Interannual Variation of NDVI, Precipitation and Temperature during the Growing Season in Langtang National Park, Central Himalaya, Nepal

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Abstract  Vegetation is an essential component of terrestrial ecosystem, and its responses to the climate change has been recognized as a key indicator for monitoring global climate. This study analyses the temporal and spatial changes of Normalized Difference Vegetation Index (NDVI) in the Langtang National Park (LNP), Nepal, during 2000-2018, using the MODIS 16-day NDVI product, and the ERA-5 precipitation and temperature reanalysis. Regression models were applied to estimate temporal trends in NDVI, and Pearson correlations between NDVI and climatic variables (i.e., temperature and precipitation) were employed to assess vegetation responses to climate change. Average annual NDVI increased significantly (0.002yr\(^{-1}\), \(p = 0.001\)), and the average growing season (AGS: April-October) NDVI also increased significantly (overall, 0.0023yr\(^{-1}\)) including in spring (April-May, 0.003yr\(^{-1}\)) and autumn (September-October, 0.002yr\(^{-3}\)). During summer (June-August), NDVI increased by 0.002yr\(^{-1}\) (\(p > 0.05\)). Temperature and precipitation both increased significantly during the growing season, and significant increases in NDVI during spring in LNP indicate high levels of photosynthesis, biomass accumulation and productivity. The NDVI relative change ratio (RCR) was 12.79% during the last 19 years in LNP. The spatial distribution of NDVI increased by 30% (\(p < 0.05\)) of the area during growing season. Overall, during the AGS, 66% of the study area showed a positive correlation with temperature, of which 9.09% was significant. Positive correlation was observed between temperature and NDVI, and negative correlation between precipitation and NDVI, in the forest, shrubland, grassland and agriculture vegetation types. In the AGS, NDVI was positively correlated with temperature, but weakly related to precipitation. The results demonstrated that increasing temperature promotes vegetation growth. Quantifying the spatial response of NDVI to temperature and precipitation will support further studies on conservation and on vegetation responses to climate changes across this Himalayan national park.

Keywords: NDVI, growing season, precipitation, temperature, Langtang National Park


1. Introduction

Climate change is a serious challenge facing the Third Pole (i.e., the Tibetan Plateau and adjacent high-elevation areas) [1,2]. The Tibetan Plateau (TP) is often called the ‘roof of the world’ due to its distinctive high elevation and geographical features [3], and this high elevation is the main reason for the TP’s pivotal role in global climate change [4]. The TP is regarded as a natural laboratory in climate change studies, providing important information on feedback processes [5]. Meanwhile, the third pole is experiencing rapid warming (0.045°C/decade) [6], with major ecological consequences. In this context, vegetation is a key component with which to monitor climatic impacts on the terrestrial ecosystem [7]; such monitoring can then enable projections of further vegetation growth, environmental change, and ecosystem dynamics [8]. Vegetation responses can be linked to the atmosphere, pedosphere and hydrosphere [9], yielding information on the wider effects of a changing climate on the earth.
system. In mountain ecosystems, species with narrow habitat tolerance are at the greatest risk from the environmental effects of climate change. Therefore, it is an urgent need to understand the vegetation-climate interaction in alpine ecosystems.

Different approaches have been used to investigate the responses of vegetation growth to climate over the past 30 years. One approach employs the satellite-derived normalized difference vegetation index (NDVI), which is the normalized ratio of red and near-infrared (NIR) reflectance [10,11]; specifically, the stronger absorption of visible light by healthy plants indicates a greater rate of photosynthesis (and vice versa) [12]. Satellite-derived NDVI data have been incorporated into vegetation productivity models based on monthly leaf area index (LAI) and annual changes in net primary productivity [13,14]. Globally and regionally, satellite-based remote sensing analysis could help observations of plant phenology; however, the approach still has some limitations regarding spatial resolution [15]. Availability of long-term NDVI data derived from the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High-Resolution Radiometer (AVHRR) has enabled studies of vegetation changes that are of scientific interest because of their socio-ecological importance [16]. In the current study, MODIS NDVI data were selected instead of AVHRR data because of the superior spectral and spatial resolution [17].

