ICIMOD Research Report 2017/1

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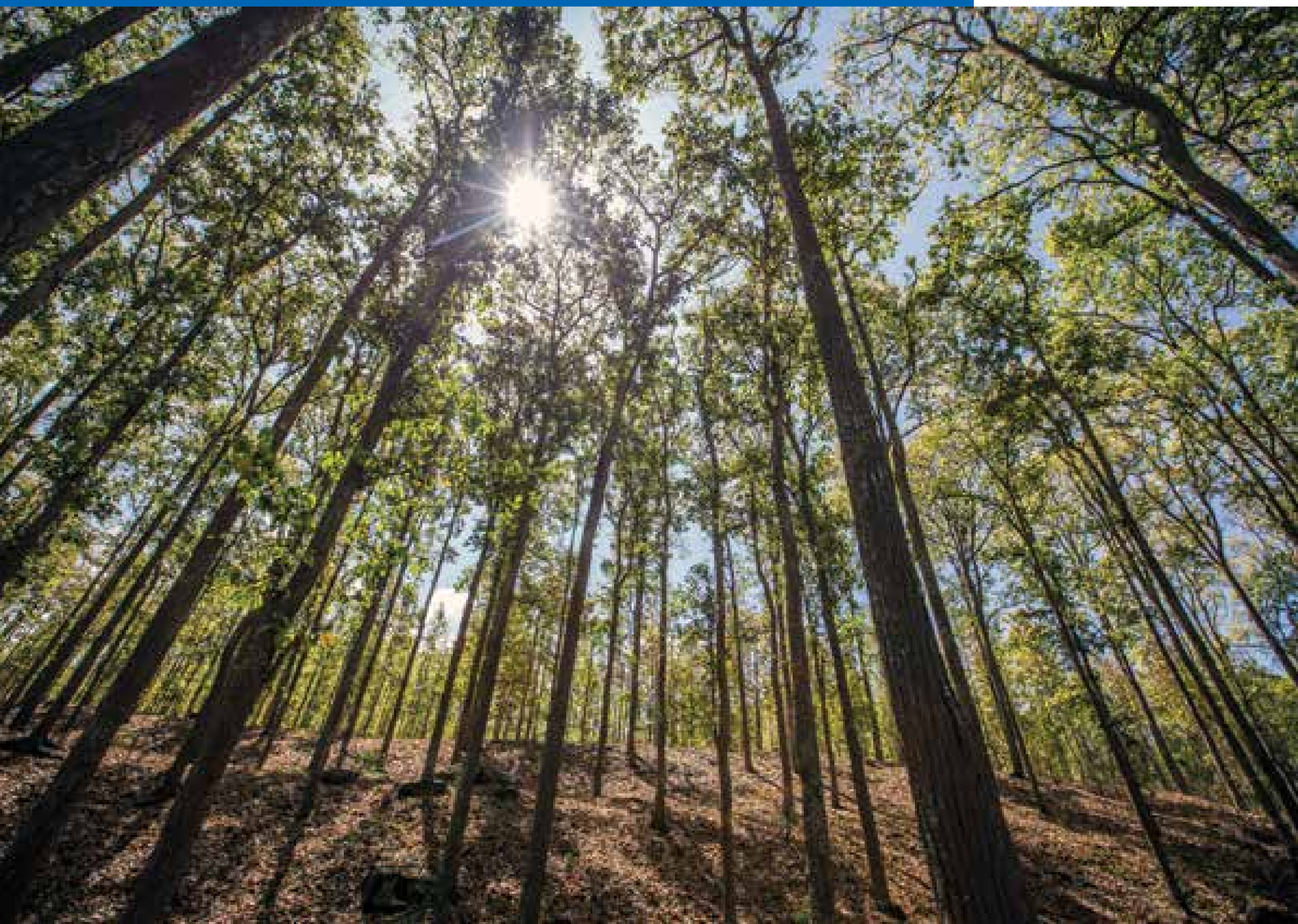
Projected Impacts of Climate Change on Forests in the Brahmaputra, Koshi, and Upper Indus River Basins

INDIAN INSTITUTE OF SCIENCE



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The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

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The Himalayan Climate Change Adaptation Programme (HICAP), one of the initiatives under ICIMOD's Regional Programme on Adaptation to Change, is a six-year research programme initiated in 2012. It is implemented by ICIMOD in collaboration with CICERO and GRID-Arendal, with responsibilities for overall research competence and communication and outreach respectively. With 28 international and regional partners, HICAP carries out basic and applied research as well as policy engagement to contribute to enhanced resilience to change, particularly climate change, through improved understanding of vulnerabilities, opportunities, and potentials for adaptation. It covers five river sub-basins: upper Indus (Pakistan), Koshi (Nepal), upper Brahmaputra (Tibetan Autonomous Region, China), eastern Brahmaputra (India), and upper Salween-Mekong (China). The programme is supported by the Governments of Norway and Sweden.

For more information, please visit **www.icimod.org/hicap**

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Projected Impacts of Climate Change on Forests in the Brahmaputra, Koshi, and Upper Indus River Basins

Investigators

N.H. Ravindranath and G. Bala

Research Team

S. Upgupta; J. Mathangi; D.S. Anitha; K. Sindhu; V. Kumar; J. Sharma; A. Chaitra; R.K. Chaturvedi; I.K. Murthy; L.D. Bhatta; N.K. Agrawal; M.S.R. Murthy; F.M. Qamer

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Dharma R Maharjan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

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Contents

Foreword

The climate of the Hindu Kush Himalaya (HKH) has changed rapidly in the last fifty years and that trend seems likely to continue. And forests ecosystems are part and parcel of HKH livelihoods supporting mountain communities. The HKH is rich in forests that contribute heavily to biodiversity, carbon storage, water quality, and tourism. But the future of these forests is uncertain. Climate change over the next century is projected to change temperatures and rainfall pattern, which will impact tree distribution and abundance in the region. There is good agreement among global climate models (GCM) on future temperature trends in the region, but projections of future precipitation patterns differ widely. As a result, the demand for increased knowledge about future forests and climate change scenarios is still high.

The Indian Institute of Science (IISc) is one of India's oldest academic institutions dedicated to science and technology. ICIMOD is pleased to join hands with IISc on this publication to share our expertise and knowledge about forests, biodiversity and climate related issues in the HKH. Together, we have conducted a detailed review on the state of knowledge regarding climate change in the HKH how these changes are affecting forest ecosystems in three selected river basins: the Upper Indus in Pakistan, the Bhramaputra in India, and the Koshi in Nepal. In these pages we present a review and summary on the latest knowledge regarding these important ecosystems, and we hope that these findings, and the recommendations drawn from them, will strengthen future research plans for assessing the impacts of climate change on forests, in particular, the distribution and abundance of forests in sub-basins throughout the region.

David J Molden, PhD
Director General
ICIMOD

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Acronyms and Abbreviations

DGVM	dynamic global vegetation model
NPP	net primary productivity
RCP	representative concentration pathway
GCM	general circulation model
ESM	earth system model
IBIS	Integrated Biosphere Simulator (model)
LPJ	Lund-Potsdam-Jena (model)
CMIP5	Coupled Model Inter-comparison Project 5

Summary

Two dynamic global vegetation models (DGVMs), IBIS and LPJ, were used to assess the projected impacts of climate change on forests in terms of the shifts in vegetation types and changes in NPP (net primary productivity) in the mid Brahmaputra, Koshi, and upper Indus river basins. Changes were assessed for the mid-term (2021–2050) and long-term (2071–2100) periods with respect to the baseline (1961–1990) under the RCP4.5 and RCP8.5 scenarios using precipitation and temperature as the key climate variables. The DGVMs were driven by the ensemble mean climate projections from five CMIP5 climate models. While both DGVMs projected vegetation shifts in the forest areas of the basins, there were differences in the area projected to be affected by the shifts. This can be attributed mainly to differences in the representation of land surface processes and in the number of vegetation types (plant functional types) defined and simulated in the two models. There was some agreement in the changes in NPP projected by the two models under the high emission RCP8.5 scenario, but with differences in degree.

Notwithstanding the uncertainties with respect to climate change projections at watershed and sub-basin level, and the variation in impact assessment from the two DGVMs, it is necessary to make some attempt to assess the vulnerability of the forest ecosystems and forest dependent communities and to develop and implement resilience or adaptation measures. In the absence of more DGVMs to enable the results to be refined, assessment of vulnerability and designing of adaptation strategies could be undertaken for all the forested grids shown to be impacted by either the IBIS or the LPJ models.

Introduction

Climate is one of the most important determinants of vegetation patterns globally. Several climate-vegetation studies have shown that climatic regimes determine the specific plant communities or functional types in a region (Walter 1985). Climate has a significant influence on the distribution, structure, and ecology of forests (Kirschbaum et al.1996) and it is therefore logical to assume that changes in climate will alter the distribution of forest ecosystems. A range of vegetation modelling studies indicate a potential for forest dieback towards the end of this century and beyond, especially in the tropics, boreal, and mountain regions (Miles 2002; McClean et al. 2005; IPCC 2007).

Climate change

Climate is generally defined as the average or typical weather conditions in an area, and more rigorously in terms of the mean and variability of relevant quantities such as temperature, precipitation, humidity, and wind over a period of time ranging from months to thousands or millions of years. The typical period for averaging variables is 30 years, as defined by the World Meteorological Organization.

Climate change is an identifiable change in the climate that persists for an extended period, typically decades or longer. Anthropogenic climate change is a change attributed directly or indirectly to human activity that has altered the composition of the global atmosphere (e.g.an increase in greenhouse gases and aerosols due to fossil fuel emissions) and/or the surface characteristics (e.g. deforestation) and which is different from the natural climate variability observed over comparable time periods (UNFCCC 1992).

Climate change is of particular relevance in policymaking. The present rise in average global temperature is expected to change the hydrological cycle, affecting evaporation and altering the magnitude, timing, and intensity of the prevailing precipitation, and to have an impact on many conditions that affect human life. Climate change is one of the biggest environmental threats to food production, water availability, forest biodiversity, and livelihoods, and will have multiple impacts on natural resources (IPCC 2012). It is widely believed that developing countries such as India and other countries in the Himalayan region will be impacted more severely than developed countries.

Potential impact of climate change on forest

According to IPCC (2014), "for many natural systems on land and in the ocean, new or stronger evidence exists for substantial and wide-ranging climate change impacts"; the model-based projections indicate large-scale forest dieback and loss of biodiversity. Non-climate stressors such as unsustainable dependence of communities on forests, land-use change, forest management practices associated with harvesting of wood and other forest products, and raising of single-species plantations are expected to further exacerbate the adverse impacts of climate change (IPCC 2014). Climate change is expected to be be the dominant stressor on terrestrial ecosystems in the second half of the 21st century, especially under RCP6.0 and 8.5; up to 2040, non-climatic stressors such as land-use change and pollution will continue to dominate threats to most freshwater ecosystems and most terrestrial ecosystems (IPCC 2014).

A modelling study for India (Gopalakrishnan et al. 2011) indicated that 31% of the forest area is likely to experience a shift in forest types in the mid-term (2030s) and 45% in the long-term (2080s) under the climate change projected under the A1B scenario,. The impact of climate change on forests has serious implications for the people who depend on forest resources for their livelihoods. It is important to assess the likely impacts of projected climate change on both primary and plantation forests and to develop and implement adaptation strategies to enhance the resilience of forests to climate change.

The study

The present study used two dynamic global vegetation models (DGVMs) to assess the projected impacts of climate change on forests in the mid Brahmaputra, Koshi, and upper Indus river basins – specifically the shifts in vegetation types and changes in NPP (net primary productivity). Changes were assessed for the mid-term (2021–2050) and long-term (2071–2100) periods with respect to the baseline (1961–1990) under the RCP4.5 and RCP8.5 scenarios using precipitation and temperature as the key climate variables.

The investigation was limited to vegetation shifts and NPP because these two variables are fundamental to ecosystems and have also been validated in our previous studies. It was not possible to analyse carbon stocks as the observations of biomass and soil carbon needed to validate model simulated values are lacking.

The River Basins

The study focused on the forest areas of the three basins: the midstream (hill) area of the Brahmaputra basin within India; the upper and midstream part of the Koshi basin in Nepal; and the upper part of the Indus basin in Pakistan. The major characteristics of the basins, their climate, and the major forest types are described in the following sections.

Brahmaputra

The Brahmaputra has its origin in the Kanglung Kang glacier in the southwestern part of the Tibetan plateau and northern side of the Himalayas near to the Kailash range at an elevation of 5,300 masl (82°10°E; 30°30′N). Starting as the Yarlung Tsangpo, the river traverses a distance of 2,880 km through China, India, and Bangladesh before joining the Bay of Bengal. It has a catchment area of 580,000 km^2, average annual discharge of 19,820 cusec, average annual sediment load of 735 million tonnes, and a specific flood discharge of 0.149 cusec/km^2. The catchment area of the river falls in four countries; 96% of Bhutan's area falls within the river basin even though the main river does not flow through the country. The basin is irregular with a maximum east-west length of 1,540 km and north-south width of 682 km, between 23°–32°N and 82°–97°50′ E. In India, the Brahmaputra basin covers all or part of six states – Arunachal Pradesh, Assam, Meghalaya, Nagaland, Sikkim, and West Bengal. The cultivated area of the basin is around 121,500 km^2.

The climate of the Brahmaputra valley varies from the harsh, cold, and dry conditions found on the Tibetan plateau to the generally hot and humid conditions prevailing in Assam and Bangladesh. Tibetan winters are very cold, with average temperatures below 0°C, summers are mild and sunny, and precipitation is relatively low, about 400 mm per annum at Lhasa, as the river valley in this part lies in the rain shadow of the Himalayas.

About 30% of the mid Brahmaputra basin is covered by forest, and 23% by the dominant tropical semi evergreen forest type, which covers Anjaw, the lower Dibang valley, Lohit, and parts of Tinsukia (Figure 1). The forest density varies considerably with mainly medium dense forest and some dense forest, in northeastern parts of the basin, and the remainder open forest, especially in the central and southern parts (Figure 2).

Koshi

The Koshi river drains the northern slopes of the Himalayas in Tibet Autonomous Region (TAR) in China and the southern slopes of the Himalayas in Nepal; it is also known as the Saptakoshi, from its seven major sub basins. The river flows for 720 km through TAR China, Nepal, and Bihar in India before joining the Ganges, draining an area of about 74,500 km^2 of which only 11,070 km^2 lie within India. The basin is bounded to the north by the Himalayas, to the east by the Mahananda basin, to the west by the Gandaki basin, and to the south by the Ganges river. Within India, the basin extends over seven districts in Bihar: Darbhanga, Khagaria, Madhubani, Muzaffarpur, Purnea, Saharsa, Sitamarhi. During the last 200 years, the river has shifted westwards by about 112 km, laying waste large tracts of agricultural land in Darbhanga, Purnea, and Saharsa districts.

