresholds of species will provide mechanistic explanations for range shifts, help parameterize future models, and may highlight species endangered by climate change [120]. Corresponding research on cane toads in northern Australia found enhanced species invasion due to increased population growth with range expansion [121], providing an important case for understanding evolutionary changes that may be caused by the effects of climate change. This is particularly important for Nepal, where invasive plants including *Parthenium hysterophorus*, *Lantana camara*, and *Ageratina adenophora* outcompete much of the native flora [122]. These observational lacunae present opportunities for significant, much-needed research on organism-level impacts of climate change on biodiversity.

Of the world's 10 highest mountains, 8 are found in Nepal, as is lowland, subtropical forest starting at 50 m a.s.l., providing the steepest elevational and climatic gradients on Earth. More than 1.3 billion people rely on water resources provided by one of the world's largest glacier covers found in the Himalayas [123], and many human livelihoods depend on the reliability of Nepal's climate. Increasing evidence of extremes in monsoon variability and temperature trends highlight the climatic vulnerability of Nepal, the surrounding Himalayan region, and, more broadly, the South Asian subcontinent. The flora and fauna of the region constitute a significant biodiversity hotspot that requires research attention and protection, given the observed climatic trends and alarming future projections. Further research and publications on physiological thresholds and population dynamics of species in this region are needed to establish fundamental baseline information regarding the biodiversity of the South Asian subcontinent. Additionally, further published research on changes to productivity and distributions of species will fortify these foundational studies and provide a broader understanding of how regional climatic change will affect the valuable biodiversity of this region.

Supplementary Materials: The following are available online at www.mdpi.com/2225-1154/5/4/80/s1. Scientific articles collated for review.

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