Previous studies have suggested that climate change plays an essential role in the variations of NDVI [18,19]. In recent decades, a positive relationship between northern hemisphere NDVI and increasing temperature has been associated with a lengthened growing season and enhanced photosynthesis [20]. A study in China [21] suggested that precipitation pattern can also influence vegetation growth. The relationship between NDVI and climate variables has been briefly studied at the global scale [22,23,24,25]; however, a global correlation analysis of NDVI response to precipitation and temperature was insignificant [26], whereas most regional studies have found significant relationships between these climate variables. For example, a study in the central USA Great Plains using AVHRR NDVI (1989-1997) reported a strong relationship between precipitation and NDVI, while temperature was positively correlated with NDVI during the early and late growing season [27]. Due to the high altitude and low temperature on the TP, the plant growing season is rather short: from May to September for herbaceous plants [28]. Using the SPOT VGG NDVI data, a study in Inner Mongolia found higher correlation between growing season NDVI and precipitation [29]. Vegetation growth during the growing season in most permafrost zones is controlled by temperature [30].

Langtang National Park (LNP) was the first Himalayan national park in Nepal, established to preserve the environment from modification by human activities such as grazing and deforestation [31,32]. The vegetation of the LNP is the best example of how the habitat can support large populations of sheep, goats and other herbivores, thus providing the main economic activity for local communities in the Central Himalaya [23]. Consequently, LNP represents an ideal experimental region for studying climate change and vegetation growth. Because of climatic and anthropogenic effects, the park’s ecology has been severely impacted, and is sensitive to ongoing environmental changes. Temporal and spatial analysis of NDVI has revealed significantly increased vegetation growth in the hills and central regions of Nepal during 1982-2015 [33]; in addition, a recent study demonstrated that the annual mean temperature increased by 0.05°C yr⁻¹ and precipitation decreased by -16.09 mm yr⁻¹ in Nepal during this period [34]. Many studies have explored the importance of growing season vegetation changes, increased seasonal vegetation growth, and links to the physical environment. However, few studies have employed a dendro-ecological approach [35,36,37,38] in alpine ecosystem, and a comprehensive assessment of vegetation patterns in high-altitude landscapes is still lacking [39]. The inter-annual and seasonal NDVI trends across the whole of Nepal have been analyzed [33] but the growing season vegetation changes have not been considered. The growing season (April to October) is an essential period indicating changes in ecosystem dynamics and climate [40], dominated mainly by vegetative change [20]. To avoid interference in observed NDVI trends from winter snow and winter dormant vegetation growth [11,41], this study focuses only on the growing season NDVI changes over LNP.

In present study, we used MODIS13Q1 NDVI data from 2000 to 2018, together with information on temperature and precipitation changes in LNP. The main objectives were (i) analyze trend in average growing season (AGS) NDVI, air temperature and precipitation during 19 years, (ii) compare correlations between NDVI, temperature and precipitation and (iii) quantify changes in vegetation patterns within the different vegetation types (forest, shrubland, grassland and agriculture land) throughout the LNP. Our study will provide baseline study on vegetation dynamics over the high altitude national park, which can be beneficial in conservation strategies.