The climate in the Koshi basin ranges from arctic in the high mountains to tropical in the low river valleys, passing through alpine, cool temperate, and warm temperate conditions as the elevation decreases. In narrow valleys with steep slopes, the influence of aspect and slope on microclimate conditions yields a vast diversity of vegetation. As for all mountain ranges in the northern hemisphere, radiation on the north-facing slopes is more diffuse than on south-facing slopes, which receive more direct sunlight. As a result, the relative humidity on north-facing slopes is higher for a longer time after the monsoon ends than on south-facing slopes. Due to the combination of radiation effects and altitude, two areas in close proximity can have very different moisture regimes that can also vary significantly from year to year.

Figure 1: **Forest types in the Mid-Brahmaputra River basin**

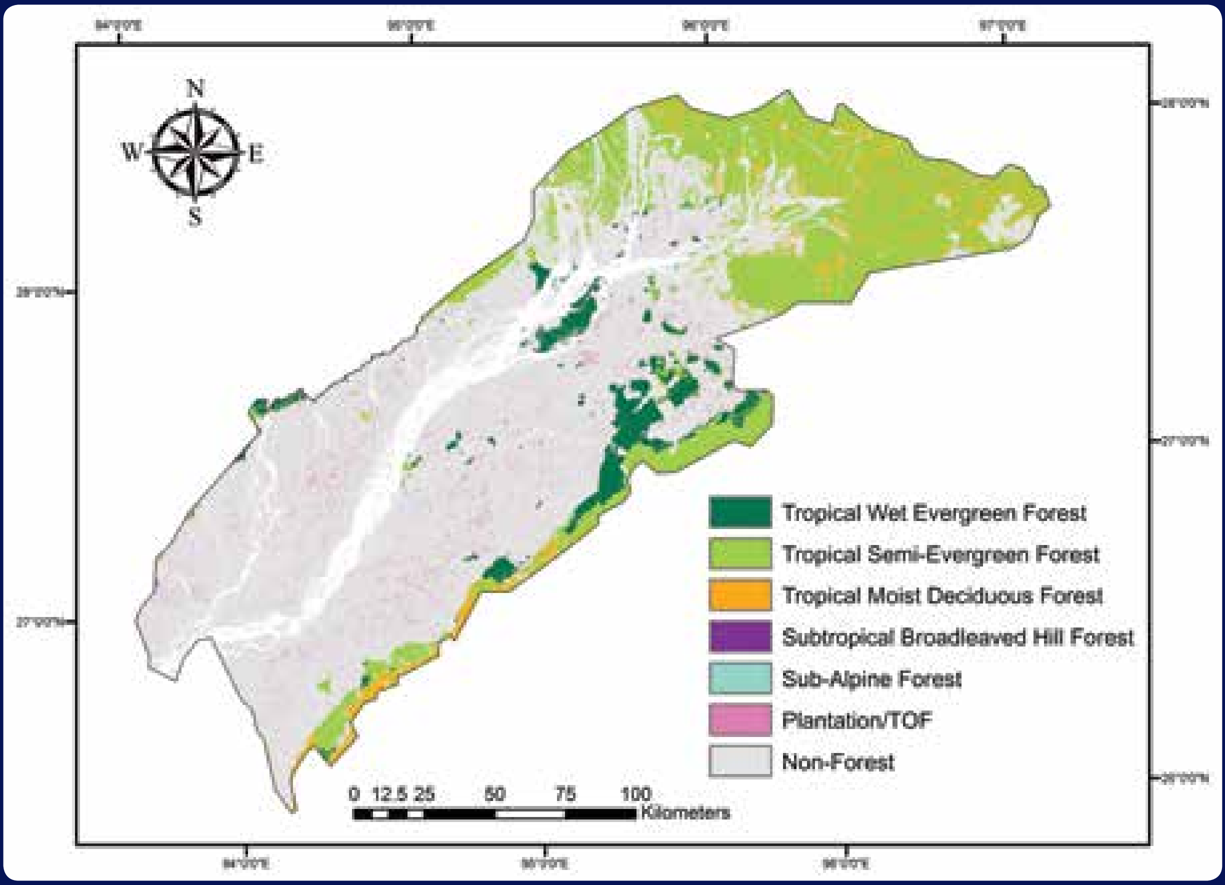
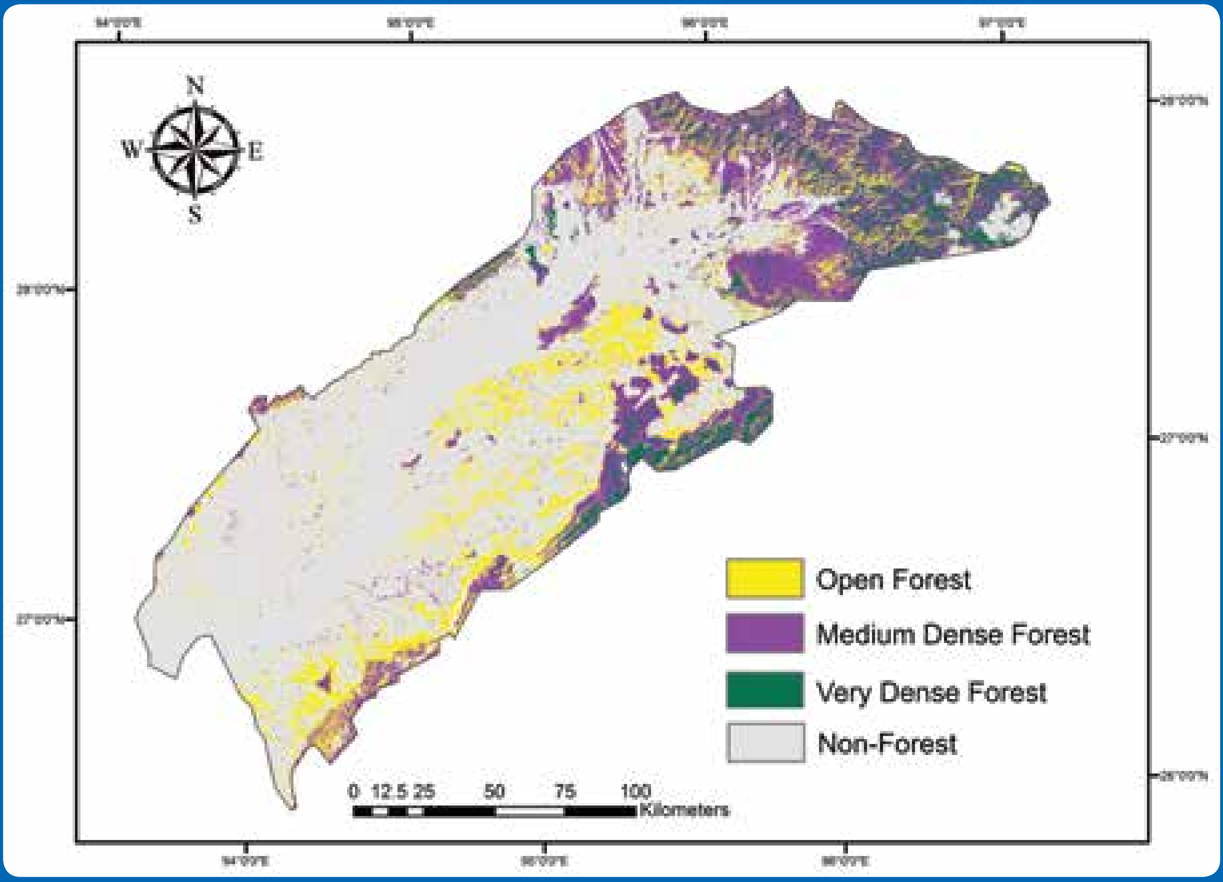


Figure 2: **Forest density in the Mid-Brahmaputra River basin**



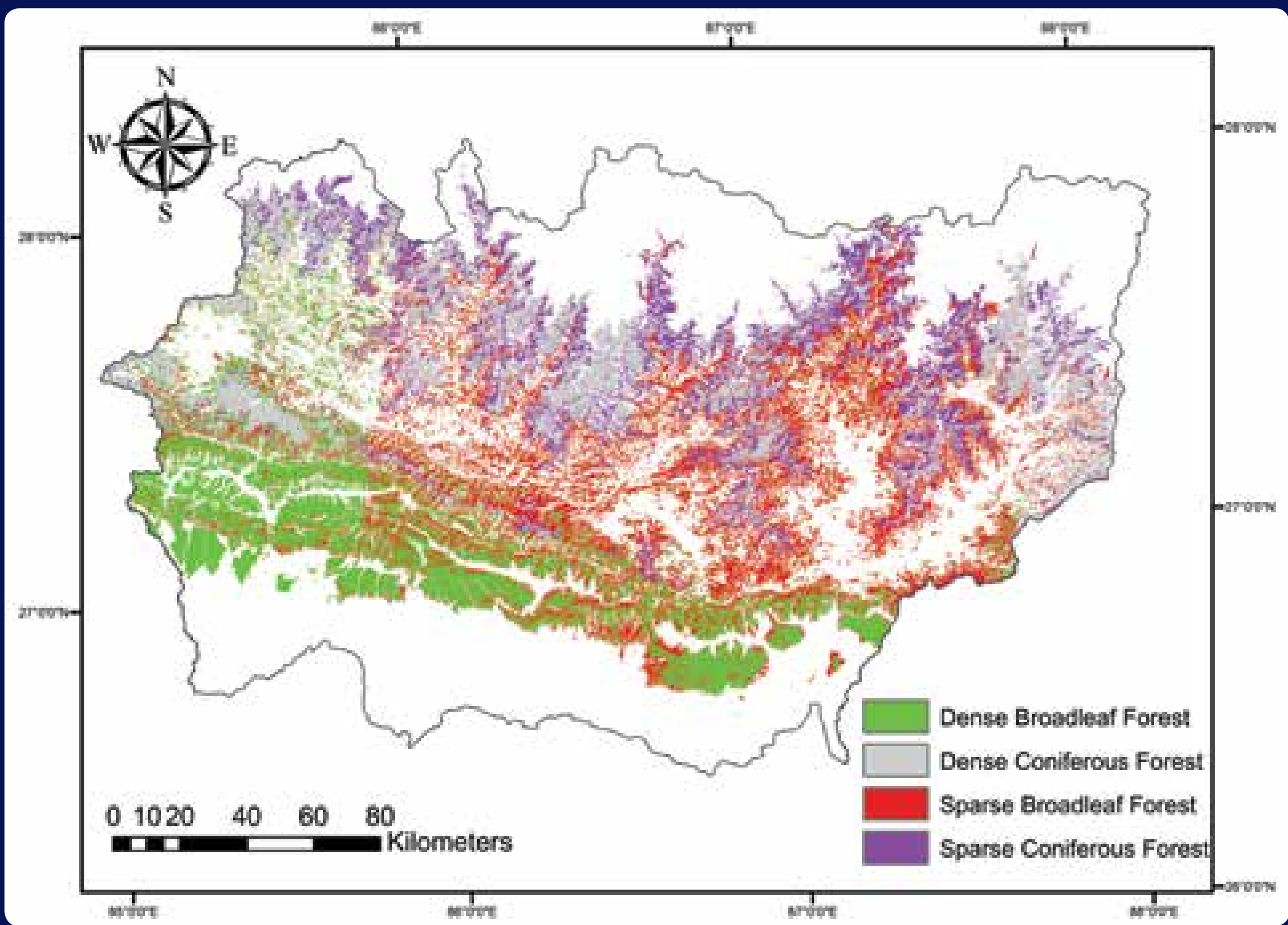
Rainfall is intense during the monsoon, which lasts from June to September. The orographic effect causes large local variations even within a single valley. In the hills, sudden cloudbursts are common and can generate as much as 500 mm of rainfall in a single day. However, in the rain-shadow regions of the Tibetan plateau, the conditions are dry and desert like. The Koshi river has seasonal variations in flow and sediment load. Often these changes are sudden and great; the river can rise 7 to 10 m in 24 hours. In the smaller tributaries of the Koshi, the impact of flooding is localized, but can become widespread when there is greater volume, extent, and/or duration of rainfall.

The Koshi river basin has two main types of forest: coniferous forest, predominantly in the mountainous areas to the north, and broadleaved forest, predominantly in the mid hills areas to the south (Figure 3). The major part of the forested area is dense broadleaved forest (covering 32% of the study area).

Indus

The Indus river basin covers a total area of 1.12 million km^2 in Pakistan (47%), India (39%), China (8%), and Afghanistan (6%). The main river originates at Lake Ngangla Rinco on the Tibetan Plateau in China and includes the flow of the tributaries Astor, Beas, Chenab, Chitral, Gilgit, Hunza, Indus, Jhelum, Kabul Ravi, Shigar, Shyok, Sutlej, Swat, and Shingo draining parts of Afghanistan, China, India, and Pakistan. The Indus basin stretches from the Himalayan Mountains in the north to the dry alluvial plains of Sindh province in Pakistan to the south and finally flows out into the Arabian Sea. In Pakistan, the basin covers around 520,000 km^2, or 65% of the country, comprising the whole of the provinces of Punjab and Khyber Pakhtunkhwa, most of Sindh, and the eastern part of Balochistan. The drainage area within India is approximately 440,000 km^2, nearly 14% of the total area of the country, across the States of Chandigarh, Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, and Rajasthan. Approximately 300 million people are estimated to live in the river basin, which ranks among the most important in the world in terms of human dependence, providing water for agriculture, energy production, industrial use, and human consumption.

