BioOne COMPLETE

Responses of Montane Forest to Climate Variability in the Central Himalayas of Nepal

Authors: Mainali, Janardan, All, John, Jha, Pramod Kumar, and Bhuju, Dinesh Raj

Source: Mountain Research and Development, 35(1) : 66-77

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-13-00101.1

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non - commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainResearch
Systems knowledge

Responses of Montane Forest to Climate Variability in the Central Himalayas of Nepal

Janardan Mainali[1], John Ali[2], Pramod Kumar Jha[3], and Dinesh Raj Bhuju[4]*

** Corresponding author: mt.clim8@gmail.com*

[1] Research Solutions Nepal, Kirtipur-3, Kathmandu, Nepal

[2] Western Kentucky University, Department of Geography and Geology, Bowling Green, KY, USA

[3] Central Department of Botany (CDB), Tribhuvan University (TU), Kiritipur, Kathmandu, Nepal

[4] Resources Himalaya, Sanepa, Lalitpur, Nepal

Open access article: please credit the authors and the full source.

Climate changes are having dramatic ecological impacts in mid- to high-latitude mountain ranges where growth conditions are limited by climatic variables such as duration of growing season, moisture, and ambient temperature. We document patterns of forest vegetative response for 5 major alpine forest communities to current climate variability in the central Himalayas of Nepal to provide a baseline for assessment of future changes, as well as offer some insight into the trajectory of these changes over time. We used mean monthly surface air temperature and rainfall and the monthly averaged normalized difference vegetation index (NDVI) to compare relative vegetation productivity among forest types and in relation to both climatic variables. Because changes in temperature and precipitation are directly manifested as changes in phenology, we examined current vegetative responses to climate variability in an effort to determine which climate variable is most critical for different alpine forest types. Our results show that correlations differ according to vegetation type and confirm that both precipitation and temperature affect monthly NDVI values, though more significant correlations were found with temperature data. The temperature response was more consistent because at the maximum increased temperatures, there was still an ongoing increase in vegetative vigor. This indicates that temperature is still the major limiting factor for plant growth at higher-elevation sites. This part of the Himalayas has abundant moisture, and some forest types are already saturated in terms of growth in relation to precipitation. Clear increases in productivity are documented on the upper treeline ecotones, and these systems are likely to continue to have increasing growth rates.

Keywords: *Normalized difference vegetation index (NDVI); climate change; forests; vegetation change; Manaslu Conservation Area (MCA); Nepal.*

Peer-reviewed: *November 2014* ***Accepted:*** *December 2014*

Introduction

The Himalayas contain protected wilderness areas and preserves with limited human perturbation that provide ecologically sensitive areas for differentiating between anthropogenic and climate impacts on biodiversity. Among the 34 major global biodiversity hotspots, 4 are located in the Himalayas (Mittermeier et al 2004). In comparing species richness and endemism richness in Nepal, Vetaas and Grytnes (2002) found that while maximum species richness occurred at lower elevations (1500–2500 m) with more optimal growing conditions, endemism richness had a maximum peak around 4000 m, close to the rapid falloff in overall species occurrence because of harsh habitat conditions in elevations higher than 4000 m. The presence of an underpopulated upper-elevation region may provide new habitat for species migration during global warming. Often, the relationship between species richness and elevational gradient in the central Himalayas is one of moisture (from the Asian monsoon) rather than purely one of energy availability (temperature and growing season length), especially below the treeline (Bhattarai et al 2004). Monitoring of vegetation thus generally allows a fine-scale examination of both temperature and moisture climate components, and for the central Himalayas, it gives information on subtle variations within the Asian monsoon. As growth conditions in the upper Himalayan elevations improve, a higher total number of species, along with concomitant stress on endemics from increased competition, can be expected.

The global average surface temperature has increased by 0.85°C over the period 1880–2012 (Hewitson et al 2014), but the recent rate has accelerated to +0.2°C per decade since 1975 (Hansen et al 2006). High-elevation areas are particularly susceptible to climate variability (Körner 1998) and have been shown to have warmed more, and perhaps sooner, than the rest of the globe (Beniston et al 1997; Diaz and Bradley 1997; Gobiet et al 2014; IPCC 2014). Limited studies found that the warming

 http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00101.1 © 2015 by the authors

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

in the Himalayas is 3 times greater than the global average (Liu and Chen 2000; DIIR 2009; Xu et al 2009). Analysis of maximum surface temperature records from 49 stations in Nepal for the period 1971–1994 revealed a consistent increase after the mid-1970s, with a higher rate than the global average (Shrestha et al 1999) and an average warming in annual temperature between 1977 and 1994 of 0.06°C y^{-1}. Warming is more important in most of the middle mountain and Himalayan regions and has been found to be even more pronounced in the high altitudes of the Nepal Himalayas (Shrestha et al 1999). It has also been found that the warming trend is still continuing ($R = 0.85$) and that the rate of warming has never decreased between 1977 and 2000 (Shrestha and Aryal 2011). However, no distinct long-term trends in precipitation have been observed, although precipitation in Nepal is found to be influenced by, or correlated to, several large-scale teleconnections, including the El Niño-Southern Oscillation (Shrestha et al 2000). According to projections made by the Intergovernmental Panel on Climate Change (IPCC), average annual mean warming of the Asian land mass, including the Himalayas, will increase about 3°C by 2050 and about 5°C by 2080—with much higher rates toward the Tibetan Plateau (Cruz et al 2007; IPCC 2007). Similarly, average annual precipitation in this region will increase by 10 to 30% by 2080 (IPCC 2007).

Because the phenology of plants is strongly driven by environmental factors such as temperature and precipitation, climate change has already altered the vegetative and reproductive phenology of many species at middle to high latitudes (Menzel and Fabian 1999; Menzel 2000; Parmesan and Yohe 2003; Menzel et al 2006; Morin et al 2010; Richardson et al 2013). Such a trend is also reported for China (Fan et al 2009; Liang et al 2009), central Asia (Kariyeva et al 2012), the Tibetan Plateau (Yu et al 2010; Zhang et al 2011; Sun et al 2013), and the Himalayas (Shrestha et al 2012; Gaire et al 2014). There is evidence of the impacts of climate change on natural forest productivity, vegetation dynamics, and tree species distributions since the middle of the 20th century (Saxe et al 2001; Boisvenue and Running 2006; Fan et al 2009), and the rate of increase in temperature predicted for the 21st century is likely to be unprecedented (Saxe et al 2001; Hewitson et al 2014). These changes in climate have also altered the growing season, structure, and composition of forests (Walther et al 2002; Lindner et al 2010). Shrestha et al (2012) analyzed annual and seasonal trends for temperature, rainfall, and normalized difference vegetation index (NDVI) data from the period 1982 to 2006 for 13 ecoregions of the Himalayas (Olson and Dinerstein 2002) and found that changes in temperature and precipitation were greater than predicted by the IPCC and that higher-elevation ecoregions were the most affected. Their results indicate that over a 25-year period, the Himalayas have warmed by 1.5°C and at an average rate of 0.06°C y^{-1}. The greatest increase, 1.75°C, was observed in winter (rate of 0.07°C y^{-1}) and the least increase, 0.75°C, was observed in summer (rate of 0.03°C y^{-1}). The average annual precipitation has increased by 163 mm over the same period (rate of 6.52 mm y^{-1}), and the pattern is consistent in almost all ecoregions. This increase is more pronounced during the summer months (June to August). Shrestha et al (2012) also demonstrated that changes in the phenology of local ecosystems all across the Himalayas were well correlated with changes in climate. They found that both the average start of the growing season and the length of the growing season have advanced by 4.7 d or 0.19 d y^{-1} but that there have been no changes in the end of the growing season.

Phenological patterns are still poorly understood in the Himalayas because of the region's richness in species and the lack of historical data and ground references (Xu et al 2009). Consequently, changes at the regional level remain to be documented. Understanding the response of Nepal's montane forest to short-term climate variability is critical to assess the overall ecological response to long-term changes. This research documents the impact of climate variability and change on forest stands that currently have minimal anthropogenic impacts because of either local community protection or remoteness. We classified land cover and selected forest types using satellite imagery, existing classification (Barnekow Lillesø et al 2005), and field data collected during 2 expeditions to our study site. We used mean monthly surface air temperature, precipitation, and monthly averaged NDVI to compare relative vegetation productivity among forest types and in relation to both climatic variables. Because changes in temperature and precipitation are directly manifested as changes in phenology, we examined current vegetative responses to climate variability in an effort to determine which climate variable is most critical for different alpine forest types.