2. Materials and Methods

2.1. Study Area

Langtang National Park is the highest elevation national park, extending from 600 to 7200 m a.s.l. and from 28°-28°20’N to 85°20’-86° E, covering a total area of 1710 km². It is the first Himalayan and second-largest national park, established in 1976 by the government of Nepal [32] and extending to the northern border to china (Figure 1). The northern and eastern borders of the LNP coincide with the international border and are linked with the Qomolangma (National Nature Preserve) in Tibet, while the western boundary follows the Bhote Kosi and Trishuli River [42]. The park consists of diverse climate and vegetation zones (from 1000 m a.s.l. the alpine zone) due to its complex topography and geology, and as reflected in its broad bio-diversity [43] comprising over 46 species of mammals, 345 species of birds and 1000 species of plants (including 172 used for medical purposes). Globally endangered wildlife, such as the Snow leopard (Uncia uncia) [44] and Red panda (Ailurus fulgens) [42] occur in the park, along with other rare mammals such as Himalayan thar (Hemitragus jemlahicus), Musk deer (Moschus chrysogaster), and wild dog (Cuon alpinus) [45].
2.2. NDVI and Climate Data Sets

To quantify the response of vegetation to changes in climate, this study utilized the MODIS NDVI product MOD13Q1 and calculated the temporal and spatial variations of annual and growing season vegetation cover in LNP during 2000-2018. The MODIS NDVI, Land Process Distributed Active Archive Center (LPDAAC), MOD13Q1 Terra product was downloaded from https://modis.gsfc.nasa.gov/. The data are provided at 16 day temporal resolution and 250 m spatial resolution, spanning 2000 to 2018. The tiles were mosaicked and re-projected to Albers equal-area projection, using the nearest neighbor re-sampling method and WGS84 datum with the MODIS Re-projection Tool (MRT) acquired from the NASA website. ERA-5 (total precipitation and average temperature) climate datasets produced by the global reanalysis dataset the European Centre for Medium-Range Weather Forecasts (ECMWF) were obtained from the Copernicus Climate Change Services (C3S) Climate Data Store (CDS) at the native grid spacing [47] (downloaded from https://climate.copernicus.eu/). The datasets contain numerous atmospheric, land and oceanic variable at approximately 30 km spatial resolution and are available at multiple temporal resolutions [48].

2.3. Methods

The NDVI and its changes attributed to climate were examined based on annual, growing season and pixel-wise trends in NDVI, temperature and precipitation time series. The average growing season (AGS: April-October) in LNP was divided into three seasons defined as spring (April and May), summer (June to August) and autumn (September and October) following a previous study of the Khosi River basin of Nepal [49]. Based on a vegetation map produced by the International Centre for Integrated Mountain Development (ICIMOD), LNP vegetation was classified into four types (forest, shrubland, grassland and agriculture) (Figure 1). We then extracted growing season precipitation, temperature, and NDVI for each vegetation type during 2000 to 2018. An average over all grid cells belonging to the same vegetation type then yielded the average values of NDVI, temperature, and precipitation associated with that vegetation type.

2.3.1. Long-term Changes in NDVI

To detect vegetation and climate variations over the 19 years, annual and Average NDVI, temperature and total precipitation were calculated. To evaluate long-term changes in NDVI and climate parameter, generalized linear regressions models (equation 1) was used.

$$\text{Slope} = \frac{n \times \sum_{i=1}^{n} \Delta NDVI_i - \sum_{i=1}^{n} \sum_{j=1}^{n} NDVI_i}{n \times \sum_{i=1}^{n} \Delta^2 - \left( \sum_{i=1}^{n} \Delta_i \right)^2}$$

Where, slope is the trend of vegetation dynamics or climate variables, n is the number of years in the study period, i is the year and NDVI in the ith year. The positive slope indicates increasing trends while negative slopes indicates decreasing trends [50].

2.3.2. Rate of NDVI change

The relative change ratio (RCR) that either increase or decrease in all vegetation types during annual or AGS were estimated using slope and mean NDVI value. The rate of NDVI change calculated as follows:

$$\text{Rate of NDVI change (\%)} = \frac{\text{Regression slope} \times \text{mean NDVI value}}{N} \times 100$$

Here, regression slope is the linear regression slope of annual or monthly average NDVI; mean value is the average NDVI over the study period; and N is the length
of the study period (2000-2018). The rate of change in NDVI can also be calculated as the difference between the final NDVI and initial NDVI divided by initial NDVI [51].