Figure 3: **Forest types in the Koshi River basin**



The climate in the Indus basin ranges from arctic at the higher elevations to arid to semi-arid in the plains. The upper basin is a high mountain region and the mountains limit the intrusion of the summer monsoon. Most of the precipitation falls in winter and spring and originates from the west. Monsoonal incursions bring occasional rain to the trans-Himalayan areas, but even during the summer months, not all precipitation derives from monsoon sources. Climatic variables are strongly influenced by elevation. The northern valley floors are arid with annual precipitation of 100–200 mm, increasing to 600 mm at 4,400 masl, while glaciological studies suggest annual accumulation rates of 1,500 to 2,000 mm at 5,500 masl. Winter precipitation (October to March) is highly correlated with the position north or south of the Himalayan divide. Between 1961 and 1999, significant increases were observed in winter, summer, and annual precipitation, and significant warming in winter, but a cooling trend in summer. These changes are likely to affect water availability (Fowler and Archer 2005). In the upper plains, the mean monthly temperature varies from 23 to 49 °C during summer and from 2 to 23 °C during winter. In the lower plains, December to February is the cold season, with mean monthly temperatures varying from 14 to 20°C, and March to June the warm season, with mean monthly temperatures varying from 42 to 44°C. The average annual rainfall on the Indus plains is about 230 mm, varying from 90 mm around Larkana and Jacobabad in the lower plains, to 150 mm at Multan and 510 mm at Lahore in the upper plains. The evaporation rate is very high, with a mean annual evaporation of 204 mm in the lower plains (Nawabshah) and 1,650 mm in the upper plains (Sargodha)

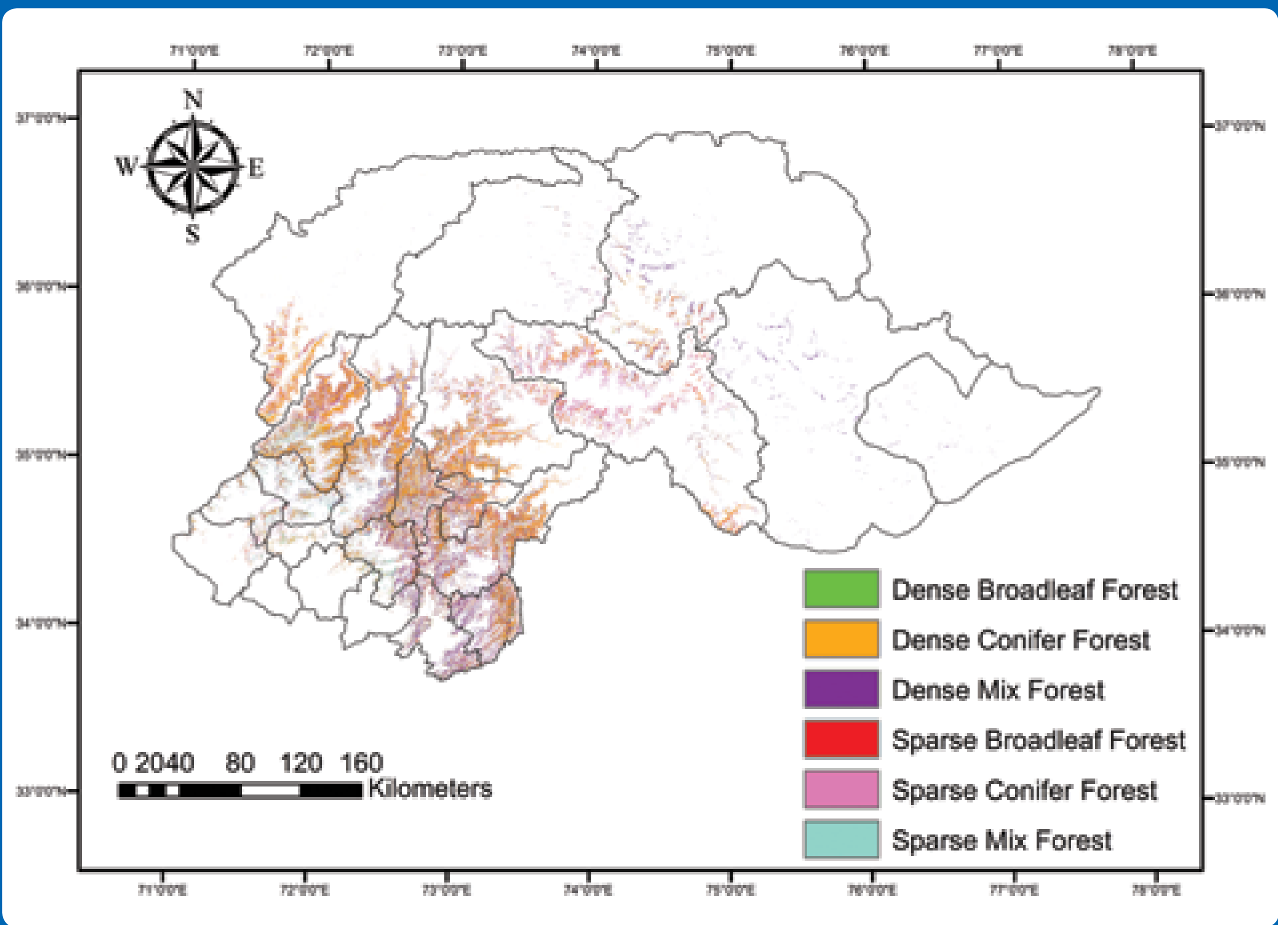
Most of the forest in the upper Indus basin is concentrated in the southwestern area (Figure 4). Close to 66% of the forest is coniferous (dense 39%, sparse 27%) while 6% is broadleaf, with the remainder mixed.

Methods and Models

Climate change projections and scenarios

Climate change projections are obtained using GCMs (global circulation models) and RCMs (regional climate models). Normally, climate change projections are made for variables such as surface air temperature (average,

Figure 4: **Forest types in the Upper Indus River basin**



maximum, minimum, at height 1.5 m), precipitation (both snow and rainfall), relative humidity, cloud fraction, incoming radiation (both shortwave and longwave), and wind speed (at height 1.5 m). In this study the newly-developed representative concentration pathways (RCPs) emission scenarios (Moss et al. 2010) and data from the Coupled Model Inter-comparison Project 5 (CMIP5) were used to develop climate projections for the three river basins.

The RCPs represent pathways of radiative forcing rather than detailed socioeconomic narratives or scenarios. The central concept is that any single radiative forcing pathway can result from a diverse range of socioeconomic and technological development scenarios. There are four scenarios – RCP2.6, RCP4.5, RCP6.0, and RCP8.5 – formulated to represent the full range of stabilization, mitigation, and baseline emission scenarios available in the literature (Hibbard et al. 2011). The naming convention reflects socioeconomic pathways that lead to a specific radiative forcing by the year 2100, for example RCP8.5 leads to a radiative forcing of 8.5 Wm-2 by 2100.

Climate projections for impact assessment were obtained from CMIP5 (Coupled Model Inter-comparison Project 5) models. CMIP5 data have been used recently to generate climate change projections for India (Chaturvedi et al. 2012). The ensemble means from five CMIP5 models (Table 1) for RCP4.5 (moderate emission scenario) and RCP8.5 (high emission scenario) were used to develop mid-term (2021–2050) and long-term (2070–2100) climate change projections for the three river basins. An earlier study by Chaturvedi et al. (2012) showed that the ensemble mean climate was closer to the observed climate than any individual model. The five ESMs provided all the climate variables required for running the DGVMs. The data derived from the CMIP5 model outputs – both historic data and climate projections – were at different spatial scales. The data was therefore regridded to a common spatial scale of 0.5×0.5° (50 x 50 km) resolution using bilinear interpolation. Further, district-wise averages were obtained using appropriate weights (based on the area occupied) for all grid points falling into a district. The spatial distribution of the projected temperature and precipitation values is shown in the Annex.

Table 1: **CMIP5 climate models used to generate the ensemble mean climate**

Model name	Modelling centre
BCC-CSM1-1	Beijing Climate Centre, China, Meteorological Administration
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France
MIROC-ESM	Japan Agency for Marine- Earth Science and Technology
MIROC-ESM-CHEM	Japan Agency for Marine- Earth Science and Technology
MIROC5	Japanese research community

The dynamic global vegetation models

We used two DGVMs in order to provide an estimate of the uncertainty and robustness, and hence the reliability, of the projections on future changes in vegetation characteristics. If a given forested grid is shown to be impacted by both the DGVMs, then the confidence is high. Although using more DGVMs would increase the robustness of estimates, it would also entail considerable extra resources and using two different models was considered sufficient.

The dynamic vegetation model IBIS has a hierarchical, modular structure (Kucharik et al. 2000) with four modules: land surface, vegetation phenology, carbon balance, and vegetation dynamics. The modules, operate with different time steps but are integrated into a single physically consistent model that can be directly incorporated into atmospheric general circulation models (AGCMs) to receive climate data. IBIS is currently incorporated into two AGCMs: GENESIS-IBIS (Foley et al. 1996) and CCM3-IBIS (Winter 2006). In this study, we provided the climate date for driving IBIS which was run in an offline mode.

The Lund-Potsdam-Jena (LPJ) model is a dynamic global model of vegetation biogeography and vegetation/soil biogeochemistry developed by the Potsdam Institute for Climate Impact Research (PIK), Germany. Driven by climate data, and soil and atmospheric information, it dynamically computes spatially explicit transient vegetation composition in terms of plant functional groups and their associated carbon and water budgets. The LPJ model combines process-based, large-scale representations of terrestrial vegetation dynamics and land-atmosphere carbon and water exchanges in a modular framework. Features include feedback through canopy conductance between photosynthesis and transpiration, and interactive coupling between these fast processes and other ecosystem processes including resource competition, tissue turnover, population dynamics, soil organic matter and litter dynamics, and fire disturbance.

There are several modeling studies in the literature that infer increased water use efficiency by simulating reduced plant transpiration and increased runoff for elevated CO_2 levels. Both IBIS and LPJ have explicit representation for increased water use efficiency for elevated CO_2 by parameterizing stomatal conductance as a function of atmospheric CO_2 concentration. However, in this report our focus was on the impacts of climate change on the dynamics of vegetation and forest productivity and we did not generate runoff and canopy transpiration from the models.

IBIS and LPJ have many differences in their inputs, functionality, and outputs (Table 2). LPJ requires three climate variables: temperature, precipitation, and cloudiness. IBIS requires eight climate variables: temperature, precipitation, cloudiness, relative humidity, temperature range, wet days, wind speed, and delta T (minimum temperature ever recorded at a particular location minus average temperature of the coldest month).

There is also a big difference in the vegetation types represented in the two models. IBIS defines 15 vegetation types (most found in India), whereas LPJ defines 9 types found globally (Table 3). This is likely to lead to differences in the results of the models.

Table 2: **Variables used to drive the IBIS and LPJ models**

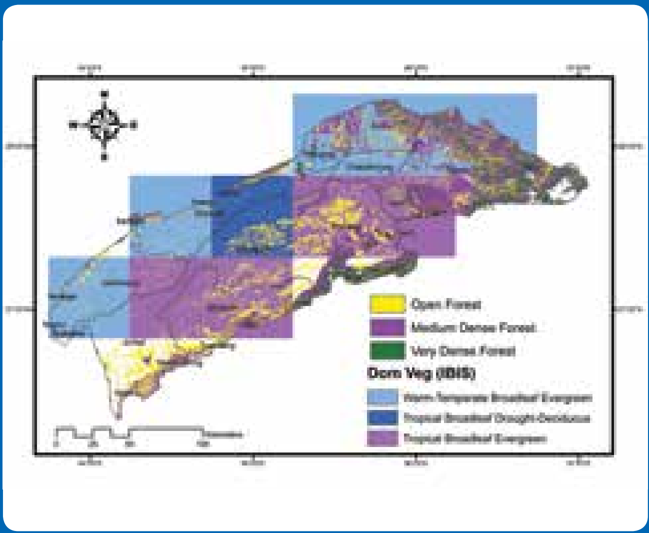
IBIS		LPJ	
Climate variables	Other variables	Climate variables	Other variables
Temperature	CO_2 value	Temperature	CO_2 value
Precipitation	Initial vegetation	Precipitation	Soil data
Cloudiness	Clay percentage	Cloud cover	Grid data
Temperature range	Sand percentage		
Wet days	Land mask		
Wind speed	Topography		
Relative humidity			
delta T			

Figure 5 (a-c) shows the plant functional types (PFTs) simulated by IBIS and LPJ in the baseline climate in (a) the mid Brahmaputra, (b) the Koshi, and (c) the upper Indus basins. There is a high degree of agreement between the models in the mid Brahmaputra and upper Indus basins, but less agreement in the Koshi basin. The dominant vegetation projected in the mid-Brahmaputra basin is Warm Temperate Broadleaf Evergreen forest in the upper reaches and Tropical Broadleaf Evergreen forest in the plains. The dominant vegetation projected in the central part of the Koshi basin is Warm Temperate Broadleaf Evergreen forest (IBIS) or Temperate Needle Leaved Evergreen forest (LPJ). The dominant vegetation projected in the upper Indus basin is Boreal Coniferous (Needle-Leaved) Evergreen forest.

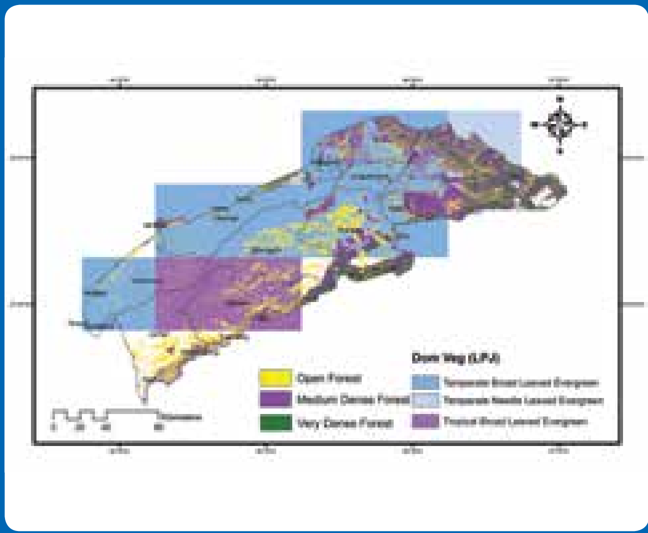
Table 3: **Plant functional types represented in the IBIS and LPJ Models**

IBIS Plant functional types	LPJ Plant functional types
Tropical Broadleaf Evergreen Trees	Tropical Broadleaved Evergreen Tree
Tropical Broadleaf Drought-Deciduous Trees	Tropical Broadleaved Raingreen Tree
Warm-Temperate Broadleaf Evergreen Trees	Temperate Needleleaved Evergreen Tree
Temperate Conifer Evergreen Trees	Temperate Broadleaved Evergreen Tree
Temperate Broadleaf Cold-Deciduous Trees	Temperate Broadleaved Summergreen Tree
Boreal Conifer Evergreen Trees	Boreal Needleleaved Evergreen Tree
Boreal Broadleaf Cold-Deciduous Trees	Boreal Broadleaved Summergreen Tree
Boreal Conifer Cold-Deciduous Trees	C3 Perennial Grass
Evergreen Shrubs	C4 Perennial Grass
Cold-Deciduous Shrubs	
Warm (C4) Grasses	
Cool (C3) Grasses	
Tundra	
Desert	
Polar Desert	

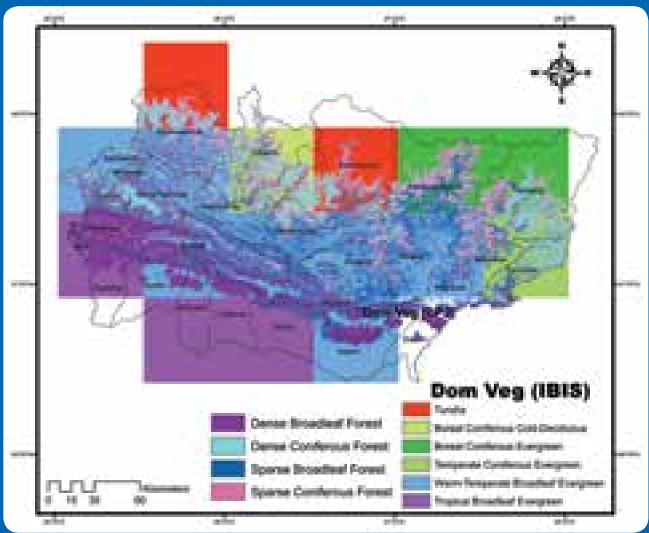
Figure 5: **Plant functional types (PFTs) in the baseline climate by basin as modeled in IBIS and LPJ**