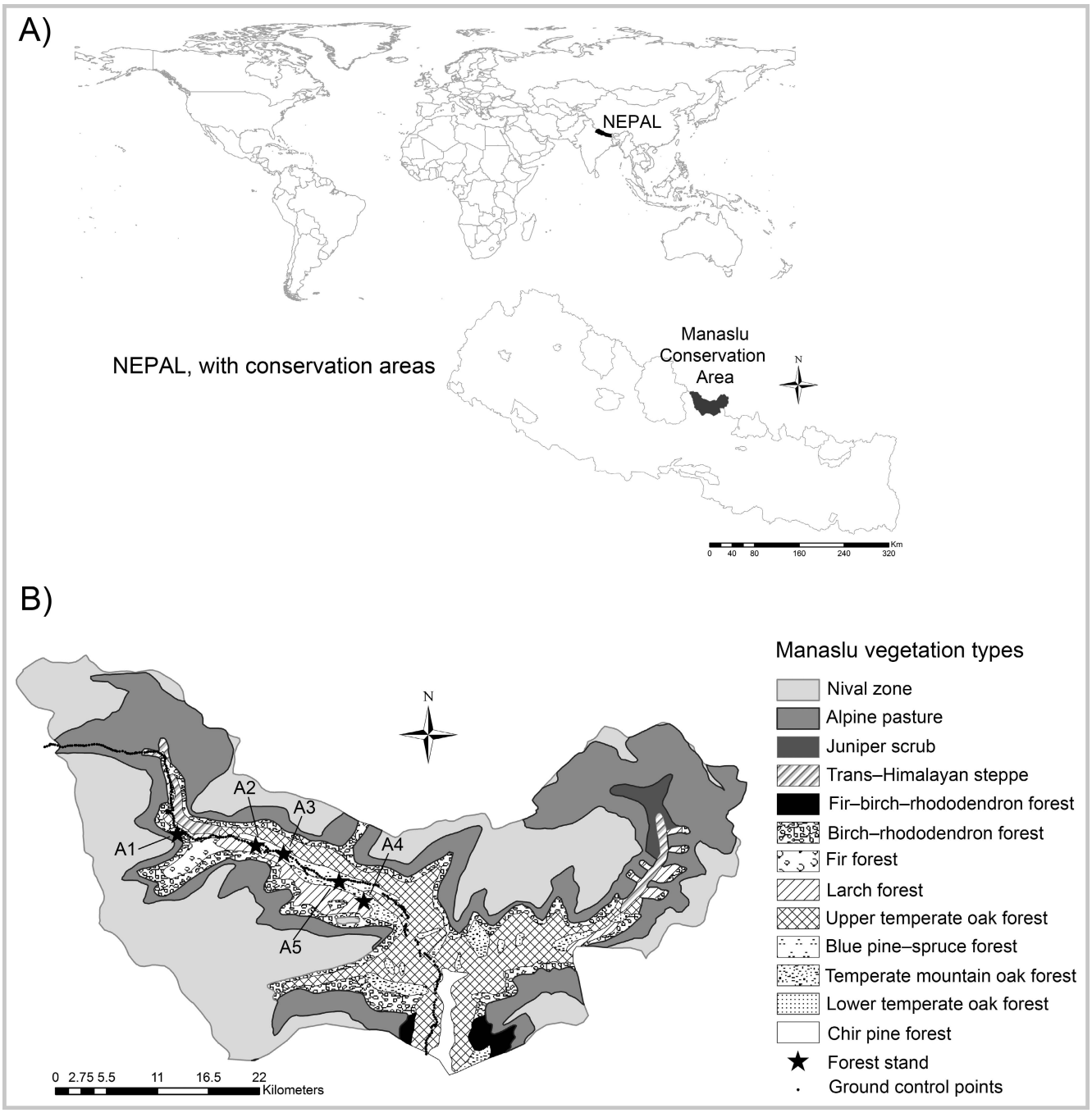
Material and methods

Study area and climate

The Manaslu Conservation Area (MCA) is located in central Nepal (Figure 1A). Created in 1998 under the National Parks and Wild Life Conservation Act, MCA is managed by the National Trust for Nature Conservation (NTNC) of Nepal. There has been little infrastructure development in this relatively inaccessible area. MCA lies between 28°20′ to 28°45′N and 84°29′ to 85°11′E and encompasses an area of 1663 km^2. MCA is home to 15 peaks higher than 6000 masl, including the seventh highest peak of the world, Mt Manaslu (8136 m), and 5 lakes situated above 3000 m. MCA is the remotest area of the Gorkha district and is bordered by the Tibet Autonomous Region of China to the north and east, the remainder of the Gorkha district to the south, and the Manang and Lamjung districts to the west (Rana 2001). The area covers 6 climatic zones, ranging from the lower

http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00101.1
Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

FIGURE 1 (A) Study area location in Nepal. (B) Map of MCA vegetation types and studied forest stands. (Map data modified from Barnekow Lillesø et al 2005, accessible through ICIMOD MENRIS 2010; map of study area by Janardan Mainali and John All.)

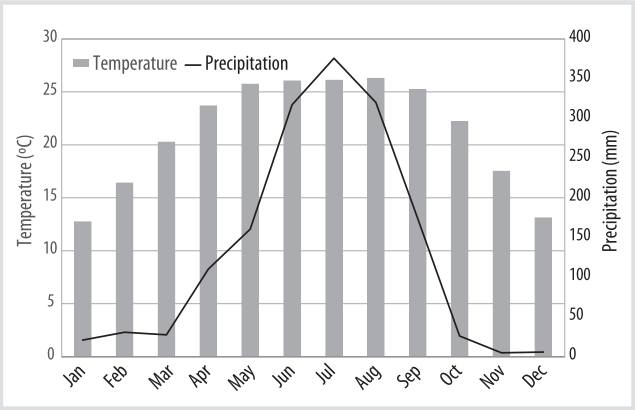


subtropics to the arctic zone, and includes 3 ecoregions: the eastern Himalayan broadleaf forests (EHBFs; 1500–3000 m); the eastern Himalayan subalpine conifer forests (EHSCFs; 3000–4000 m), and the eastern Himalayan alpine shrub and meadows (EHASMs; up to 5000 m; Olson and Dinerstein 2002). Between 1982 and 2006, these 3 ecoregions showed significant advancement in the start of the growing season of 0.21, 0.22, and 0.26 d y^{-1}, respectively (significant ≤ 0.05). The largest increase in the length of the growing season (all 13 ecoregions included) was observed in the EHASM, with 0.34 d y^{-1}. The EHSCF and EHBF values were 0.33 and 0.28 d y^{-1}, respectively (Shrestha et al 2012).

Within these elevation zones, 19 major vegetation communities have been reported in the MCA by the Nepali NTNC (Rana 2001). The area contains more than

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

FIGURE 2 Gorkha Weather Station temperature and precipitation averages from 2000 to 2008. Gorkha Weather Station is located about 50 miles from MCA. (Data source: DHM 2010; graph by Janardan Mainali and John All.)



19% of Nepal's total species of mammals and 13% of its birds. A preliminary biodiversity survey conducted in 1997 recorded 33 species of mammals, 110 species of birds, 3 species of reptiles, 11 species of butterflies, and 222 species of plants in 11 forest types. Park administrators have reported more than 200 species of flowering plants (Rana 2001). Barnekow Lillesø et al (2005) identified 13 vegetation types in Nubri Valley (1 of the 2 main valleys of the MCA), with fir forest and birch–rhododendron forest as the most dominant in the area (Figure 1B), and 147 species of locally used plants (Gurung and Pyakurel 2006).