2.3.3. Correlation between NDVI and Climatic Variables

Annual and growing season average temperature, precipitation and NDVI maps were developed to identify the correlation between NDVI and climate in each pixel. NDVI data from different regions and time series at varying resolutions have been widely used to study the relationships between vegetation and climate [52,53]. The Pearson correlation coefficient (r) measures the strength of the relationships between NDVI and climatic parameters; a 95% confidence level was selected to determine the statistical significance of the correlations. The correlation r indicates the strength of the linear relationship and the p-value indicates the corresponding probability level. If the correlation between the two variables is positive, and the p-value is less than 0.05, the correlation is statistically significant. The spring, autumn, summer and AGS average temperature and total precipitation were used to test the relationships with NDVI.

3. Results and Discussion

3.1. Inter-annual Variation of Growing Season-NDVI and Climatic Factors

The magnitude of the monthly NDVI indicates vegetation activity in different months of the AGS. In LNP, monthly NDVI reached a maximum in October (0.41), followed by September (0.37), and was rather small in June and July (Figure 2). The monthly NDVI trend was increasing, except in September and October. The highest NDVI trend was observed in August (0.007 yr⁻¹) and the lowest in September, October, June and July (below 0.002 yr⁻¹). The average monthly NDVI was 0.30 during the growing season, and positive trends were observed in most period except September and October. June-August had low monthly mean NDVIs, possibly due to drought which might have reduced the vegetation intensity/canopy [54].

Annual variations in mean NDVI, precipitation, and temperature are presented in Figure 3a-c. The mean annual NDVI increased significantly (P = 0.001), the maximum annual NDVI was in 2018, and the year 2000 had the lowest NDVI (0.27). The average annual increase in NDVI was 0.0022 yr⁻¹ (Figure 3a). Precipitation and temperature showed slightly increasing but non-significant trends. Annual temperature increased by 0.030°C yr⁻¹. Inter-annual variations in AGS NDVI, precipitation, and temperature in LNP are presented in Figure 3d-f. The maximum growing season NDVI was in 2017 (Figure 3c) and the minimum was in 2014. The temporal trend in AGS NDVI was statistically significant over the entire study period (P = 0.023). Similarly, precipitation and temperature demonstrated significant increasing trends Figure 3d-f. The change in vegetation dynamics as a response to climate change suggests that vegetation dynamics have significantly increased on both regional and global scales [20,49,55]. For example, a study on the Khosi River, central Himalaya, indicated a significant increasing trend in vegetation growth (R² = 0.19, p = 0.03) from 1982-2011 [49], compared with an annual increasing trend in Nepal (R² = 0.33, p = 0.0001) [33]. Increased growing season vegetation growth was also noted in the mountainous ecosystem [56]. The trend in annual mean temperature (+0.003°C yr⁻¹) (Figure 3f) was consistent with findings from other studies [33] during similar periods, for example +0.006°C yr⁻¹ during 1997-1994 [57] and +0.04°C yr⁻¹ from 1975-2007 [58]. Here, the increasing trend of growing season NDVI corresponded closely to that of temperature (Figure 3). The overall change in precipitation was relatively small but showed a significant increase (R = 0.49: p =0.032), despite the considerable inter-annual variability.