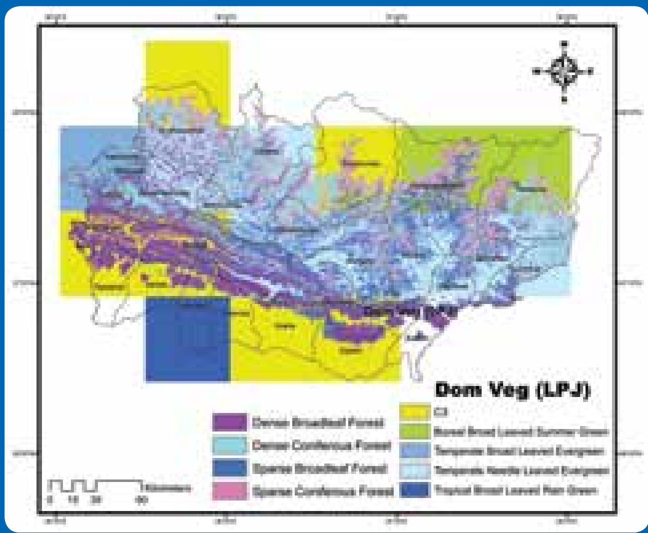
a) IBIS for the mid Brahmaputra basin



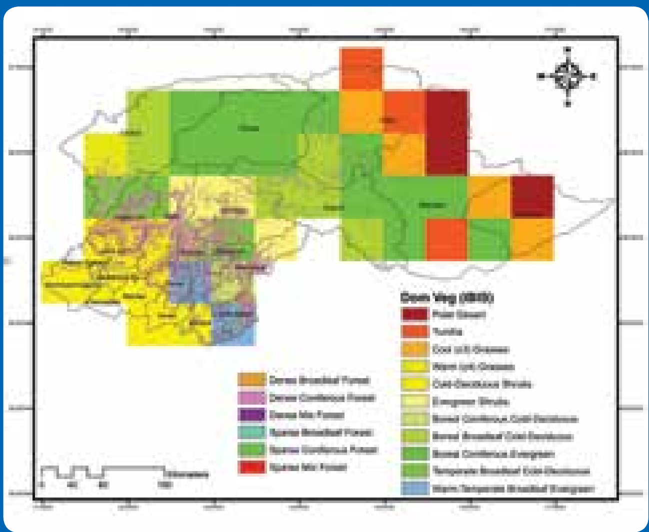
b) LPJ for the mid Brahmaputra basin



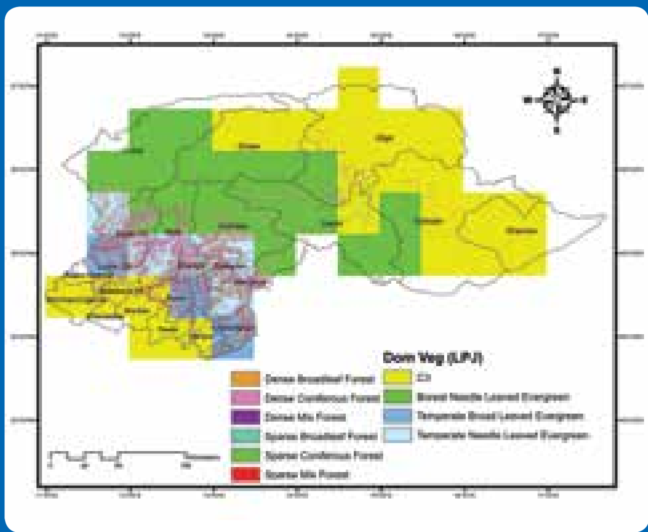
c) IBIS for the Koshi basin



d) LPJ for the Koshi basin



e) IBIS for the upper Indus basin



f) LPJ for the upper Indus basin

Note: solid black lines indicate district boundaries.

Assessment of climate change impact

The impact of climate change was assessed by comparing the distribution of forest types projected under the baseline (current climate) scenario with the distribution projected under climate change scenarios. The number of forested grid points belonging to different forest types undergoing change under the climate change scenarios was compared. Climate change impact in the form of vegetation shift means that the projected future climate is not suitable for the existing forest type, species, and biodiversity, leading to potential forest dieback and loss of biodiversity.

There are certain limitations in the models which need to be taken into account when interpreting the results. In the real world, vegetation changes take place over an ecological continuum. However, in the models, vegetation and climate are represented on discrete grid points and are not a continuum. This is also true for the land surface processes in the model where the complex heterogeneity of the real land surface is not precisely represented by a discrete grid. Further, the models simulated a limited number of vegetation types in the baseline climate which may not exactly match the numerous vegetation types defined by the Forest Survey of India (FSI) at the model grid scale, thus we focussed only on identifying the grid points in the model where a vegetation shift is projected. We also used the model projected changes in NPP in order to address productivity. In reality, large changes in NPP are accompanied by changes in water availability or water use efficiency, but the study did not include an assessment of hydrological parameters.

Impact of Climate Change on Forest Ecosystems in the mid Brahmaputra River Basin

Forest vegetation shift under RCP4.5 and 8.5 in the mid-term

Figure 6 shows the grid points projected to undergo a change in forest type in the mid-term (2021–2050) under RCP4.5 and 8.5 as simulated by IBIS and LPJ. IBIS projects a vegetation type shift in one grid point in the central part of the basin covering the districts of Dhemaji and Dibrugarh under both RCPs. In the baseline, these districts are covered by low density tropical semi-evergreen and plantation forest. LPJ does not show any change in forest type under RCP4.5, but does show a vegetation change under RCP8.5 in the northeast part of the basin covering Anjaw, Lohit, and Tinsukia. In the baseline, these districts are covered by tropical semi-evergreen and tropical moist-deciduous forest with medium dense crown cover.

Forest vegetation shift under RCP4.5 and 8.5 in the long-term

Figure 7 shows the grid points projected to undergo a change in forest type in the long term (2071–2100) under the two RCPs as simulated by IBIS and LPJ. IBIS projects a vegetation shift in the same grid in the central part of the basin as in the mid-term under both RCP scenarios. LPJ projects a vegetation shift in five grids covering parts of the districts of Anjaw, Dhemaji, Dibrugarh, Jorhat, Lohit, Sivasagar, and Tinsukia under both RCPs. In the baseline, Anjaw and Lohit are covered by tropical semi-evergreen forest, Tinsukia by tropical wet evergreen forest and plantations, and Dibrugarh, Sivasagar, and parts of Dhemaji and Jorhat mostly by plantations.

NPP change under RCP8.5 in the mid and long-term

Figure 8 shows the grid points projected to undergo change in NPP in the mid and long-term under RCP8.5 as simulated by IBIS and LPJ. In the mid-term, IBIS projects an increase in NPP by 12–18% in the districts of Anjaw, Dibrugarh, Lohit, Sivasagar, and Tinsukia, while LPJ projects an increase of 10–20 % in the districts of Lohit, Sivasagar, and Tinsukia. In the long-term, IBIS projects an increase in NPP of more than 40% in all districts, and more than 50% in Dibrugarh and Sivasagar, while LPJ projects an increase in NPP of more than 50% in Dibrugarh, Lohit, and Tinsukia.

Figure 6: **Vegetation shifts in the Mid-Brahmaputra River basin in the mid-term (2021-2050) as modeled in IBIS and LPJ**

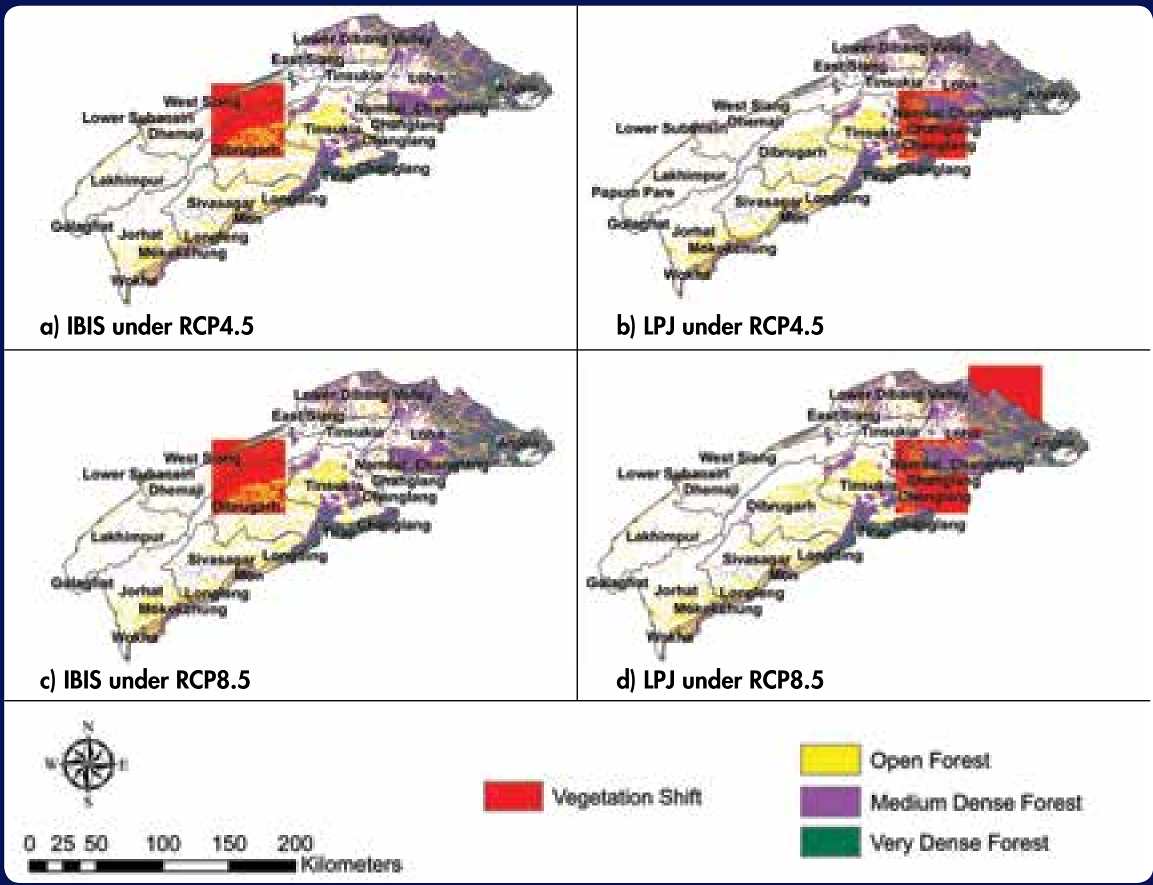


Figure 7: **Vegetation shifts in the Mid-Brahmaputra River basin in the long-term (2071-2100) as modeled in IBIS and LPJ**

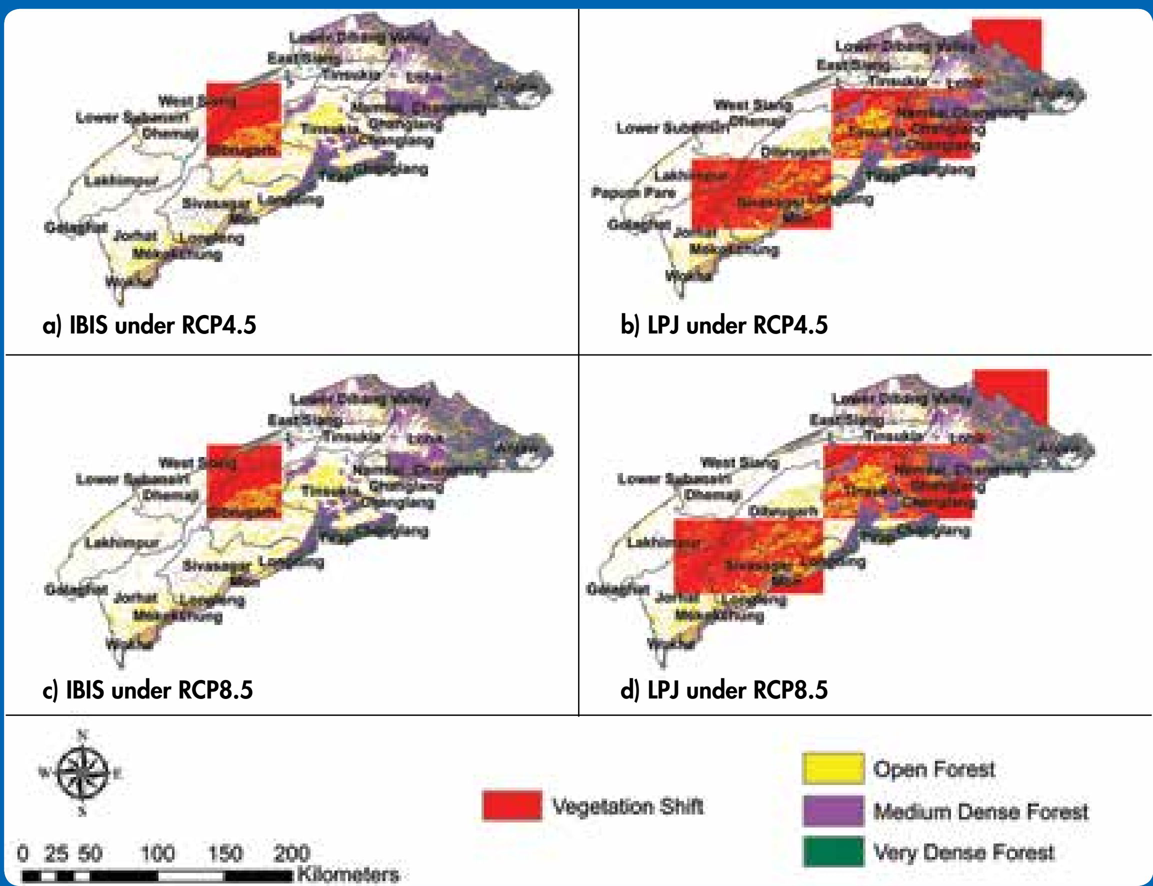
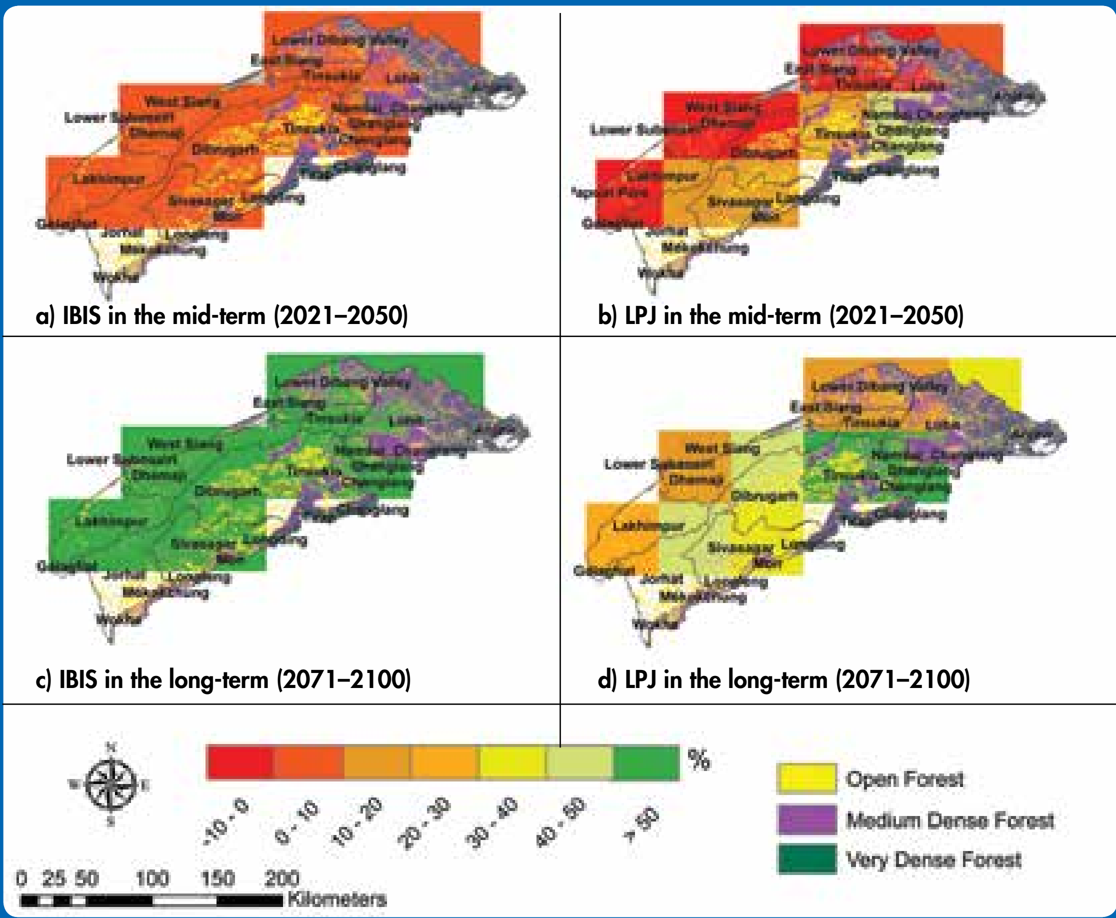