The climate of MCA is essentially dominated by the southeasterly monsoon, which provides most of the precipitation during the rainy summer months (June to September; Figure 2). The mean annual rainfall over the past 30 years (1980–2009) was 967 mm at Chame (2680 m; Gaire et al 2014) and 1252 mm at Gorkha (1097 m). Gaire et al (2014) found that over the past 30 years, Chame Station experienced a decreasing trend in rainfall by 3.9 mm y^{-1} and an increasing trend in mean annual temperature by 0.017°C y^{-1}. In Chame, the monthly average temperature was found to be the highest in July and lowest in November, and monthly mean minimum temperature was decreasing while monthly mean maximum temperature was significantly increasing. In Gorkha, the average temperature ranges from 12.75°C in January to 26.30°C in August, and the region receives approximately 1574 mm of rain per year. The monthly mean maximum and minimum temperatures recorded at Gorkha Station during the study period were 31.16°C (August) and 6.38°C (January), respectively. June, July, and August are the hottest and wettest months (Figure 2).

Conservation areas within Nepal are meant to protect local resources while allowing the persistence of traditional community livelihoods and resource management (All et al 2014). There are 56 small villages within the MCA, and there is a historic pattern of cross-border trade with Tibet. The current economy depends on marginal agriculture, grazing, and botanical plant harvesting. An increase in transportation infrastructure will lead to an influx of both foreign tourists and Nepali workers to service the tourism industry. The environmental effects of such population increases and of increases in the intensity of land use are well documented in similar nearby protected areas, such as the Annapurna Conservation Area and Sagarmatha National Park. The present study documents the impacts of climate variability on relatively untouched forest stands while they still exist.

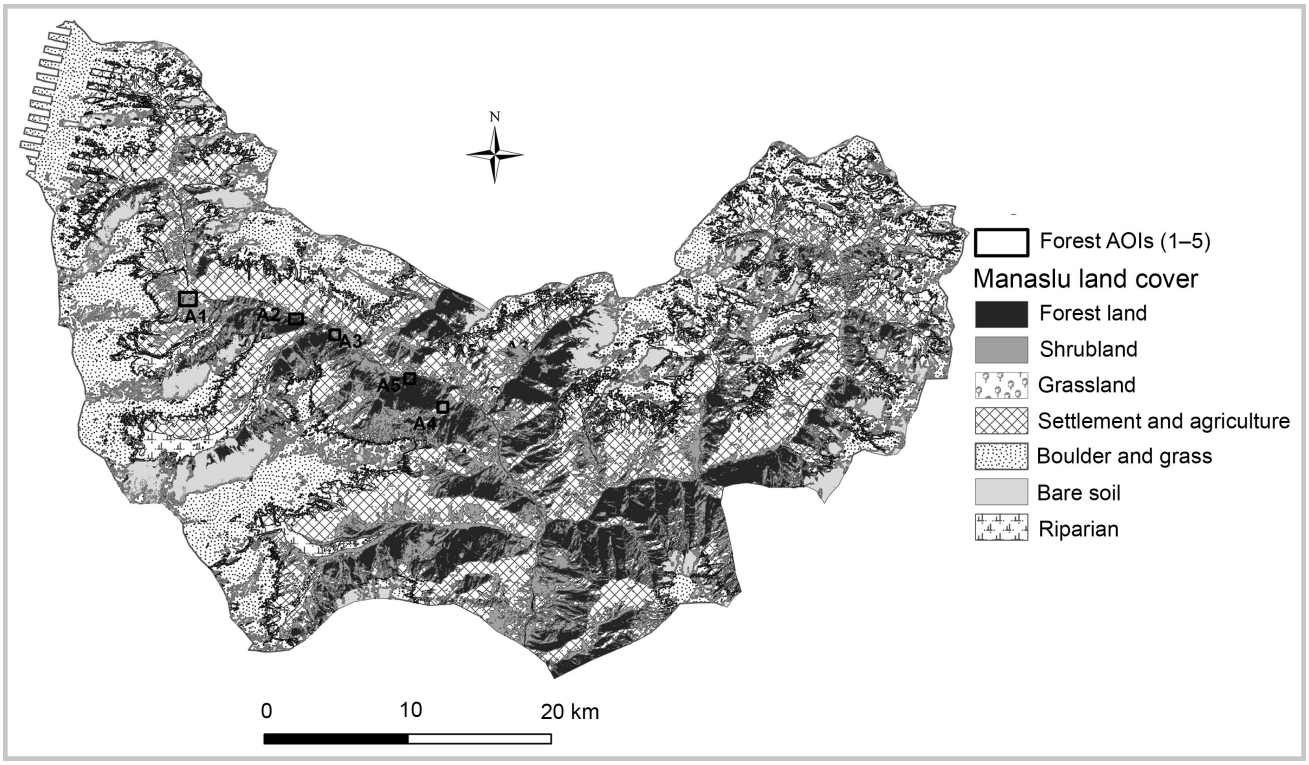
Land cover classification and forest area delineation

Land cover mapping is one of the earliest applications of remote sensing technology and is especially useful in remote or rugged regions where surface data may be limited (Cihlar 2000; Zomer et al 2001; Foody 2002; All 2014). We used a 2009 Landsat 5 Thematic Mapper (TM) image for the land cover classification because it was the best, cloud-free image close to the date of our first ground expedition. An ArcInfo shape file with the MCA's boundaries was acquired from the International Centre for Integrated Mountain Development (ICIMOD), and all data were reprojected to Universal Transverse Mercator (UTM) WGS-84 Zone 45-N. The MCA was subset from the Landsat image for the classification analysis using the ICIMOD shape file. Initial spectral signatures for our supervised classification were taken from an unsupervised classified image created using an Iterative Self-Organizing Data Analysis Technique (ISODATA) algorithm. ISODATA uses the minimum spectral distance formula to form clusters. The algorithm is robust and has the advantage that the clusters generated are not biased to any particular location in the image. There were 7 land cover classes delineated during the unsupervised classification. During the supervised classification, generated signature files were used to classify the given image, and the accuracy of the supervised classified map was assessed through a correlation matrix.

Fieldwork was carried out in 2 expeditions. Ground reference data were collected in the field with a random, systematic sampling method using a global positioning system, compass, and inclinometer. An initial land cover classification for the MCA was created after a monthlong field data collection visit in December 2009. A total of 287 ground control points were collected, and 5 forest areas of interest (AOIs) were delineated using the land cover analysis. Our major criteria for selection during forest area delineation were based on the existing classification identified by Barnekow Lillesø et al (2005), as well as on the results of extensive interviews with local residents and resources managers (Figure 1B). The data collected included latitude, longitude, UTM coordinates, altitude, slope, aspect, land cover type, and a description of the upper and middle canopy and the ground vegetation, with all species within a radius of 10 m identified to the genus level and recorded by a team of US and Nepali botanists. Disturbances such as grazing, erosion, limb

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

FIGURE 3 MCA land cover classification and forest AOIs. (Data source: U.S. Geological Survey Landsat 5 TM, October 2009, 30-m resolution and ICIMOD MCA shape file; map by Janardan Mainali and John All.)



cutting, timber harvest, and fire were also noted at each ground data location. Our preliminary results were validated during a second field visit in May–June 2010 (Figure 3).

Forest covers 197.82 km^2 in MCA, which is only 12.34% of the total land cover area (Table 1). Alpine forest was represented in the study by a mixed *Betula–Abies* forest stand (A1 in Figures 1B, 3). This type of treeline forest is often called fir forest *(Abies spectabilis).* However, in the treeline region of MCA, there are more mature individuals of *Betula utilis* than *A. spectabilis* (Gaire et al 2014). Generally, high-montane mixed forest in the central Himalayas has *B. utilis* as major component, followed by *A. spectabilis* and other species (Singh and Singh 1987). Other forest patches were examined, including the Himalayan larch forest (*Larix* sp), representing deciduous subalpine habitat (A2 in Figures 1B, 3), the evergreen temperate coniferous forest (blue pine–spruce forest) with dominant blue pine (*Pinus wallichiana;* A3 in Figures 1B, 3), *Quercus semecarpifolia* forest representing temperate broadleaf forest or lower temperate oak forest (A4 in Figures 1B, 3), and *Picea–Tsuga* as lower temperate conifer or spruce forest, where *Picea smithiana* is dominant (A5 in Figures 1B, 3).