Figure 2. The comparison of average monthly NDVI (bar) and its trend (red line) over LNP during 2000 to 2018
Next, we discuss trends in NDVI, precipitation and temperature during the three seasons. NDVI images for spring (April and May), summer (June through August), and autumn (September and October) were generated by averaging over the respective months (Figure 4a-c), showing that growing season NDVI in LNP significantly increased at the rate 0.002 yr\(^{-1}\) (p = 0.03), mainly in the autumn season. Both mean NDVI and annual NDVI trends were high in autumn. The growing season NDVI significantly increased during spring which indicate high levels of photosynthesis, biomass accumulation and productivity [49]. At the end of the growing season, the high mean NDVI suggested that a longer growing season, especially in autumn (September-October) followed by spring (April and May), was a primary contributor to the increasing NDVI (Figure 4). The treeline ecotones between 3300 m and 4300 m altitude showed high NDVIs, as well as positive trends in the annual and growing season [59]. The duration between the beginning and end of the growing season is closely linked with climatic parameters such as precipitation [60] and temperature [61]. The increased NDVI in spring and summer were apparently strongly related to temperature (Figure 4a-b). Summer average temperature significantly increased (p = 0.001), at a rate of 0.003°C yr\(^{-1}\) during 2000-2018. However, the spring and autumn seasons experienced increases at rates of 0.01°C yr\(^{-1}\) and 0.006°C yr\(^{-1}\), but these were not statically significant. Our results showed that the enhanced NDVI in the early growing season is associated with higher growing season temperatures. This is consistent with past studies [10,11,18]. Summer season
precipitation increased significantly \((p=0.004)\), at a rate of 3.24 mm yr\(^{-1}\). The increasing trends in both temperature and precipitation in the summer season may improve the light efficiency and moisture availability in plants, thus leading to an increase in plant growth (Table 1). The precipitation in Nepal-focused studies does not show a long-term significant trend \([62,63]\). In a regional study of hydro-climatic variability in the Karnali River basin, the annual (-4.91 mm yr\(^{-1}\)), winter (-1.21 mm yr\(^{-1}\)), and monsoon (-1.58 mm yr\(^{-1}\)) trends were negative for the period 1981-2012 \([64]\). A similar previous study in the Gandaki River basin (central region) reported decreasing annual (-4.27 mm yr\(^{-1}\)) and winter (-1.46 mm yr\(^{-1}\)) trends, and an increasing trend in the monsoon season (0.42 mm yr\(^{-1}\)) \([65]\). However, our study showed a significant increasing trend in summer.

Table 1. Annual, AGS and seasonal correlation coefficients between NDVI and temperature \(R_{T-NDVI}\) and precipitation \(R_{P-NDVI}\) in LNP from 2000-2018

<table>
<thead>
<tr>
<th>Correlation coefficient (r)</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Average Growing</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{T-NDVI})</td>
<td>0.03</td>
<td>0.48</td>
<td>0.23</td>
<td>0.38</td>
<td>0.56</td>
</tr>
<tr>
<td>(R_{P-NDVI})</td>
<td>-0.49</td>
<td>0.06</td>
<td>-0.12</td>
<td>0.18</td>
<td>-0.02</td>
</tr>
</tbody>
</table>

Table 1 summarizes the annual and growing season correlations between NDVI and the climatic factors. The temporal correlations between AGS-NDVI, precipitation and temperature were positive but non-significant (precipitation, \(r = 0.18, p = 0.45\); temperature, \(r = 0.38, p = 0.10\)). Similarly, the correlation between annual NDVI and temperature \((r = 0.56)\) was positive \((p = 0.06)\), but correlation with precipitation \((r = -0.22)\) was negative \((p = 0.9)\) at the annual scale (Table 1). The average temperature across all of Nepal increased by 0.003°C yr\(^{-1}\) from 1982-2015 \([65]\), which might reflect a positive response to vegetation growth over LNP, respectively.

### 3.2. Spatial Variation of AGS-NDVI

The linear trends in annual and AGS-NDVI over the study period were estimated using ordinary least-squares regression (Figure 5). Out of the total area of the national park, 25.17% of pixels exhibited a significant increasing trend \((p < 0.05; \text{green in Figure 5})\), and 1% presented a significant downward trend \((p < 0.05; \text{red in Figure 5})\). In the AGS, 30.16% of the area showed a significant upward and 2.3% of the area showed a downward trend (Figure 5). Significant AGS trends were mainly observed in the north of the LNP, which is covered by grassland, while southern parts showed no significant changes. The southern LNP is dominated by agriculture and the more intensive anthropogenic activities, for example grazing and deforestation, which mostly take place during the growing season. Although the annual trend was notably heterogeneous over the whole study area, the majority of the area showed positive NDVI trends; however, a few pixels showed negative trends. Countries such as Bangladesh, Bhutan, India and Nepal have experienced an increase in the forest cover density. For instance, the Community Forest (CF) scheme in the central hills of Nepal has increased the forest capital, while the paucity of labour in the agricultural land has boosted natural reforestation \([66,67]\). NDVI variations in different altitudinal zones have shown trends towards a high NDVI, due to the adoption of community forestry and agricultural practices \([59]\).