Figure 8: **NPP change in the Mid-Brahmaputra River basin under RCP8.5 as modeled in IBIS and LPJ**



Impact of Climate Change on Forest Ecosystems in the Koshi River Basin

Forest vegetation shift under RCP4.5 and 8.5 in the mid-term

Figure 9 shows the grid points projected to undergo a change in forest type in the mid-term (2021–2050) under RCP4.5 and 8.5 as simulated by IBIS and LPJ. IBIS projects a vegetation type shift in two grid points covering the districts of Dolakha, Ramechhap, and Solukhumbu under both RCPs. In the baseline, these districts are predominantly covered by dense and sparse coniferous forest. LPJ projects a shift in five grids covering the districts of Dhanusha, Mahottari, Okhaldhunga, Saptari, Siraha, Sindhuli, Solukhumbu, and Udayapur under both RCPs. In the baseline, these districts are predominantly covered by dense and sparse broadleaved forest.

Forest vegetation shift under RCP4.5 and 8.5 in the long-term

Figure 10 shows the grid points projected to undergo change in forest type in the long-term (2071–2100) under the two RCPs as simulated by IBIS and LPJ. IBIS projects a vegetation shift in the same two grid points as in the mid-term under RCP4.5, and in these and a further five grid points covering Dolakha, Sankhuwasabha, Solukhumbu, Taplejung, and parts of Ramechhap and Sindhupalchok under RCP8.5. In the baseline, these districts are predominantly covered by dense and sparse coniferous forest. LPJ projects a vegetation shift in the same five grid points as in the mid-term under both RCPs in districts predominantly covered by dense and sparse broadleaved forest.

NPP change under RCP8.5 in the mid and long-term

Figure 11 shows the grid points projected to undergo change in NPP in the mid and long-term under RCP8.5 as simulated by IBIS and LPJ.

Figure 9: **Vegetation shifts in the Koshi River basin in the mid-term (2021-2050) as modeled in IBIS and LPJ**

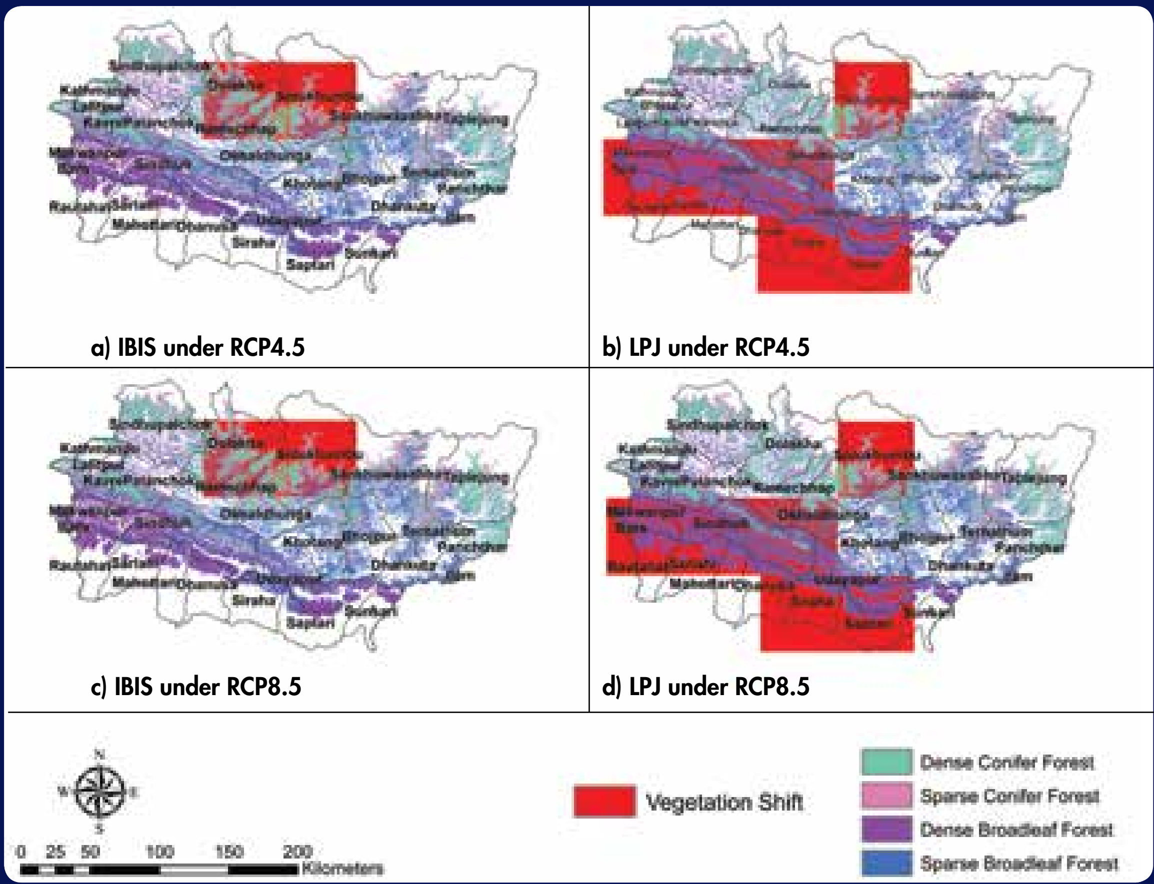


Figure 10: **Vegetation shifts in the Koshi River basin in the long-term (2071-2100) as modeled in IBIS and LPJ**

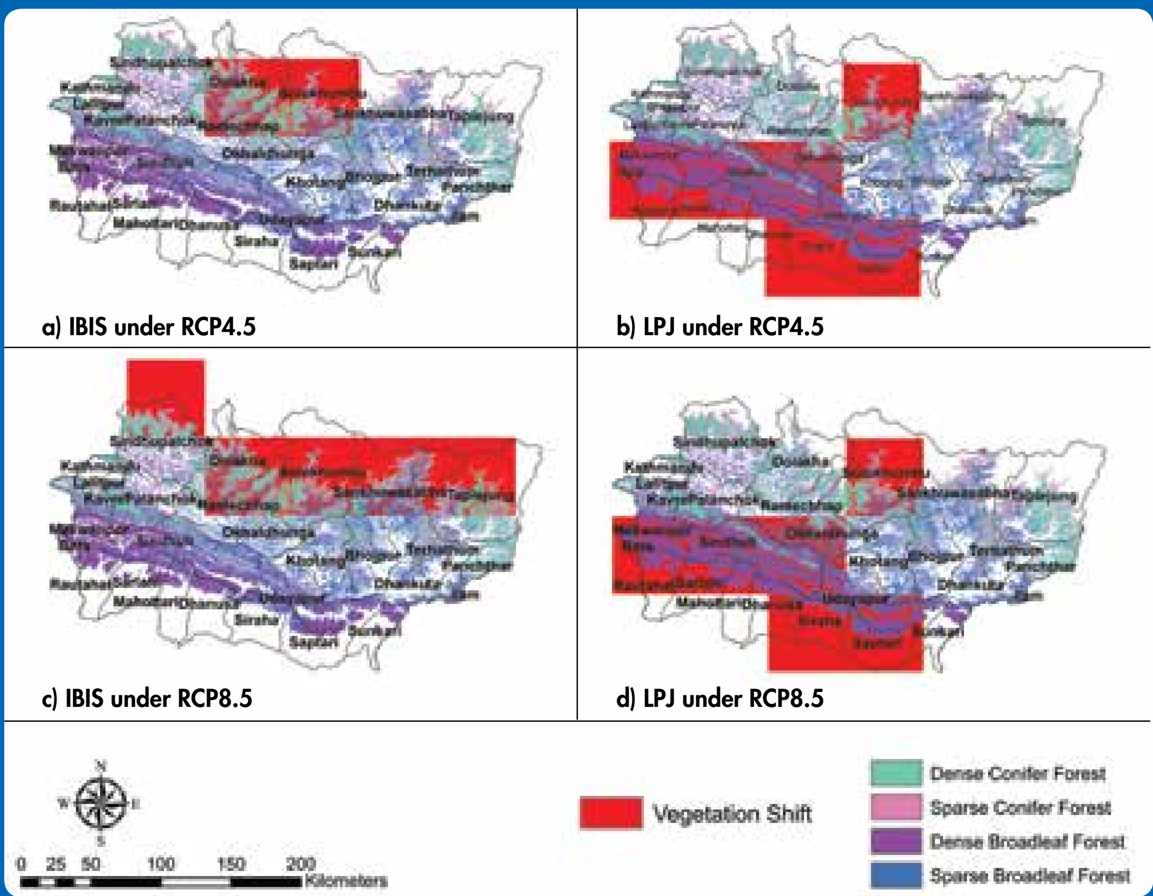
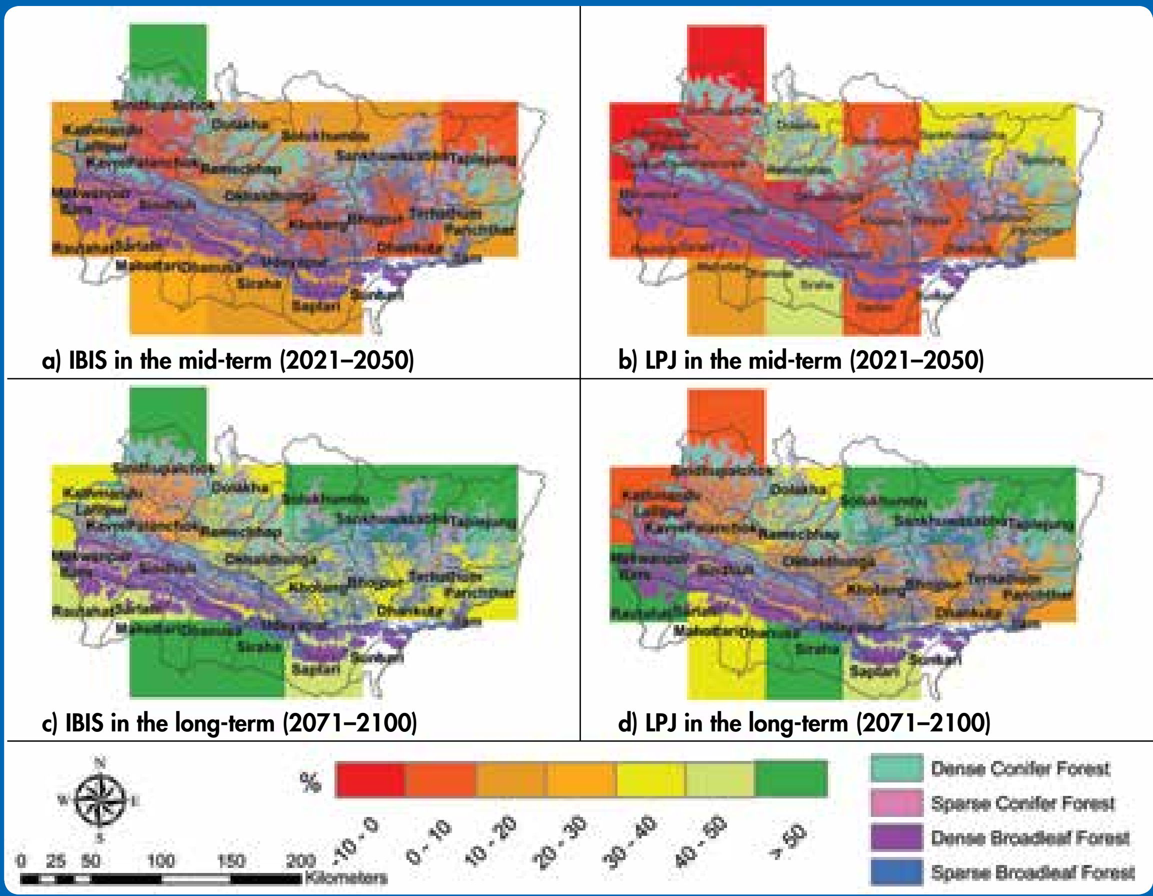


Figure 11: **NPP change in the Koshi River basin under RCP8.5 as modeled in IBIS and LPJ**



In the mid-term, IBIS projects an increase in NPP of 10–30% in most areas, and of more than 50% in one grid point covering Sindhupalchok, which has sparse and dense coniferous forest. LPJ projects an increase of 20–40% in Dolakha, Solukhumbu, and Taplejung, and more than 40% in Siraha, which has dense coniferous and broadleaf forest, but a reduction in NPP for Sindhupalchok.