NDVI and climatic data analysis

NDVI analysis has found wide application in vegetative studies and has been used for land cover classification (Loveland et al 1991; Brown et al 1993; Baidya et al 2009), estimation of crop yields (Wang et al 2005; Xiao et al 2006), and rangeland carrying capacities (Kawamura et al 2003; Piao et al 2007). NDVI is often directly related to other ground parameters such as percentage of ground cover, photosynthetic activity of the plant, surface water, leaf area index, and amount of biomass (Tucker and Sellers 1986; Running and Nemani 1988; Dong et al 2003; Wijaya et al 2010). Analysis of NDVI data helps in understanding the temporal trend of vegetation's biophysical character at different spatial scales. The National Oceanic and Atmospheric Administration advanced very high resolution radiometer, Terra, Aqua moderate resolution imaging spectroradiometer (MODIS), and Spot/Vegetation sensor data can also be used in vegetation trend analysis at different regional and local scales (Tucker et al 2001; Huete et al 2002; Chu et al 2007). Soil moisture is widely recognized as a key parameter that links precipitation, temperature, and NDVI—thus allowing the linkage of vegetation and climate impacts (Wang et al 2003).

The correlation of NDVI to precipitation and temperature has been shown by a number of previous studies in different parts of world, but there is a great deal of variability in the published results. Richard and Poccard (1998) analyzed the relationship between rainfall and NDVI in southern Africa, and their study shows that the strongest correlations occur when NDVI monthly

http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00101.1
Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

TABLE 1 Land cover types in MCA.

Classification	Area (km^2)	Percentage (%)	Classification accuracy (%)
Forest	**197.82**	**12.34**	**52.38**
Shrubland	215.53	13.45	60.91
Grassland	50.61	3.16	20.15
Settlement and agriculture	419.31	26.17	50.38
Bare soil	104.38	6.51	100.00
Riparian	154.64	9.65	91.66
Boulder and grass	460.24	28.72	100.00

values are compared with preceding bimonthly rainfall amounts, attesting to a 1- to 2-month lagged vegetation growth response to rainfall. Prasad et al (2005) studied different forest types in India and found that the correlation between mean monthly NDVI and precipitation is highest, with a lag of 30 days. Chu et al (2007) reported that there is strong correlation ($r = 0.75$) between NDVI and precipitation in Lhasa area of Tibet. However, a study of the Tibetan Plateau done by Ding et al (2007) reports that correlation between mean monthly maximum NDVI and monthly precipitation from 1982 to 1999 is very weak in the western, northern, and southern plateau and very strong in the central and eastern plateau. Liang et al (2009) found a significant association between a 20-year-long growing-season NDVI time series of a typical steppe in North China and precipitation. Most recently, Zhang et al (2011) investigated the role of antecedent vegetation conditions over East Asia for the East Asian summer monsoon variation and prediction using March, April, May, and spring mean NDVI for the period 1982–2009. Their results indicated that May vegetation greenness on the southeastern Tibetan Plateau had significant and positive correlations with summer rainfall over the southeastern Tibetan Plateau, East Asian summer subtropical frontal region, and many areas of northern China. Over the same period, Shrestha et al (2012) found maximum significant correlations of the start of the growing season with average temperature and cumulative precipitation of 2 months before average start of the growing season dates. Similarly, maximum correlations were observed among the average end of the growing season date, the average temperature of 3 months before the end of the growing season, and the cumulative precipitation of one month before end of the growing season. Given the uncertainty in the literature and the variability depending on specific local environmental variables, we tested numerous temperature and precipitation time lags to determine the best correlation with NDVI.

From the land use classified Landsat 5 TM image, comparable-sized AOIs for each forest stand were delineated (Figure 3). NDVI data for each forest AOI were then acquired from MODIS 16-day maximum value composite (MVC) dataset from January 2000 to December 2008 and analyzed using ERDAS Imagine software. MODIS datasets are preprocessed to provide well-quantified and calibrated datasets of the earth surface, corrected for instrument radiometry, geometric distortions, atmospheric attenuation, and cloud effect (Justice et al 1998). An MVC dataset compiles images over a 16-day period and takes the clearest image for each pixel to remove most cloud and atmospheric effects. The MODIS images were reprojected to UTM WGS-84 Zone 45-N before subsetting. We used the classified Landsat 5 TM image to create a subset for each of the 5 forest AOIs. From the forest AOI subsets, the average 16-day NDVI for each forest stand was acquired and the monthly averaged NDVI from 2000 through 2008 was calculated and used for the NDVI trend analysis. These values measure the seasonal and temporal pattern of vegetation greenness, vigor, or productivity. The NDVI data were then used in a productivity analysis of the forest AOIs compared to climatic variables. Monthly surface air temperature (mean, maximum, and minimum) and precipitation data from 2000 to 2008 for the nearest weather station in Gorkha were purchased from the Nepali Department of Hydrology and Meteorology.

NDVI values of each month were statistically correlated with temperature and precipitation using Pearson's correlation. Correlation of NDVI with precipitation from the same month and with a 1-, 2- and 3-month lag were examined. Similar analysis was performed for each stand with temperature. Regression analyses were also performed between the best correlated climatic factors and NDVI.

Results and discussion

NDVI trend analysis

The trend and magnitude of the NDVI values for the vegetation classes were correlated with the spatial and temporal variability of precipitation. In Nepal, the months of September and October are normally the best

http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00101.1
Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

growing period (transition monsoon to postmonsoon period; Figure 2), while April, May, and June are the driest months (premonsoon). We expected these trends to be reflected in our results.

Seasonal NDVI trend: Each forest type was analyzed individually using the NDVI data to examine seasonal patterns and look for overall changes in productivity during the study period (Figure 4A). As expected, the NDVI seasonal variation generally showed a peak during the summer monsoonal months of June, July, August, and September and a decrease in forest productivity from October to May. However, the evergreen *Q. semecarpifolia* (A4) and *Picea–Tsuga* (A5) forests had a less well-defined version of this pattern because of differences in their physiologies compared to the other species and the similarities in the microclimate of the locations where they thrive. *P. smithiana* (spruce) is a tall evergreen tree growing from 2300- to 2500-m elevation in open, dense, pure, and mixed forests with wide ecological amplitude. It is mainly a dry temperate species but can also be found in subalpine and moist temperate areas of Nepal (Nasrullah et al 2008). *Tsuga dumosa* (Himalayan hemlock) is found in Nepal between 2100 and 3600 m. In the lower parts of its range it occurs in *Q. semecarpifolia* forest, and higher up it occurs as a constituent of *P. wallichiana, Abies,* and *Picea* forest. *Q. semecarpifolia* is a typical tree on south-facing slopes (Dobremez 1976; Singh and Singh 1987), and it requires a high potential solar radiation (Vetaas 2000). In central and eastern Nepal it tends to be confined to warmer, drier south-facing slopes. It is absent from the very high rainfall areas north of Pokhara and from the upper Arun and Tamar valleys. In the Humla–Jumla area it is dominant, with *A. spectabilis* and *B. utilis,* especially on south-facing slopes, above 3000 m.

Betula–Abies, Larix, and *P. wallichiana* forests have their maximum NDVI during the summer rainy months. The *Betula–Abies* class has a distinct peak (A1 in Figure 4A), revealing the high-altitude forests' response to the seasonal climatic cycle. The distinct seasonality of NDVI can also be related with the phenology and reflectance property of *Betula–Abies* forest in different seasons. *B. utilis* is dominant for this class (Gaire et al 2014) but is a deciduous tree. Consequently, this forest has lowest NDVI value during the leafless period, as well as the lowest mean NDVI value (Figure 4B). Though *Larix* forest is also deciduous, it is shown to have comparatively less dramatic seasonal fluctuations (A2 in Figure 4A) because of the greater heterogeneity of the species. The *Larix* forest is a mixed type of forest that also includes evergreen species like *P. wallichiana* and *A. spectabilis,* which retain their chlorophyll and thus a higher NDVI even during the dry season. The *P. wallichiana* forest is an evergreen forest but shows a distinct seasonality in its NDVI values because of the stress of the alpine conditions during the cold, dry season (A3 in Figure 4A).