![Image](image.png)

Figure 5. The spatial pattern of NDVI trends at (a) Annual Scales and (b) AGS over the period 2000-2018. Green shows a significant increasing trend and red shows a significant decrease.
3.3. Correlation between Annual, AGS-NDVI and Climate Variables

The pixel-wise correlation between annual and growing season NDVI and climate (precipitation and temperature) in the LNP is shown in Figure 6. Correlation between annual mean NDVI and temperature is positive in 74.31% of the total area, and negative in 25.68%. Meanwhile, 2.03% of the study area showed positive correlation between NDVI and precipitation and 97.97% showed negative correlation (Figure 6). The spatial distribution of precipitation over Nepal is dominated by the summer monsoon; however, the central regions observed comparatively higher amounts of precipitation than the other regions of Nepal [68]. This study did not find significant correlation between NDVI, temperature and precipitation in the study area. Topographical effects may affect the correlation coefficient between NDVI and climatic parameters; in addition, precipitation falling in the form of snow can reduce the surface reflectance [69]. Therefore, caution is required when assessing correlation with NDVI in such specific locations.

Figure 6. Spatial correlation between (a) annual NDVI and precipitation (RP), (b) annual NDVI and temperature (RT)

Figure 7. Spatial correlation between (a) AGS-NDVI and precipitation (RP), (b) AGS-NDVI and temperature (RT)
Positive correlations between AGS-NDVI and temperature were observed in 66% of the study area, of which 9.09% was significant (Figure 7); 30.45% of the area showed negative correlation. Meanwhile, 30.2% of the study area presented a positive correlation between NDVI and precipitation (with 0.70% significantly positive) and 69.8% showed negative correlation. AGS NVDI was more positively correlated with precipitation than the annual NDVI. The dry mountains, mainly in the Trans-Himalayan region, demonstrated positive correlation between vegetation and precipitation [70,71]. The pixel-wise correlation indicated relatively stronger and more significant positive correlation of NDVI with temperature than with precipitation. The positive correlation between NDVI and temperature showed that vegetation growth in mountain regions is promoted by warmer temperatures. Precipitation is also important in dry regions, such as the Trans-Himalayan region of Nepal, where the average annual precipitation is very low. However, plants show quick responses to temperature but delayed responses to precipitation, indicating that the vegetation growth is most strongly influenced by increasing temperature [72]. Annual and AGS NDVI increased in LNP during 2000-2018, consistent with results from several other parts of world, especially in the northern hemisphere, which have shown increasing trends in NDVI [11,41,49,73].

