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Spatial-Temporal NDVI Variation of Different Alpine Grassland Classes and Groups in Northern Tibet from 2000 to 2013

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The Normalized Difference Vegetation Index (NDVI) can usually be used as a good proxy for evaluating potential variability in regional ecosystems and under climate change. We used 16-day MODIS-NDVI composite satellite data with 250-m resolution for the period 2000 to 2013 to assess the temporal and spatial variation of the NDVI among different alpine grassland classes and groups in northern Tibet. The annual average NDVI of the whole alpine grassland area in northern Tibet generally increased slightly from 2000 to 2003, and the annual average NDVI values ranged from 0.112 to 0.492 across all alpine grassland groups and years. The NDVI clearly decreased from the southeastern to the northwestern areas, with 22.50% of total grasslands significantly having increased or decreased, while 77.50% presented little change during 2000–2013. Both temperature and precipitation were key factors that controlled the NDVI variations of the entire alpine grassland. However, for different alpine grassland classes and groups, the NDVI displayed different correlation patterns with temperature and precipitation. Our results demonstrate that the NDVI variations of alpine grassland generally increased slightly but differed among different classes and groups. Although temperature and precipitation were the driving forces influencing the NDVI of the entire alpine grassland, it was more difficult to define the driving forces for the individual classes and groups, and more detailed analyses covering prolonged observation periods are still needed.

Keywords: *Normalized Difference Vegetation Index (NDVI); alpine grassland; precipitation; temperature; northern Tibet.*

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Introduction

Green vegetation cover is a significant component of terrestrial ecosystems and plays an important role in sustaining the planet's habitability for humans (Aguilar et al 2012). The Normalized Difference Vegetation Index (NDVI)—a popular indicator of green coverage and vegetation growth—has been widely used to assess the spatiotemporal characteristics of vegetation in ecological studies, including to quantify and map green vegetation with the goal of estimating net primary productivity, phenological changes, vegetation cover, and other landscape-level fluxes (Butt et al 2011; Cong et al 2012; Chen et al 2013). The NDVI can be exploited because of the striking differences in spectral reflectance between the red and near-infrared wavelengths (Bremer et al 2011). It is not only a distinct biophysical phenomenon but is also influenced by environmental factors such as climatic variables (Revadekar et al 2012). The NDVI can also be used to assess coupled climate and vegetation distribution at a large spatial and temporal scale because it captures seasonal dynamics throughout the growing season (Holm et al 2003; Gu et al 2013).

On a global scale, studies have focused on examining the annual, seasonal, and geographical distribution of global vegetation trends and their correlations with climatic factors. In general, the monthly timing of NDVI variables is found to be closely associated with seasonal patterns in maximum and minimum temperature, as well as precipitation (Los et al 2001; Sen Roy and Yuan 2007). More specifically, temperature has been found to be the primary climatic factor associated with greening in the northern high latitudes (Zeng et al 2013), whereas precipitation has been shown to be a strong correlate of vegetation growth in fragmented or arid regions (Wang et al 2010). Using the NDVI has made it possible to show that in some temperate and cool temperate regions, vegetation dynamics are limited by both precipitation and temperature (Suzuki et al 2001; Sen Roy and Yuan 2007). In addition, in mountainous areas the NDVI variables have been found to present a clear gradient from the lowlands to the alpine regions, corresponding to the decreasing gradient of mean air temperature along with the increase in altitude (Karlsen et al 2008).

Alpine ecosystems—which are believed to be exposed to a rate of warming that is higher than the global mean warming level—are highly sensitive and fragile (Lu et al 2013). Alpine grassland is the dominant ecosystem on the Tibetan Plateau, occupying about two-thirds of the total Tibetan Plateau (Cui and Graf 2009). It is a particularly sensitive ecosystem, and many studies have used the NDVI to examine spatiotemporal variations of vegetation and their relationships with climatic variables here as well (Immerzeel et al 2005). A 1982 to 1999 NDVI time series of alpine grassland on the Tibetan Plateau has demonstrated a positive trend ascending by a magnitude of 0.001 per year and a ratio of 0.41% per year during the growing season (Yang and Piao 2006). The NDVI of alpine grassland also presents very strong seasonal cycles and interannual variations (Cai et al 2014). However, the spatial distribution of NDVI interannual dynamics is different: A remarkable decrease in the NDVI was observed in the eastern sector and an increase in the central and eastern sector, whereas little change was observed in the western and northwestern sectors over the last 2 decades of the 20th century (Ding et al 2007; Sun et al 2013). In addition, precipitation has been found to be the main climatic factor that affected the vegetation cover; by comparison, a weak correlation between the NDVI and temperature has been observed over the entire Tibetan Plateau (Sun et al 2013).