NDVI temporal trend: Among the 5 forest types studied, the maximum NDVI of only the *Larix* forest statistically increased from 2000 to 2008 (A2 in Figure 4C). The other forest types did not show a significant trend of increasing or decreasing NDVI. Interestingly, no forest type showed a significant trend for minimum NDVI values. For established forests in MCA, this indicates that there is an overall stability despite changing climate parameters. Kawabata et al (2001) extracted the following distinct NDVI trend: in the northern mid- and high latitudes (eg Europe, Russia, and northern China), a distinct increase in the NDVI was found for both the annual average and the spring to autumn period. Our research supports this finding, albeit at a lesser magnitude. A recent study in Koshi Basin (central east Himalaya region) has also revealed a small increase in NDVI in the central Himalaya region (Zhang et al 2013).

Correlation analysis between climatic variables and NDVI

To better assess the impact of local climate variables on specific growth patterns, the monthly NDVI value of each forest type was statistically compared with mean monthly temperature and monthly total precipitation values using Pearson's correlation. Precipitation and temperature directly influence the local water balance, causing changes in the soil moisture regime that, in turn, influences plant growth. This is reflected in our results, because there is a strong correlation between climatic factors (precipitation and temperature) and NDVI among all forest types (Tables 2 and 3).

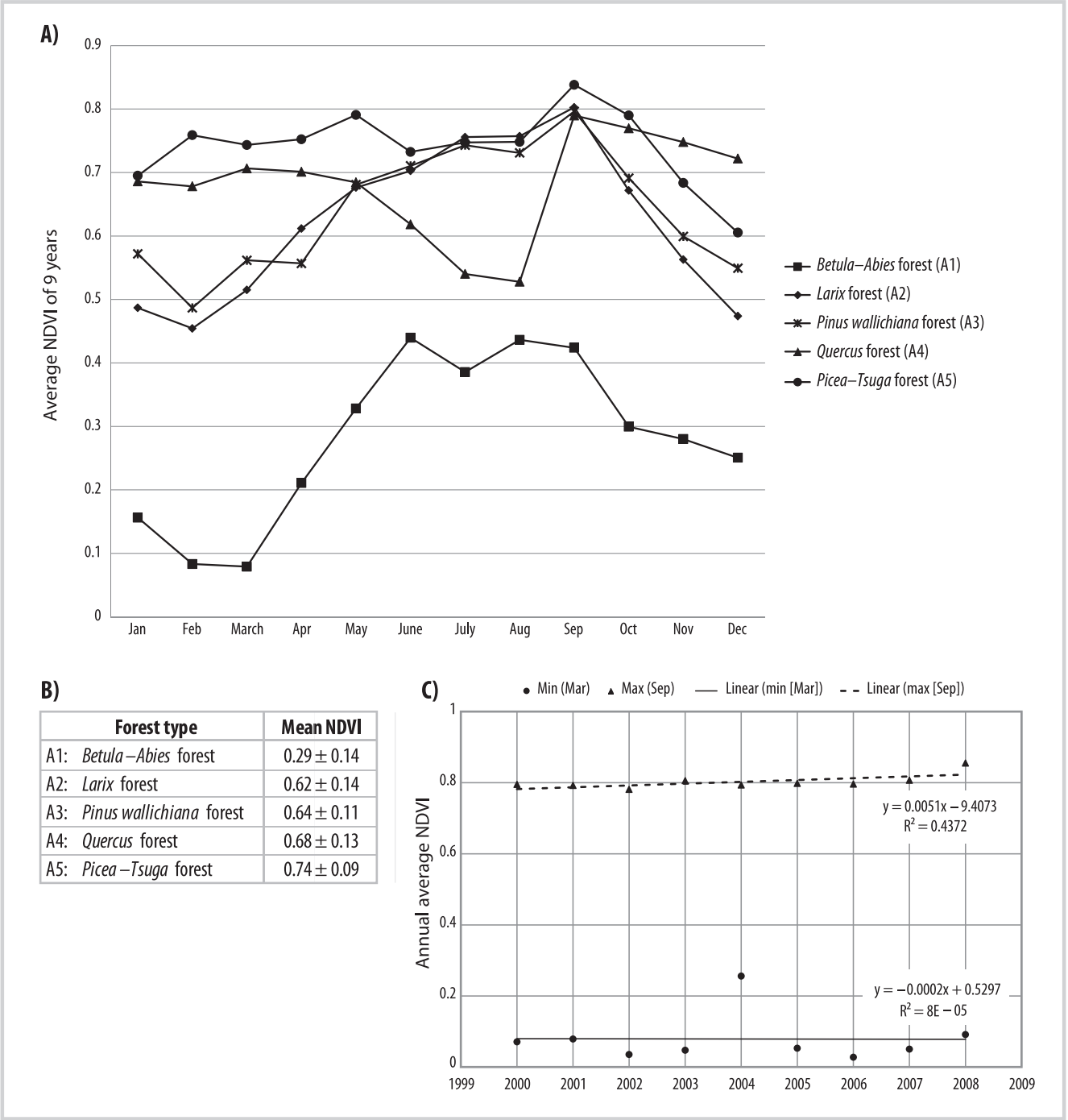
A correlation analysis between NDVI and temperature of the current month and temperature of the preceding month were performed (Table 2). NDVI values for *Betula–Abies, Larix,* and *P. wallichiana* forest had a higher correlation with the temperature of the preceding month than that of the same month. *Picea–Tsuga* forest and *Quercus* forest showed higher correlation with the temperature of the same month, but the correlation coefficients were weaker.

Most of the forest types exhibited fairly good correlation between NDVI and precipitation (Table 3). *Betula–Abies* and *Larix* forests had the highest correlation between NDVI and sum of precipitation for the 2 months before the measured NDVI. *P. wallichiana* and *Picea–Tsuga* forest had the highest correlation with NDVI and sum of precipitation for 2 months beginning 3 months before the measured NDVI. *Quercus* forest NDVI revealed an odd relationship with precipitation. It showed a negative correlation with precipitation of the same month. Because of its specific autecology, this species is known to be more sensitive to variations in temperature than to precipitation (Vetaas 2000).

Although our results underscored that both temperature and precipitation affect monthly NDVIs, they showed better correlations with temperature. Recent studies of tree rings in the Himalayan region have also shown that temperature strongly correlates with tree

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

FIGURE 4 (A) NDVI seasonal trend for each forest type (2000 to 2008). (B) Mean NDVI values for each forest type. (C) Trend of maximum and minimum NDVI for *Larix* forest ($p \geq 0.05$). (Design by Janardan Mainali and John All.)



Forest type	Mean NDVI
A1: *Betula–Abies* forest	0.29 ± 0.14
A2: *Larix* forest	0.62 ± 0.14
A3: *Pinus wallichiana* forest	0.64 ± 0.11
A4: *Quercus* forest	0.68 ± 0.13
A5: *Picea–Tsuga* forest	0.74 ± 0.09

growth (Borgaonkar et al 2011), but at treeline, broadleaved forest growth is primarily limited by moisture availability (Liang et al 2014). The correlations also differ according to vegetation types (Zhang et al 2011; Shrestha et al 2012; Chuai et al 2013; Sun et al 2013).

Regression analysis between NDVI and climatic variables

Using a regression analysis, the average monthly NDVI of *Picea–Tsuga* forest showed the best correlation with the temperature for that month, but more significant relationships were found when using a 1-month lag. The

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

TABLE 2 Correlation coefficients between NDVI and temperature. Bolded values represent highest correlation coefficients.

Forest type	Correlation coefficients between temperature and NDVI	
	Same month	Preceding month
Betula–Abies	0.621	**0.784**
Larix	**0.723**	**0.756**
P. wallichiana	0.634	**0.760**
Picea–Tsuga	0.390	0.253
Quercus	−0.164	−0.041

NDVI value of *Betula–Abies* (R^2 = 0.618), *Larix* (R^2 = 0.572), and *P. wallichiana* (R^2 = 0.578) forests showed the strongest correlation with the average temperature of the prior month—for example, February NDVI had the highest correlation with January temperature. The trend line of all of these forests showed an initial decline of NDVI with increasing temperature (possibly because of a decrease in soil moisture) followed by an increase as temperatures increase further and the growing season is lengthened. Temperature is a limiting factor for vegetation growth in this area; even at the highest temperatures measured during our study, there was still a major increase in NDVI.