3.4. Growing Season NDVI Trends in Different Vegetation Type

NDVI increased for all four vegetation types (forest, shrubland, grassland and agriculture) over the 19 years of the study, but the rate of increase varied between the vegetation types (Figure 8; Table 2). The greatest increase was in forest (0.0045 yr\(^{-1}\)), followed by agriculture (0.0044 yr\(^{-1}\)), shrubland (0.0042 yr\(^{-1}\)) and grassland (0.0041 yr\(^{-1}\)). These were all significant (\(p < 0.005\)), except for grassland. The greatest mean annual NDVI was for agricultural land (0.537), followed by shrubland (0.435) and grassland (0.297). At the national scale, forest cover increased after 1990; also, cropland increased by 13% [74]. Human encroachment into the forest was very rapid before 1980, but the forest area has increased after the initiation of the CF development program in 1980. The concept of CF is a globally comprehensive approach to forest management. A study at Dholakha (central Nepal) revealed a significant increase in forest cover following establishment of CF, thereby enhancing ecosystem services such as soil protection and water regulation [75]. In Nepal, the forest resources assessment during 2010-2014 also documented the most extensive coverage of forest and shrubland in Nepal. The relationship between climatic variables and NDVI across the different land-cover types indicates the different responses of vegetation to changes in climate. The correlations between NDVI and temperature were relatively higher than those between NDVI and precipitation over most vegetation types (Table 2): NDVI was correlated strongly with temperature in agriculture, grassland and forest (\(r = 0.51, r = 0.37, r = 0.21\), respectively). A previous study also reported that the growth of forest was strongly correlated with temperature in the growing season [37]. However, in shrubland, NDVI only showed weak correlation with temperature (\(r = 0.008\)). A similar study of NDVI over China [74] showed positive correlation with temperature for all land cover types, which is consistent with this study. Meanwhile, the correlation between NDVI and precipitation was negative for all vegetation types (Table 2). The negative correlation between NDVI and precipitation indicated a potential time lag in their relationship. The annual precipitation at LNP was 340 mm, which is far above the threshold value (the NDVI-precipitation relationship weakens when precipitation falls below 200 mm) [75], and may have affected the increase in NDVI [20].

![Figure 8. Different types of vegetation over LNP during the study period (2000-2018)](image_url)
4. Conclusions

The study presented the temporal and spatial patterns of NDVI changes in LNP (Central Himalayas) between 2000 and 2018. It also examined correlation between NDVI and climatic variables. The main conclusions of the study are as follows.

1. The LNP average AGS NDVI increased by 0.002 yr⁻¹; 30% of the area of LNP showed a significant increase.
2. Overall, NDVI was positively correlated with temperature, but weakly related to precipitation.
3. Results demonstrated that increasing temperature promotes vegetation growth.
4. In the growing season, all vegetation types except grassland showed significant increases in growth.

Although this study presented valuable information about the mountainous ecosystem of Nepal, climatic factors are not the only influences on vegetation. Several ecological factors (for example; solar radiation, soil moisture, and snow melt), which were not considered here, can be assessed in future studies. The climate data (precipitation and temperature) obtained from ERA-5 have low resolution; these should be coupled with ground-based measurements and applied over a larger scale in future research. Recent ecological restorations and environmental changes have contributed positively to the expansion of greenery (12%) in LNP, which may benefit the habitats of herbivorous animals across this region. The present research contributes to the understanding of vegetation growth in mountainous ecosystems. Understanding the relationship between climate and long-term NDVI improves our scientific knowledge of mountain ecosystems which are very sensitive to climate change.

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References


Table 2. Growing season mean, trend, relative ratio and correlation coefficients between NDVI and temperature ($R_t$), precipitation ($R_p$) in LNP from 2000-2018

<table>
<thead>
<tr>
<th>Vegetation type</th>
<th>Annual mean</th>
<th>Trend (yr⁻¹)</th>
<th>Relative trend (%)</th>
<th>$R_t$-NDVI</th>
<th>$R_p$-NDVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>0.487</td>
<td>0.0045</td>
<td>17.55</td>
<td>0.21</td>
<td>-0.13</td>
</tr>
<tr>
<td>Shrubland</td>
<td>0.435</td>
<td>0.0042</td>
<td>18.34</td>
<td>0.008</td>
<td>-0.27</td>
</tr>
<tr>
<td>Grassland</td>
<td>0.297</td>
<td>0.0041</td>
<td>26.22</td>
<td>0.37</td>
<td>-0.21</td>
</tr>
<tr>
<td>Agriculture areas</td>
<td>0.537</td>
<td>0.0044</td>
<td>15.9</td>
<td>0.51</td>
<td>-0.03</td>
</tr>
</tbody>
</table>

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