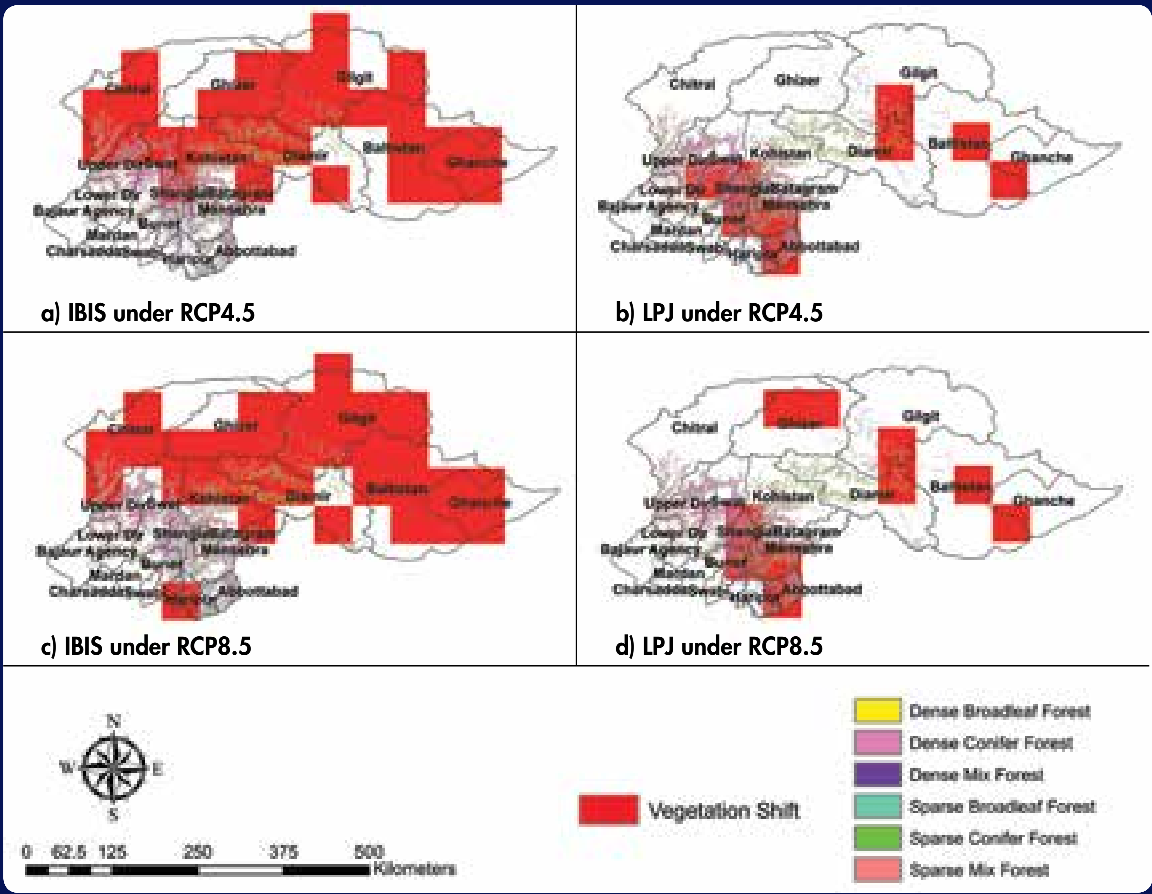
In the long-term, IBIS projects a 25–45% increase in NPP over most of the basin, and of more than 55% in the districts of Mahottari, Sankhuwasabha, Solukhumbu, and Taplejung, which are predominantly covered by sparse and dense coniferous forest. LPJ projects a 40–80% increase in NPP in Rautahat, Saptari, Sindhupalchok, Siraha, and Taplejung districts, which are predominantly covered by dense coniferous and broadleaf forest.

Impact of Climate Change on Forest Ecosystems of the Upper Indus River Basin

Forest vegetation shift under RCP4.5 and 8.5 in the mid-term

Figure 12 shows the grid points projected to undergo a change in forest type in the mid-term (2021–2050) under RCP4.5 and 8.5 as simulated by IBIS and LPJ. IBIS projects a vegetation type shift in the majority of grid points across the central part of the basin covering the districts of Chitral, Diamir, Gilgit, Kohistan, Shangla, Swat, and Upper Dir under RCP4.5, and in the same districts together with Haripur in the south under RCP8.5. In the baseline, these districts are predominantly covered by dense and sparse coniferous forest. LPJ projects a shift in nine grid points covering the districts of Abbottabad, Batagram, Buner, Diamir Gilgit, Mansehra, Swat, Shangla, and Upper Dir under RCP4.5, and in ten grid points covering the same districts apart from Upper Dir and with the addition of Ghizer under RCP8.5. In the baseline, these districts are predominantly covered by dense and sparse broadleaved forest.

Figure 12: **Vegetation shifts in the Upper Indus River basin in the mid-term (2021-2050) as modeled in IBIS and LPJ**



Forest vegetation shift under RCP4.5 and 8.5 in the long-term

Figure 13 shows the grid points projected to undergo change in forest type in the long-term (2071–2100) under the two RCPs as simulated by IBIS and LPJ. IBIS projects a vegetation shift in the same districts as in the mid-term, and in addition in the two southern districts of Haripur and Mansehra, under both RCPs. These districts are predominantly covered by dense mixed and coniferous forest. LPJ projects a vegetation shift in the districts of Abbottabad, Baltistan, Batagram, Buner, Diamir, Ghanche, Ghizer, Haripur, Kohistan, Malakand, Mansehra, Shangla, Swabi, Swat, Upper Dir under both RCPs. These districts are predominantly covered by dense and sparse broadleaved forest.

NPP change under RCP8.5 in the mid and long-term

Figure 14 shows the grid points projected to undergo change in NPP in the mid and long-term as simulated by IBIS and LPJ.

In the mid-term, IBIS projects a decrease in NPP of 10–20% in the highly forested southwestern parts of the basin, which includes the districts of Abbottabad, Buner, Haripur, Lower Dir, Malakand PA, Mardan, Swabi, and Mohmand Agency, which have dense coniferous and mixed forest, and an increase of 20–100% in the districts in the central and eastern region, including Diamir, Gilgit, Kohistan, Swat, and Upper Dir. LPJ projects an increase in NPP of 50–70% in Baltistan, Gilgit, Ghanche, and Ghizer, which are predominantly covered by sparse and dense coniferous forest.

In the long-term, IBIS projects similar increases and decreases in the same districts as in the mid-term. LPJ projects an increase in NPP of more than 50% in most of the basin and an increase of 60-90% in the central region districts of Chitral, Diamir, Ghizer, and Kohistan, which have sparse and dense coniferous forest

Figure 13: **Vegetation shifts in the Upper Indus River basin in the long-term (2071-2100) as modeled in IBIS and LPJ**

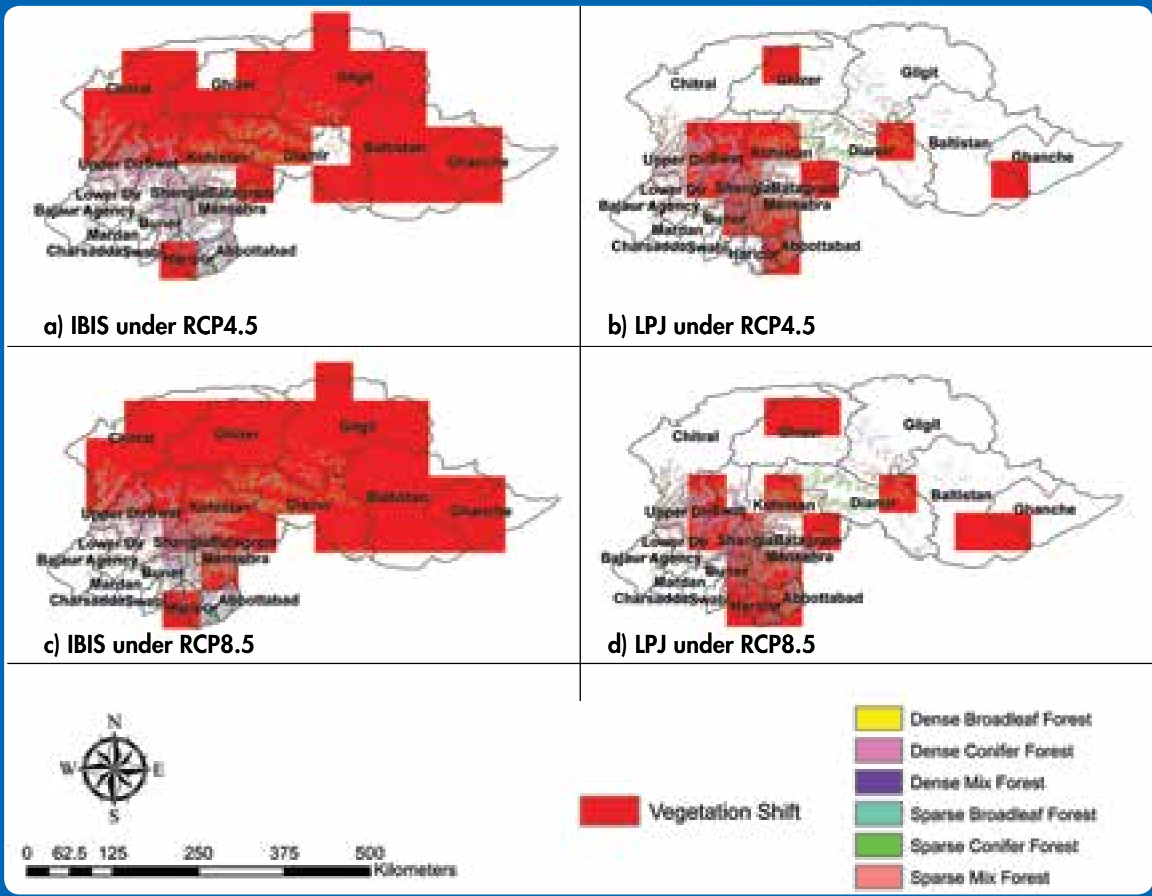
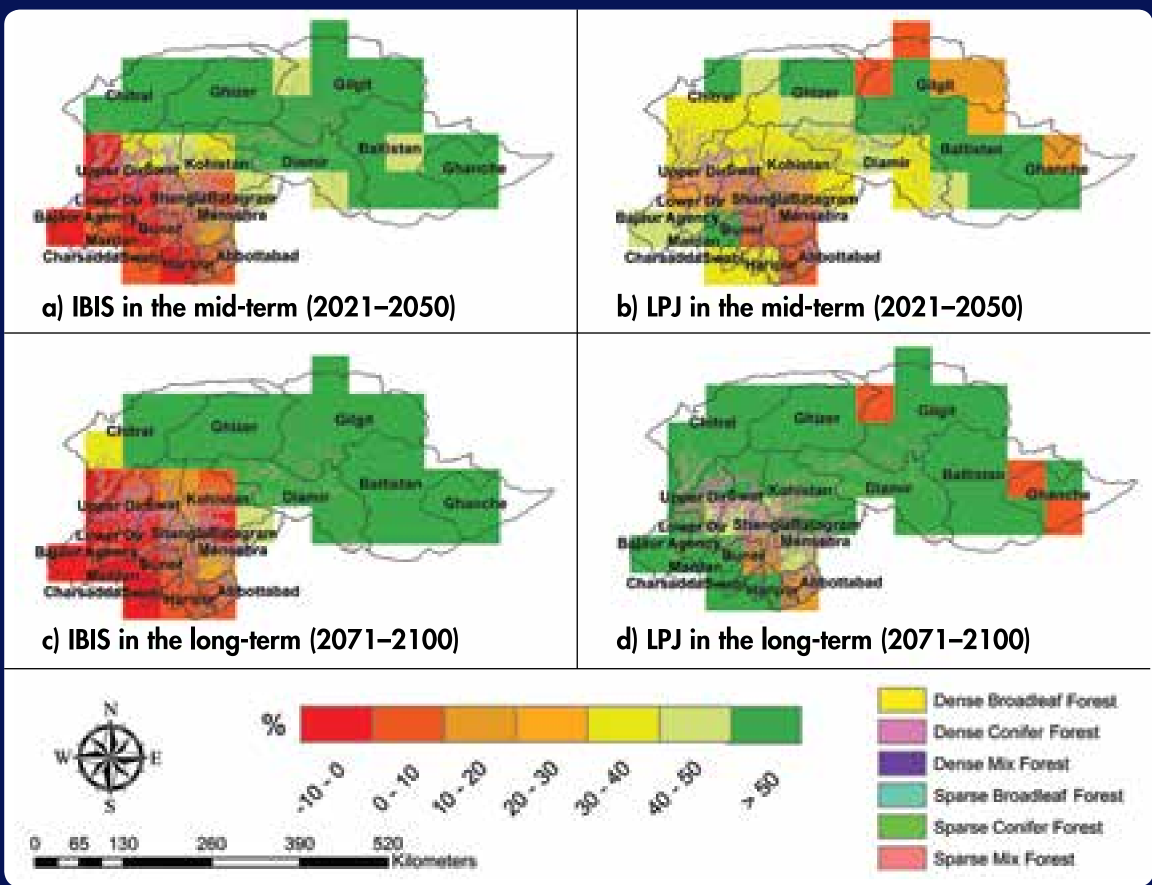


Figure 14: **NPP change in the Upper Indus River basin under RCP8.5 as modeled in IBIS and LPJ**



Summary and Conclusions

The projected impacts of climate change were assessed in terms of vegetation shifts and changes in NPP for the mid Brahmaputra, Koshi, and upper Indus river basins in the mid (2021–2050) and long (2071–2100) term under the RCP4.5 and RCP8.5 scenarios using two DGVMs – IBIS and LPJ. The DGVMs were driven by the ensemble mean climate projections from five climate models from the CMIP5 database. The use of more than one DGVM helps in assessing the uncertainty, robustness, and reliability in the model-based estimates of impacts, while using the ensemble mean of climate projections from five climate models helps to narrow down the uncertainty in climate change.

Forests are mostly prevalent in the northern part of the mid Brahmaputra basin, the middle part of the Koshi basin, and the southern part of the upper Indus basin. Tropical semi-evergreen forests dominate in the mid Brahmaputra basin, dense broadleaved forest in the Koshi basin, and dense coniferous forest in the upper Indus basin.

Both DGVMs projected vegetation shifts in the forest areas of the basins, but there were differences in the area projected to be affected by the shifts. This can be attributed mainly to differences in the representation of land surface processes and in the number of vegetation types (plant functional types) defined and simulated in the two models. There was some agreement in the changes in NPP projected by the two models under the high emission RCP8.5 scenario, but with differences in degree. The results section shows the percentage change in the individual forested grids. The overall increase in NPP for each basin projected by IBIS and LPJ for all the grid points for mid-term and long-term is summarised in Table 4.

Table 4: **Changes in NPP in the mid and long-term projected by IBIS and LPJ**

Basin	Mid-term		Long-term	
	IBIS	LPJ	IBIS	LPJ
Mid Brahmaputra	10–20%	10–50%	40–50 %	10–20%
Koshi	0–50%	-10– +40%	> 50%	> 50%
Upper Indus	-10– +30%	> 40%	-10– >+50 %	> 50%

The increased level of CO_2 and resultant CO_2 fertilization is primarily responsible for the increased vegetation productivity projected by the models. At higher elevations, the increased length of growing season is likely to play a major role in enhancing NPP, since at present, ecosystems at higher elevation are temperature-limited. Increases in annual mean rainfall are also likely to result in increased NPP. However, the results should be considered with caution because future land cover change and nutrient limitations are not represented in either model. Both land cover change and nutrient limitation could reduce the increase in NPP simulated in the study.