The regression analysis also indicated that the monthly average NDVI of *Betula–Abies* (R^2 = 0.516) forest and *Larix* (R^2 = 0.572) forest showed the strongest relationship to rainfall with the month prior, based on a quadratic regression model. *Betula–Abies* and *Larix* forest NDVIs showed unimodal relationships with total rainfall of the month before the measured NDVI. NDVI values are at a maximum with 500–700 mm of cumulative rainfall during the 2 months before the measured NDVI (Gorkha Station, 1097 m). Regression scatter plots for 2 months of total precipitation versus third month average monthly NDVI had the highest correlation with *P. wallichiana* (R^2 = 0.572) forest based on a quadratic regression model—eg January and February precipitation versus March NDVI.

At higher rainfall levels, the NDVI saturated; in extreme cases, it even decreased. These results are consistent with the general effect of precipitation on high-altitude vegetation. Once a plant's limited water needs are met, excess rainfall either moves overland toward water bodies or remains near the plant, where it may cause extremely local flooding around the rhizosphere of the plant, which can limit the availability of soil nutrients and negatively affect plant growth and productivity. Two months of accumulated rainfall was found to be the best predictor of NDVI in 4 of the 5 forest types, because the lag in time allowed plant growth from the newly available water. The effects of precipitation patterns on plant growth are not always linear: the relationship depends on the amount of precipitation available and the specific biome (Fang et al 2005). In the Himalayan region, precipitation is concentrated mostly during the Asian monsoon and winter precipitation is rare. Thus, water has to be collected in sufficient amounts in the rhizosphere before it can be adequately absorbed by trees. For most of central Asia, the NDVI response patterns show a temporal lag between precipitation anomalies and vegetation activity of 1–3 months (Gessner et al 2012).

Quercus forests have opposite climate interactions compared to the other forest types. Monthly NDVI of the *Quercus* forest was strongly negatively correlated (R^2 = 0.527) to monthly precipitation of the same month. In addition, regression analysis showed a decreasing trend of NDVI with increasing temperature. This relation indicates that the *Quercus* forest has evolved into a specific ecological niche and does not respond favorably to climatic variability.

In some locations, it is precipitation that determines vegetative growth, and in other locations it is

TABLE 3 Correlation coefficients between precipitation and NDVI. Bolded values represent highest correlation coefficients.

Forest type	Correlation coefficient between precipitation and NDVI			
	Same month (1 versus 1)	Last month (1 versus 2)	Sum of 2 months versus NDVI of third month[a]	Sum of 3 months versus NDVI of second month[b]
Betula–Abies	0.603	0.597	0.640	0.665
Larix	0.600	0.663	**0.690**	**0.700**
P. wallichiana	0.550	0.666	**0.718**	0.676
Picea–Tsuga	0.229	0.272	0.336	0.276
Quercus	−0.477	−0.271	−0.156	−0.416

[a]For example, sum of Jan and Feb versus Mar.

[b]For example, sum of Jan, Feb, and Mar versus Feb.

http://dx.doi.org/10.1659/MRD-JOURNAL-D-13-00101.1
Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

temperature—especially in the high mountain regions. But generally, the interaction of both temperature and precipitation determines vegetative growth. The relationship depends on the specific biome, amount of incident solar radiation, soil type, and topography (Brovkin 2002). Tropospheric aerosols have also been found to be an important factor influencing vegetation growth in the Indian subcontinent (Sarkar and Kafatos 2004). In MCA, we found both temperature and precipitation to be equally important drivers of growth for most of the vegetation types.

Overall comparison among different forest types

NDVI is highly sensitive to both canopy foliar and understory chlorophyll content (Dawson et al 2003) and is a reflection of vegetative productivity. Natural systems with more water availability are generally more robust (All 2009). Our analysis revealed that *Picea–Tsuga* forest had the highest NDVI values among the forests studied. This forest type was followed by *Quercus* forest, *Larix* forest, *P. wallichiana* forest, and *Betula–Abies* forest. The difference in mean NDVI values was significant when comparing all forests except *Larix* and *P. wallichiana* forest (Figure 4B). The mean NDVI value for each of these was not significantly different, implying similarity in productivity, vegetation vigor, and health.

The *Betula–Abies* forest class is the highest-altitude alpine forest. This is the ecotonal forest of treeline. The trees are dwarf and sparsely occurring; thus, this forest has the lowest productivity. Winter snow, very low temperature during winter, and low rainfall limit their productivity. The *Larix* and *P. wallichiana* forests are at lower elevations, represent the same physiography of the subalpine region, and have similar productivity. The life forms of *P. wallichiana*, *Larix himalayica* (dominant species), and *A. spectabilis* (associated species) are similar, and these trees grow to a comparable size during maturity. So overall, the NDVI of these 2 forests is similar. The *Quercus* forest we studied is the only broadleaved evergreen forest. The broad leaves of *Quercus* spp, *Rhododendron* spp, and *Lyonia ovalifolia* are diverse, so the *Quercus* forest is seen as one of the most productive forest ecosystems. The *Picea–Tsuga* forest is the most productive forest type studied because of its favorable climate parameters and the large growth form of its trees. This forest was most vigorous in terms of both plant diameter and height. Most of the trees in this forest type exceeded a diameter at breast height of 1 m and were more than 30 m tall. Associated tree species like *P. wallichiana, Rhus* spp, *Viburnum* spp, and *Acer* spp, along with mosses and lichens covering the bark of every tree, contribute to the high measured productivity.

Conclusions

Our results underscore the observation that both precipitation and temperature affect NDVI values, even though more significant correlations were found with temperature data. This not only confirms the complexity of montane forest responses to climate variability but also indicates the need for site-specific climate adaptation strategies because of the heterogeneity of the responses. In addition, the time lag of climatic factors in this region is the most important factor in determining productivity. *Betula–Abies, Larix,* and *Pinus* forests had a greater correlation with the average temperature of the month preceding the NDVI measurement, while *Picea–Tsuga* and *Quercus* forests showed greater correlations with the temperature of the same month. These results clearly depict vegetation's strong response to temperatures and raise new study questions regarding the types of temperature changes that will have the greatest impacts as global warming increases. The dominance of anthropogenic land uses in MCA even after its creation in 1998 is worrisome, but the measured increases in vegetative productivity will offset some of the ecosystem losses until better resource management techniques can be implemented. Despite intensive use of forest resources by local people, there has not been a significant decrease in overall NDVI values for the MCA as a whole, so perhaps the local climate changes are effectively compensating for increased human use.

ACKNOWLEDGMENTS

We thank the Central Department of Botany, Tribhuvan University, for allowing us to use the remote sensing and geographic information system laboratory to conduct this work, and the US Fulbright Program for funding support. We also thank the Nepal Academy of Science and Technology for their support of the second field expedition. Our greatest gratitude goes to Ms Sylvie Arques for her support in finalizing the manuscript. We thank the anonymous reviewers for their suggestions for improvement.

REFERENCES

All J. 2009. GIS/remote sensing techniques for resource management and biodiversity protection in mountainous regions. *Botanica Orientalis* 6:93–99.

All J. 2014. Remote sensing challenges in mountainous regions. *Photogrammetric Engineering and Remote Sensing* 80(8):710–711.

All J, Pricope N, Humagain K. 2014. Connecting pixels with people to examine environmental changes in the Mt. Everest region of Nepal. *Photogrammetric Engineering and Remote Sensing* 80(7):600–604.

Baidya NG, Bhuju DR, Kandel P. 2009. Land use change in buffer zone of Chitwan National Park, Nepal, between 1978 and 1999. *Ecoprint* 16:79–86.

Barnekow Lillesø JP, Shrestha TB, Dhakal LB, Nayaju RP, Shrestha R. 2005. *The Map of Potential Vegetation of Nepal: A Forestry/Agro-Ecological/*

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

Biodiversity Classification System. Development and Environment 2. Hørsholm, Denmark: Center for Skov, Landskab og Planlægning/Københavns Universitet.
Beniston M, Diaz HF, Bradley RS. 1997. Climatic change at high elevation sites: An overview. *Climatic Change* 36:233–251.
Bhattarai KR, Vetaas OR, Grytnes JA. 2004. Relationship between plan species richness and biomass in an arid subalpine grassland of the central Himalayas, Nepal. *Folia Geobotanica* 39:57–71.
Boisvenue C, Running SW. 2006. Impacts of climate change on natural forest productivity: Evidence since the middle of the 20th century. *Global Change Biology* 12:862–882.
Borgaonkar HP, Sikder AB, Ram S. 2011. High altitude forest sensitivity to the recent warming: A tree-ring analysis of conifers from Western Himalaya, India. *Quaternary International* 236:158–166.
Brovkin V. 2002. Climate–vegetation interaction. *Journal de Physique* 4(12): 10–57.
Brown JF, Loveland TR, Merchant JW, Reed BC, Ohlen DO. 1993. Using multisource data in global land-cover characterization: Concepts, requirements, and methods. *Photogrammetric Engineering and Remote Sensing* 59:977–987.
Chu D, Lu L, Zhang T. 2007. Sensitivity of normalized difference vegetation index (NDVI) to seasonal and interannual climate conditions in the Lhasa area, Tibetan Plateau, China. *Arctic, Antarctic and Alpine Research* 39(4):635–641.
Chuai XW, Huang XJ, Wang WJ, Bao G. 2013. NDVI, temperature and precipitation changes and their relationships with different vegetation types during 1998–2007 in Inner Mongolia, China. *International Journal of Climatology* 33:1696–1706. http://dx.doi.org/10.1002/joc.3543.
Cihlar J. 2000. Land cover mapping of large areas from satellites: Status and research priorities. *International Journal of Remote Sensing* 21:1093–1114.
Cruz RV, Harasawa H, Lal M, Wu S, Anokhin Y, Punsalmaa B, Honda Y, Jafari M, Li C, Huu Ninh N. 2007. Asia climate change 2007: Impacts, adaptations and vulnerability. *In:* Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE, editors. *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, pp 469–506.
Dawson TP, North PRJ, Plummer SE, Curran PJ. 2003. Forest ecosystem chlorophyll content: Implications for remotely sensed estimates of net primary productivity. *International Journal of Remote Sensing* 24:611–617.
DHM [Department of Hydrology and Meteorology]. 2010. *Rainfall and Temperature Data of Gorkha Station From 2000 to 2008*. Babarmahal Kathmandu, Nepal: Department of Hydrology and Meteorology, Ministry of Environment, Government of Nepal.
Diaz HF, Bradley RS. 1997. Temperature variations during the last century at high elevation sites. *Climatic Change* 36:253–279.
DIIR [Department of Information and International Relations]. 2009. *The Impacts of Climate Change on the Tibetan Plateau: A Synthesis of Recent Science and Tibetan Research*. [No place]: Environment and Development Desk, DIIR.
Ding M, Zhang Y, Liu L, Zhang W, Wang Z, Bai W. 2007. The relationship between NDVI and precipitation on the Tibetan Plateau. *Journal of Geographical Sciences* 17(3):259–268. http://dx.doi.org/10.1007/s11442-007-0259-7.
Dobremez JF. 1976. *Le Népal: Écologie et biogéographie*. Paris, France: Éditions du Centre National de la Recherche Scientifique.
Dong J, Kaufmann R, Myneni R, Tucker C, Kauppi P, Liski J, Buermann W, Alexeyev V, Hughes M. 2003. Remote sensing estimates of boreal and temperate forest woody biomass: Carbon pools, sources, and sinks. *Remote Sensing of Environment* 84:393–410.
Fan ZX, Bräuning A, Cao KF, Zhu SD. 2009. Growth–climate responses of high-elevation conifers in the central Hengduan Mountains, southwestern China. *Forest Ecology and Management* 258:306–313.
Fang J, Piao S, Zhou L, He J, Wei F, Myneni RB, Tucker CJ, Tan K. 2005. Precipitation patterns alter growth of temperate vegetation. *Geophysical Research Letters* 32(21):L21411, 1–5. http://dx.doi.org/10.1029/2005GL024231.
Foody GM. 2002. Status of land cover classification accuracy assessment. *Remote Sensing of Environment* 80:185–201.
Gaire NP, Koiral M, Bhuju DR, Borgaonkar HP. 2014. Treeline dynamics with climate change at the central Nepal Himalaya. *Climate of the Past* 10:1277–1290.
Gessner U, Naeimi V, Klein I, Kuenzer C, Klein D, Dech S. 2012. The relationship between precipitation anomalies and satellite-derived vegetation activity in central Asia. *Global and Planetary Change* 110:74–87.
Gobiet A, Kotlarski S, Beniston M, Heinrich G, Rajczak J, Stoffel M. 2014. 21st century climate change in the European Alps. *Science of the Total Environment* 493:1138–1151.
Gurung K, Pyakurel D. 2006. *Identification and Inventory of Non-Timber Forest Products (NTFPs) of Manaslu Conservation Area.* A report submitted to Manaslu Conservation Area Project (MCAP)/National Trust for Nature Conservation (NTNC), Gorkha. Kathmandu, Nepal: National Trust for Nature Conservation Nepal.
Hansen J, Sato M, Ruedy R, Lo K, Lea D, Elizade M. 2006. Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America* 103(39):14,288–14,293.
Hewitson B, Janetos AC, Carter TR, Giorgi F, Jones RG, Kwon WT, Mearns LO, Schipper ELF, van Aalst M. 2014. Regional context. *In:* Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom: Cambridge University Press, pp 1133–1197.
Huete A, Didan K, Miura T, Rodriguez EP, Gao X, Ferrerira LG. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment* 83:195–213.
IPCC [Intergovernmental Panel on Climate Change]. 2007. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors. Cambridge, United Kingdom: Cambridge University Press.
IPCC [Intergovernmental Panel on Climate Change]. 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL, editors. Cambridge, United Kingdom: Cambridge University Press.
Justice CO, Vermote E, Townshend JRG, Defries R, Roy DP, Hall DK, Salomonson VV, Privette JL, Riggs G, Strahler A, Lucht W, Myneni RB, Knyazikhin Y, Running SW, Nemani RR, et al. 1998. The moderate resolution imaging spectroradiometer (MODIS): Land remote sensing for global change research. *IEEE Transactions on Geoscience and Remote Sensing* 36(4):1228–1249.
Kariyeva J, Van Leeuwen WJD, Woodhouse CA. 2012. Impacts of climate gradients on the vegetation phenology of major land use types in central Asia (1981–2008). *Frontiers in Earth Science* 6(2):206–225. http://dx.doi.org/10.1007/s11707-012-0315-1.
Kawabata A, Ichii K, Yamaguchi Y. 2001. Global monitoring of the interannual changes in vegetation activities using NDVI and its relationships to temperature and precipitation. *International Journal of Remote Sensing* 22:1377–1382.
Kawamura K, Tsyoshi A, Watanabe O, Hagesawa H, Zhang FP, Yokota H, Wang S. 2003. Estimation of aboveground biomass in Xilingol Steppe, Inner Mongolia using NOAA/NDVI. *Grassland Science* 49(1):[no page range].
Körner C. 1998. A re-assessment of high elevation treeline positions and their explanation. *Oecologia* 115:445–459.
Liang E, Eckstein D, Liu H. 2009. Assessing the recent grassland greening trend in a long-term context based on tree-ring analysis: A case study in North China. *Ecological Indicators* 9:1280–1283. http://dx.doi.org/10.1016/j.ecolind.2009.02.007.
Liang E, Dawadi B, Pederson N, Eckstein D. 2014. Is the growth of birch at the upper timberline in the Himalayas limited by moisture or by temperature? *Ecology* 95:2453–2465.
Lindner M, Maroschek M, Netherer S, Kremer A, Barbati A, Garcia-Gonzalo J, Seidl R, Delzon S, Corona P, Kolström M, Lexer MJ, Marchetti M. 2010. Climate change impacts, adaptive capacity, and vulnerability of European forest ecosystems. *Forest Ecology and Management* 259:698–709. http://dx.doi.org/10.1016/j.foreco.2009.09.023.
Liu X, Chen B. 2000. Climatic warming in the Tibetan Plateau during recent decades. *International Journal of Climatology* 20(14):1729–1742.
Loveland TR, Merchant JW, Ohlen DO, Brown JF. 1991. Development of a land-cover characteristics database for the conterminous U.S. *Photogrammetric Engineering and Remote Sensing* 57:1453–1463.
MENRIS [Mountain Environment and Natural Resources Information System Division]. 2010. MENRIS, Mountain Geoportal. http://geoportal.icimod.org/Downloads/; accessed 5 May 2010.
Menzel A. 2000. Trends in phenological phases in Europe between 1951 and 1996. *International Journal of Biometeorology* 44:76–81.
Menzel A, Fabian P. 1999. Growing season extended in Europe. *Nature* 397: 659.
Menzel A, Sparks TH, Estrella N, Koch E, Aasa A, Ahas R, Alm-Kübler K, Bissoli P, Braslavská O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl A, Defila C, et al. 2006. European phenological response to climate change matches the warming pattern. *Global Change Biology* 12(10):1969–1976.