Implications for Further Research and Forest Management

The coming into force of the recent Paris agreement under the United Nations Framework Convention on Climate Change (UNFCCC) has again drawn attention to the urgent need for countries to take ambitious efforts to combat climate change and adapt to its effects. Forests and terrestrial ecosystems, especially in the Himalayan region, are increasingly assuming a more prominent role both as important carbon sinks and as an adaptation option. Forest ecosystems are critical for biodiversity, watershed protection, and the livelihoods of forest dependent communities, especially in the Himalayan river basins and it is important to make reliable and robust assessments of the projected impacts on them of climate change. In the present assessment, vegetation shifts were projected together with changes in vegetation productivity at several grid points in the forested regions of three Himalayan basins.

The analysis suggests that climate change represents a threat to many forested grids in the Himalayan region as it will lead to shifts in the type of vegetation that can be supported, with the future climate unsuitable for the existing forest types and biodiversity. The fragmented and isolated forests in low biodiversity areas are especially vulnerable to the impacts of vegetation shifts due to their limited dispersal, germination, and migration capabilities. To some extent, climate change also presents an opportunity in some forested grids in the form of increased net primary productivity due to the effect of increased carbon dioxide fertilization. However, the scenario of increased productivity could be threatened by lack of adequate water and other nutrients in a warming climate, as well as the projection of vegetation shifts, especially in low biodiversity, disturbed, and fragmented habitats.

In the Himalayas and the regions downstream, there is a large dependence on climate-sensitive sectors such as agriculture, forests, and fisheries. Forest-dependent communities form one of the poorest sections of society and the adverse impacts on them of climate change are likely to be compounded by a range of factors including limited institutional linkages, under developed markets, absence of technology-transfer pathways, and lack of financial resources. Further, with climate change, the forest sector is likely to be vulnerable to extreme events such as droughts, coupled with warming, leading to increased occurrence of fires, which are challenging for local governments and institutions to deal with, especially in the Himalayan region. Development and implementation of adaptation strategies and practices for climate change in the forest sector in the Himalayan region will require long gestation periods, and years of research and development, institutional building, and education. To enable this, it is important to have as much information about the likely future scenario as possible.

There are a number of adaptation practices that could be incorporated in afforestation and reforestation projects to help to restore and maintain forest function and address and pre-empt the potential impacts of climate change including the following.

- Promotion of regeneration of native species in degraded natural forest lands through protection and natural regeneration to reduce vulnerability to the changing climate
- Promotion of multi-species plantation forestry incorporating native species in place of mono-culture plantation of exotic species to reduce vulnerability
- Adoption of short-rotation species in commercial or industrial forestry to facilitate adaptation to any adverse impacts of climate change
- Incorporation of silvicultural practices such as sanitation harvest and increased thinning to reduce the occurrence of pests and diseases
- Incorporation of fire protection measures to reduce the vulnerability of forests to fire hazards resulting from warming accompanied by droughts
- Implementation of soil and water conservation measures to reduce the adverse impacts of drought on forest growth
- Use of soil and water conservation as a key adaptation practice for reducing vulnerability; the practice also reduces carbon loss from soils and enhances soil carbon density by increasing the biomass growth rate of forests, plantations, or grassland
- Planting of drought-resistant varieties or clones to reduce the vulnerability of tree and grass species to droughts and water stress, and also increase carbon sequestration rates
- Enhancing of soil organic matter content through organic manure to increase the moisture retention and soil fertility, both to reduce the vulnerability to drought and moisture stress and to increase carbon sequestration rates of trees and grasses
- Implementation of forest and biodiversity conservation through halting deforestation, expanding protected areas, and adopting sustainable harvest practices. This is a vital adaptation strategy to reduce the vulnerability of forest ecosystems. Most importantly, forest conservation activities in the region should be designed such that these activities reduce the fragmentation and degradation of existing forests. Anticipatory planting and assisted natural migration through transplanting of plant species could also be considered.

The results indicate a number of areas that should be considered for further investigation. Climate change projections, especially in the context of high elevation gradients, have large uncertainties, and the uncertainties are even higher for rainfall projections than for temperature. There is a need to further improve the climate change observations and projections for the Himalayan region. Use of more climate models for climate projections and more DGVMs is recommended to reduce the uncertainty and increase the confidence in assessment of the potential climate change impacts. Further, there are limitations in the DGVMs for species level assessment of the impacts of climate change. Notwithstanding the uncertainties with respect to climate change projections at watershed and sub-basin level, and the variation in impact assessment from the two DGVMs, it is necessary to make an attempt to assess the vulnerability of forest ecosystems and forest dependent communities and to develop and implement resilience or adaptation measures. The next step should be to estimate the current vulnerability of the forest ecosystems and forest dependent communities and then the inherent vulnerability as determined by the current state of forests and the stressors on them. The IPCC (2014) has concluded that non-climate stressors will exacerbate the impacts of climate change. Fragmented, degraded, and disturbed forests are likely to be more vulnerable to climate change impacts. In the absence of more DGVMs to enable the results to be refined, assessment of vulnerability and designing of adaptation strategies could be undertaken for all the forested grid points shown to be impacted by either the IBIS or the LPJ models. Based on the current vulnerability assessment, the most vulnerable forest types and districts could be identified and ranked for adaptation interventions.

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Annex: Climate Change Projections for the mid Brahmaputra, Koshi and Upper Indus River Basin

The CMIP5 ensemble mean projected changes in temperature and precipitation relative to the baseline period (1990s) across the three basin areas in the mid-term (2021–2050) and long-term (2070–2100) under the RCP4.5 (moderate) and RCP8.5 (high) emission scenarios are summarized in the following.

Temperature

Mid Brahmaputra basin

Figure A1 shows the projected annual temperature change over the mid Brahmaputra basin. The main changes projected are as follows:

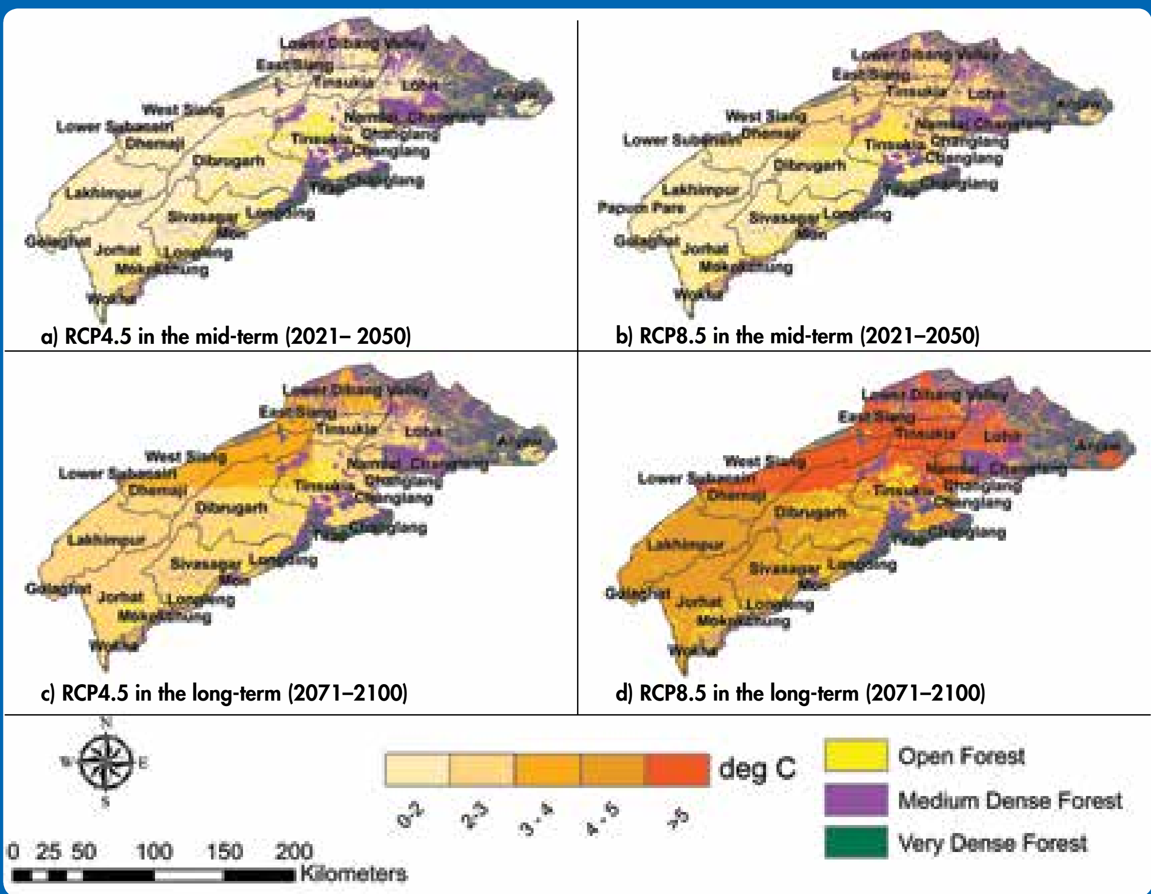
- The highest projected warming is about 6°C in the long-term.
- Under RCP8.5, districts such as Anjaw, Dhemaji, East Siang, Lohit, and Lower Dibang Valley are projected to experience a warming of around 2.0°C or more even in the mid-term.
- Under RCP8.5, most districts show a warming of >4.9°C by 2071–2100.

Koshi basin

Figure A2 shows the projected annual temperature change over the Koshi basin. The main changes projected are as follows:

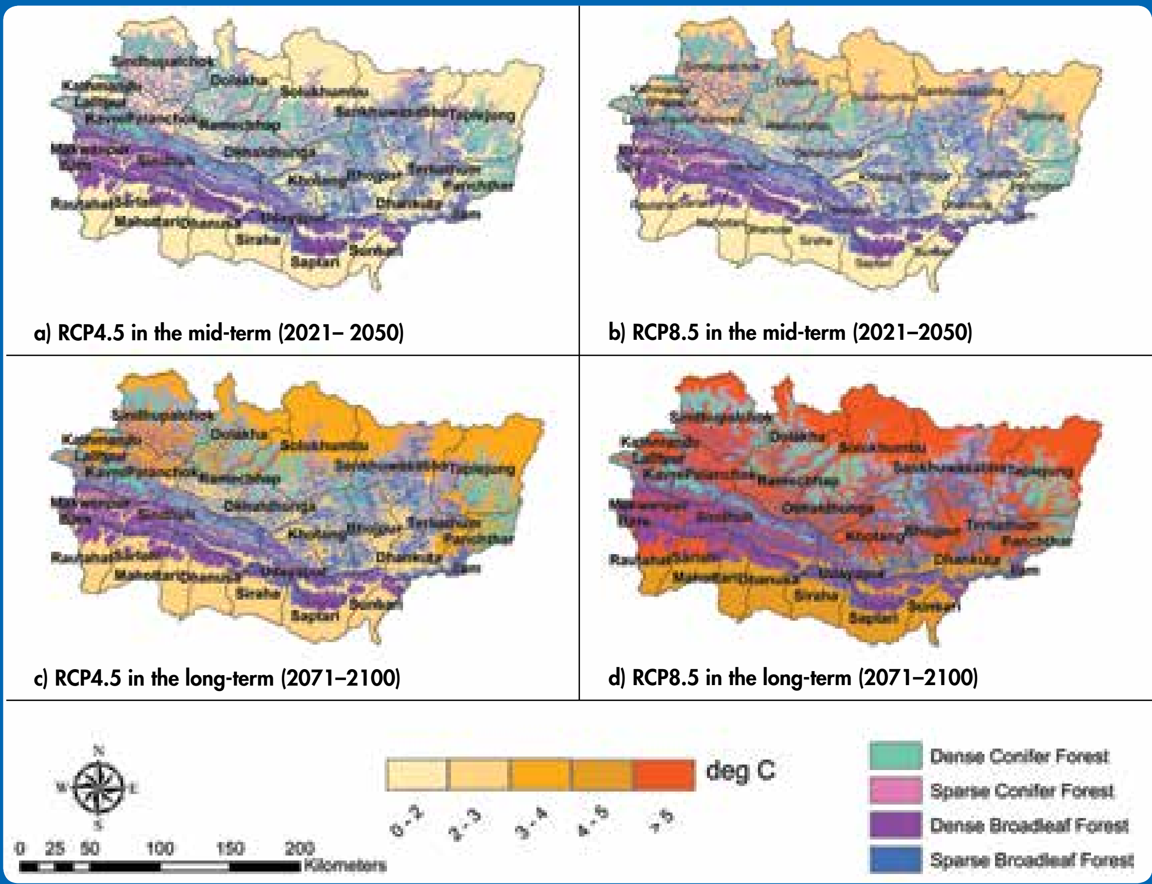
- The highest projected warming is about 6°C in the long-term.
- In under RCP8.5, districts such as Sindhupalchok and Taplejung are projected to experience warming of 2.2°C and above even in the mid-term.

Figure A1: **Projected annual temperature change (°C) relative to the baseline period (1990s) in the Mid-Brahmaputra River basin under**



Note: solid black lines show the district boundaries.

Figure A2: **Projected annual temperature change (°C) relative to the baseline period (1990s) in the Koshi River basin under**



Note: solid black lines show the district boundaries.

- Under RCP4.5, warming of 3.5°C or more is projected in most northern and central districts, including Bhaktapur, Kathmandu, Sindhupalchok, and Taplejung, in the long-term.
- Under RCP8.5, most northern districts show a warming of 5.7°C and above by 2071–2100.

Upper Indus basin

Figure A3 shows the projected annual temperature change over the upper Indus basin. The main changes projected are as follows:

- Under RCP4.5, warming of around 2.5°C is projected in districts such as Baltistan, parts of Ghanche, Ghizer, and Gilgit in the mid-term, rising to 3°C or more in the long-term.
- Under RCP8.5, warming of 7°C and above is projected in districts such as Baltistan, parts of Diamir, Ghanche, Ghizer, and Gilgit by 2071–2100.