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use

Mittermeier RA, Robles-Gil P, Hoffmann M, Pilgrim JD, Brooks TB, Mittermeier CG, Lamoreux JL, Fonseca GAB. 2004. *Hotspots Revisited: Earth's Biologically Richest and Most Endangered Ecoregions*. Mexico City, Mexico.
Morin X, Roy J, Sonié L, Chuine I. 2010. Changes in leaf phenology of three European oak species in response to experimental climate change. *New Phytologist* 186:900–910. http://dx.doi.org/10.1111/j.1469-8137.2010.03252.x.
Nasrullah K, Moinuddin A, Mohammad W. 2008. Dendroclimatic potential of *Picea smithiana* (Wall) Boiss, from Afghanistan. *Pakistan Journal of Botany* 40(3):1063–1070.
Olson DM, Dinerstein E. 2002. The Global 200: Priority ecoregions for global conservation. *Annals of the Missouri Botanical Garden* 89:199–224.
Parmesan C, Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37–42.
Piao S, Fang J, Zhou L, Tan LK, Tao S. 2007. Changes in biomass carbon stocks in China's grasslands between 1982 and 1999. *Global Biogeochemical Cycles* 21:1–10.
Prasad VK, Anuradha E, Badrinath KVS. 2005. Climatic controls of vegetation vigor in four contrasting forest type of India: Evaluation from National Oceanic and Atmospheric Administration advanced very high resolution radiometer datasets (1990–2002). *International Journal of Biometeorology* 50:6–16.
Rana ASJB, editor. 2001. *Manaslu Eco-Tourism Development Project, Upper Gorkha. Project Completion Report*. Lalitpur, Nepal: King Mahendra Trust for Nature Conservation (KMTNC).
Richard Y, Poccard I. 1998. A statistical study of NDVI sensitivity to seasonal interannual rainfall variations in Southern Africa. *International Journal of Remote Sensing* 19:2907–2920.
Richardson AD, Keenan TF, Migliavacca M, Ryu Y, Sonnentag O, Toomey M. 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. *Agricultural and Forest Meteorology* 169:156–173.
Running SW, Nemani RR. 1988. Relating seasonal patterns of the AVHRR vegetation index to simulated photosynthesis and transpiration of forest in different climates. *Remote Sensing of Environment* 24:347–367.
Sarkar S, Kafatos M. 2004. Interannual variability of vegetation over the Indian subcontinent and its relation to the different meteorological parameters. *Remote Sensing of Environment* 90:268–280.
Saxe H, Cannell MGR, Johnsen B, Ryan MG, Vourlitis G. 2001. Tree and forest functioning in response to global warming. *New Phytologist* 149:369–399.
Shrestha AB, Aryal R. 2011. Climate change in Nepal and its impacts on Himalayan glaciers. *Regional Environmental Change* 11(1):S65–S77. http://dx.doi.org/10.1007/s10113-010-0174-9.
Shrestha AB, Gautam S, Bawa KS. 2012. Widespread climate change in the Himalayas and associated changes in local ecosystems. *PloS ONE* 7(5): e36741. http://dx.doi.org/10.1371/journal.pone.0036741.
Shrestha AB, Wake CP, Dibb JE, Mayewski PA. 2000. Precipitation fluctuations in the Nepal Himalaya and its vicinity and relationship with some large scale climatological parameters. *International Journal of Climatology* 20:317–327.
Shrestha AB, Wake CP, Mayewski PA, Dibb JE. 1999. Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *Journal of Climate* 12:2775–2787.
Singh JS, Singh SP. 1987. Forest vegetation of Himalaya. *Botanical Review* 53:80–192.
Sun J, Cheng G, Li W, Sha Y, Yang Y. 2013. On the variation of NDVI with the principal climatic elements in the Tibetan Plateau. *Remote Sensing* 5:1894–1911. http://dx.doi.org/10.3390/rs5041894.
Tucker C, Sellers P. 1986. Satellite remote sensing of primary productivity. *International Journal of Remote Sensing* 7:1395–1416.
Tucker CJ, Slayback DA, Pinzon JE, Los SO, Myneni RB, Taylor MG. 2001. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. *International Journal of Biometeorology* 45:184–190.
Vetaas OR. 2000. The effect of environmental factors on the generation of *Quercus semecarpifolia* Sm. in central Himalaya, Nepal. *Plant Ecology* 146: 137–144.
Vetaas OR, Grytnes JA. 2002. Distribution of vascular plant species richness and endemic richness along the Himalayan elevation gradient in Nepal. *Global Ecology and Biogeography* 11:291–301.
Walther GR, Post E, Convey P, Menzel A, Parmesan C, Beebee T, Fromentin JM, Hoegh-Guldberg O, Bairlein F. 2002. Ecological responses to recent climate change. *Nature* 416(6879):389–395.
Wang J, Rich PM, Price KP. 2003. Temporal responses of NDVI to precipitation and temperature in the central Great Plains, USA. *International Journal of Remote Sensing* 24:2345–2364.
Wang J, Rich PM, Price KP, Kettle WD. 2005. Relations between NDVI, grassland production, and crop yield in the central Great Plains. *Geocarto International* 20:5–11.
Wijaya A, Kusnadi S, Gloaguen R, Heilmeier H. 2010. Improved strategy for estimating stem volume and forest biomass using moderate resolution remote sensing data and GIS. *Journal of Forest Resources* 21:1–12.
Xiao X, Frokling SB, Li C, Babu JY, Salas W, Moore B. 2006. Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images. *Remote Sensing of Environment* 100:95–113.
Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang Y, Wilkes A. 2009. The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology* 23(3):520–530.
Yu H, Luedeling E, Xu J. 2010. Winter and spring warming result in delayed spring phenology on the Tibetan Plateau. *Proceedings of the National Academy of Sciences of the United States of America* 107(51):22,151–22,156. http://dx.doi.org/10.1073/pnas.1012490107.
Zhang J, Wu L, Huang G, Zhu W, Zhang Y. 2011. The role of May vegetation greenness on the southeastern Tibetan Plateau for East Asian summer monsoon prediction. *Journal of Geophysical Research* 116:D05106. http://dx.doi.org/10.1029/2010JD015095.
Zhang Y, Gao J, Liu L, Wang Z, Ding M, Yang X. 2013. NDVI-based vegetation changes and their responses to climate change from 1982 to 2011: A case study in the Koshi River Basin in the middle Himalayas. *Global and Planetary Change* 108:139–148.
Zomer RJ, Ustin SL, Carpenter CC. 2001. Land cover change along tropical and subtropical riparian corridors within the Makalu Barun National Park and Conservation Area, Nepal. *Mountain Research and Development* 21(2):175–183. http://dx.doi.org/10.1659/0276-4741(2001)021[0175:LCCATA]2.0.CO;2.

Downloaded From: https://bioone.org/journals/Mountain-Research-and-Development on 28 Mar 2024
Terms of Use: https://bioone.org/terms-of-use