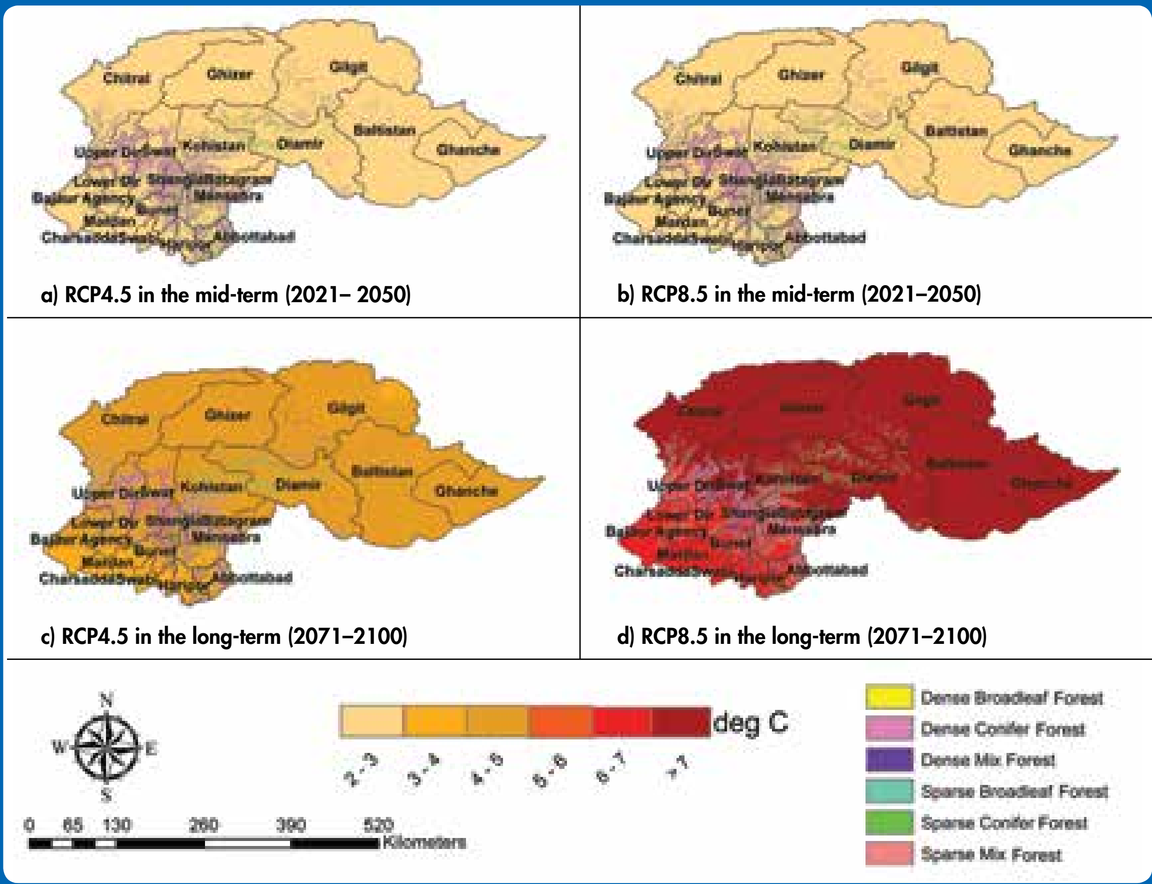
Precipitation (monsoon rainfall)

Mid Brahmaputra basin

Figure A4 shows the projected percentage change in June to September (JJAS) rainfall relative to the baseline period (1990s) in the mid Brahmaputra basin. The main changes projected are as follows:

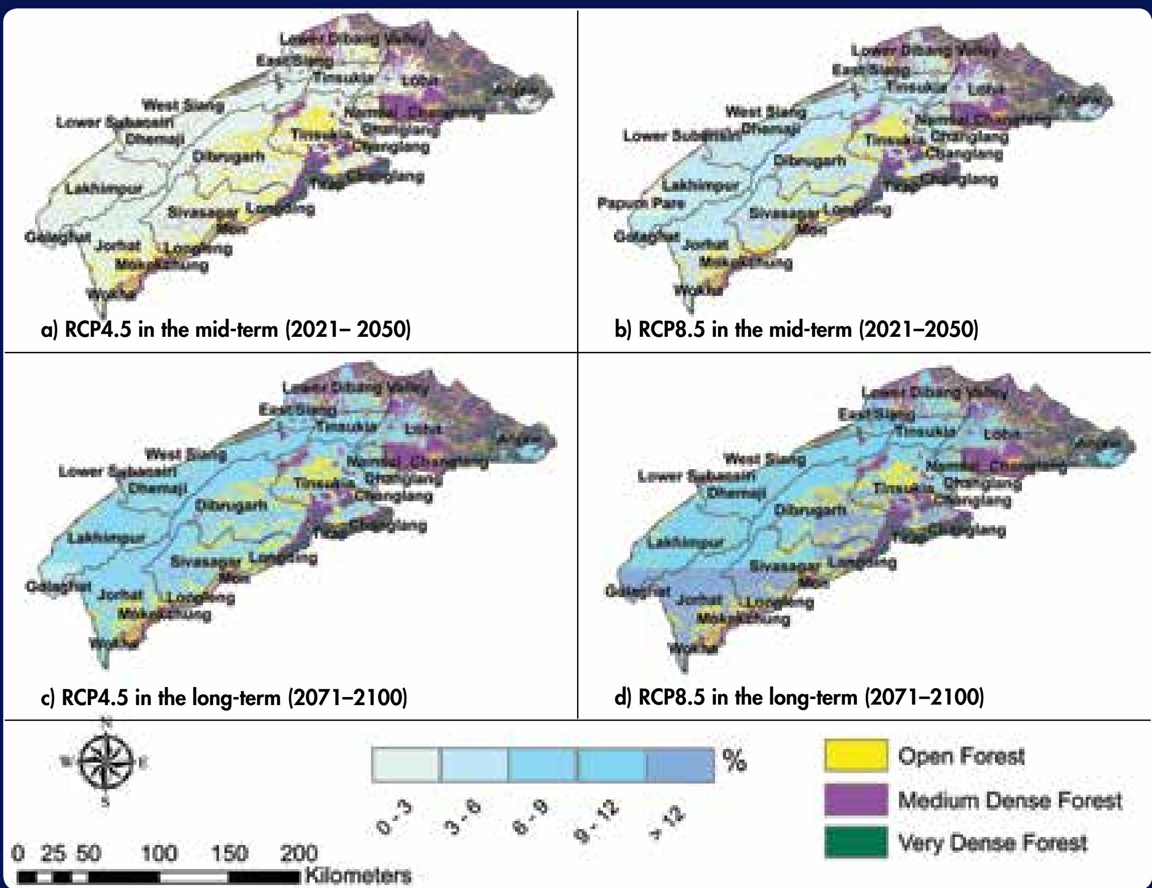
- Under RCP4.5, the northern and northwestern districts of Anjaw, parts of Dhemaji, Lohit, Sivasagar, and Tinsukia are projected to experience a marginal increase in monsoon precipitation (about 2%) in the mid-term and a slightly higher increase (>4%) in the long-term.
- Under RCP8.5, these districts are projected to experience an 11% increase in monsoon rainfall in the long-term.

Figure A3: **Projected annual temperature change (°C) relative to the baseline period (1990s) in the Upper Indus River basin under**



Note: solid black lines show the district boundaries.

Figure A4: **Projected change (%) in June to September (JJAS) rainfall relative to the baseline period (1990s) in the Mid-Brahmaputra river basin under**



Note: solid black lines show the district boundaries.

Koshi basin

Figure A5 shows the projected percentage change in June to September (JJAS) rainfall relative to the baseline period (1990s) in the Koshi basin. The main changes projected are as follows:

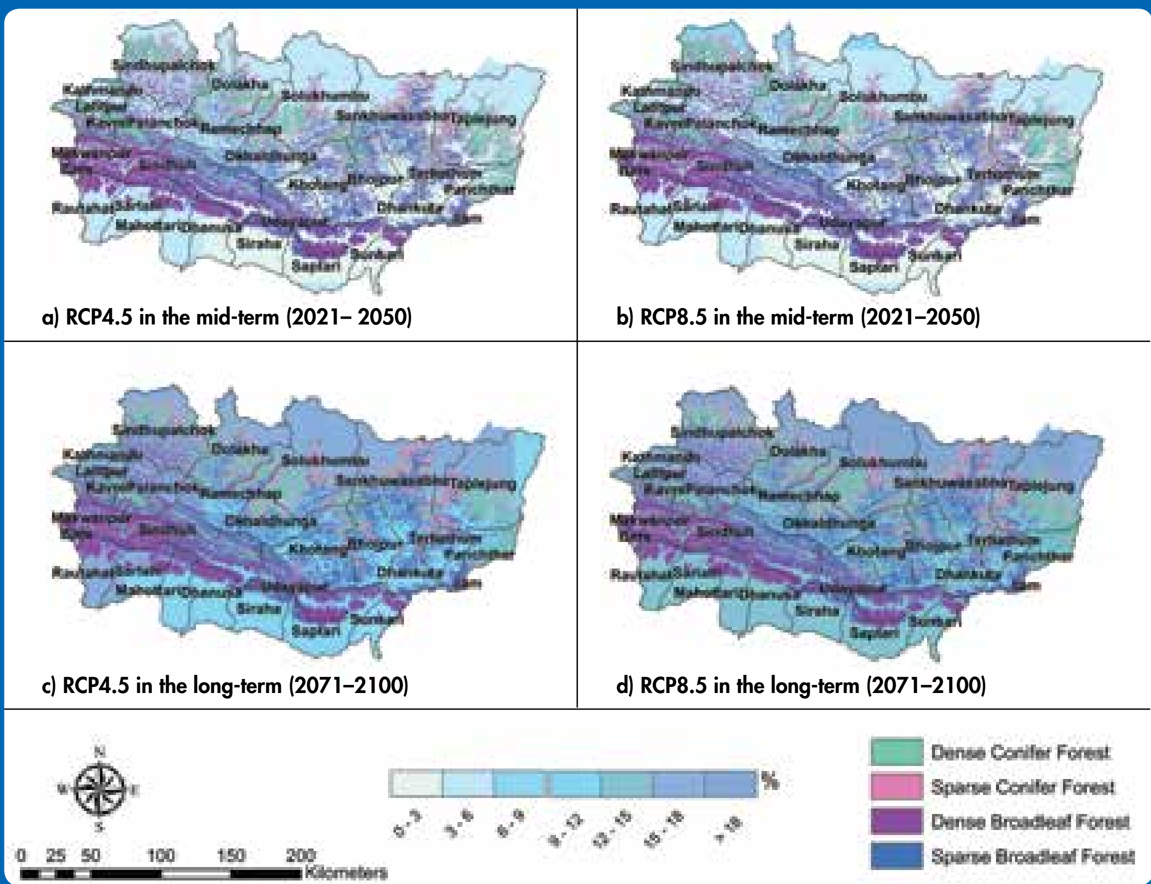
- Under RCP8.5, almost all the northern districts are projected to have a 4–7.5% increase in monsoon rainfall in the mid-term.
- Under both RCP4.5 and 8.5, the districts of Bhaktapur, Kathmandu, and Sankhuwasabha are projected to experience an increase of 14–24% in monsoon rainfall in the long-term.

Upper Indus basin

Figure A6 shows the projected percentage change in June to September (JJAS) rainfall relative to the baseline period (1990s) in the upper Indus basin. The main changes projected are as follows:

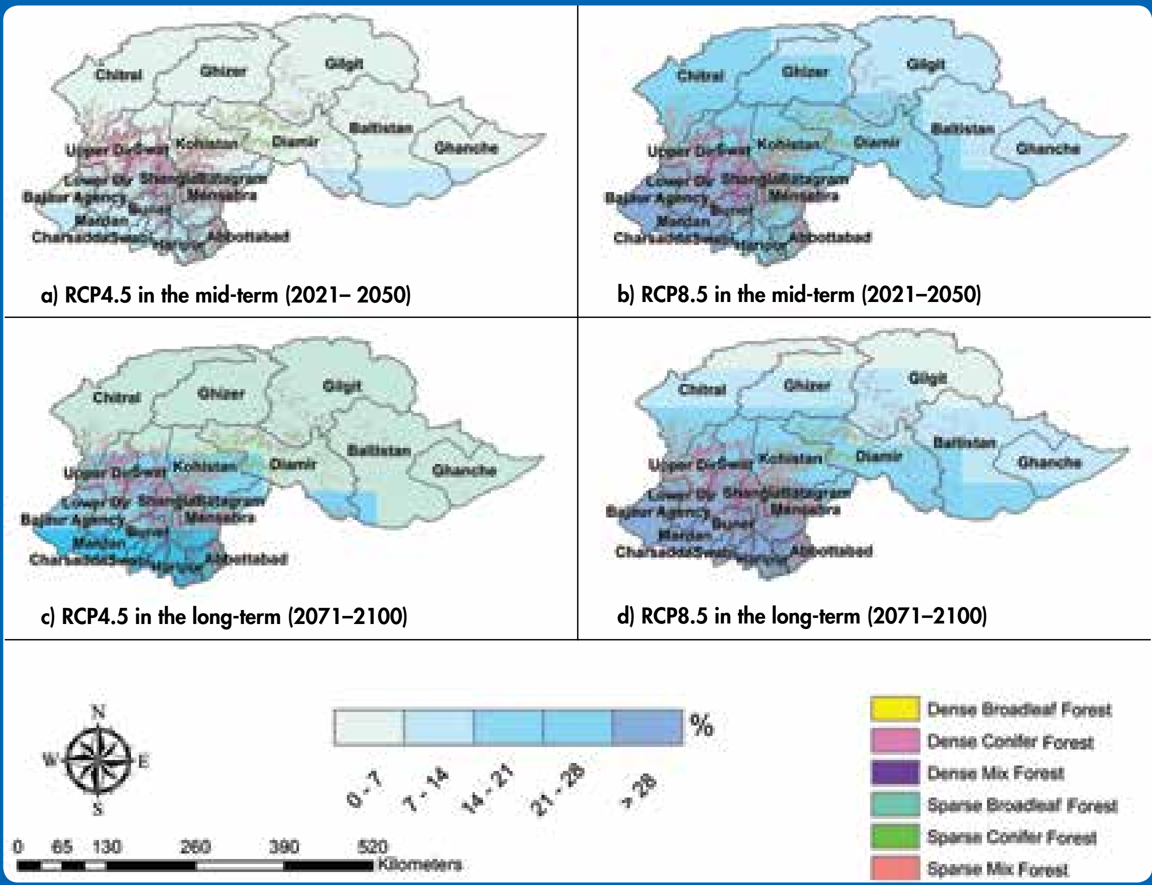
- Under RCP4.5, most of the southern districts (Abbottabad, Bajaur Agency, Buner, Charsadde, Haripur, Lower Dir, Malakand PA, Mansehra, Mardan, Mohmand Agency, and Swabi) are projected to experience a 10–14% increase in summer precipitaion in the mid-term, and a 25–32% increase under RCP8.5.
- Under RCP4.5, almost all the southern districts are projected to experience a 13–22% increase in summer precipitation in the long-term, and a 29–37% increase under RCP8.5.

Figure A5: **Projected change (%) in June to September (JJAS) rainfall relative to the baseline period (1990s) in the Koshi River basin under**



Note: solid black lines show the district boundaries.

Figure A6: **Projected change (%) in June to September (JJAS) rainfall relative to the baseline period (1990s) in the Upper Indus River basin under**



Note: solid black lines show the district boundaries.

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal
Tel +977 1 5003222 **Fax** +977 1 5003299
Email info@icimod.org **Web** www.icimod.org

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