Due to the ecological significance of the region, the number of NDVI studies of the Tibetan Plateau has been increasing. Until now studies have focused on taking the alpine grassland of the Tibetan Plateau as a whole to study seasonal, interannual, and annual variations and their responses to climate factors (Sun et al 2013; Zhang et al 2007). Little research has been carried out to study the NDVI dynamics of different vegetation types, especially at fine scales, in the alpine grassland ecosystem. The present study analyzes spatial-temporal NDVI variations of different alpine grassland types (composed of a total of 5 classes and 14 groups) in northern Tibet from 2000 to 2013 and assesses the relationship between these dynamics and climate factors. Accordingly, the objectives of this study were (1) to explore the temporal and spatial NDVI patterns of the alpine grassland ecosystem in northern Tibet; (2) to compare the annual NDVI dynamics among different classes and groups of alpine grassland; (3) to investigate the relationships between the temporal NDVI patterns of different alpine grassland types and climatic factors, that is, temperature and precipitation; and (4) to identify the main environmental limiting factors that affect NDVI dynamics.

Data and methods

Study area

Northern Tibet (29°56′–36°30′N, 85°03′–95°03′E) is located between the Tibetan Gangdise Mountains and the northern part of the Nyainqentanglha Range and has an average elevation more than 4500 m above sea level (Figure 1). This area is located in a cold and semiarid plateau; it is a monsoon climate region with dryness and coldness as prominent climatic features. The annual open water evaporation (measured using an evaporating dish) increases from 1500 mm in the southeast to 2300 mm in the northwest. High-altitude western wind currents are strong in spring and winter, and gales above force 7 are frequent (with some gales as strong as 10–12). Annual sunshine in this region is between 2400 and 3200 h, declining progressively from west to east. On account of its high elevation and clean air, the region receives adequate solar energy. The total annual solar radiation is as high as 6000 MJ/m^2, with the highest value reaching 6800 MJ/m^2 in the west (Zhang et al 2007; Gao et al 2013). The average annual temperature is rather low, with a large diurnal range, and varies from −6.8°C to 1.4°C. The average annual precipitation decreases from east to west and from south to north, ranging from 196 to 784 mm. Alpine grassland, which occupies approximately 94.4% of the total area in northern Tibet, is not only the most important and largest ecosystem in the area but also a key resource supporting the local people's subsistence (Gao et al 2009, 2013; Lu et al 2012).

Data

A NDVI time series of satellite images at 250-m spatial and 16-day temporal resolution, covering a period from 2000 to 2013 and produced by MODIS NDVI, were acquired from http://ladsweb.nascom.nasa.gov/data/search.html. We acquired 5 MODIS tiles (h24v05, h25v05, h25v06, h26v05, and h26v06) for our study region. The MODIS tiles were mosaicked and reprojected from a Sinusoidal projection to an Albers projection. Subset images for the study region were clipped from the mosaicked tiles using the northern Tibet boundary. Monthly growing season images were generated by the maximum NDVI value composite method using the two 16-day composites for each month (Hashimoto et al 2012). Mean growing season images were derived by averaging the monthly NDVI images covering May to September each year for a time-series analysis. Then we extracted the mean NDVI values from all pixels within each grassland type for further analysis (Li et al 2013).

The meteorological datasets with spatial resolutions of 0.5° (SURF_CLI_CHN_PRE_MON_GRID_0.5 and SURF_CLI_CHN_TEM_MON_GRID_0.5) for 2000–2013 were derived from the China Meteorological Data Sharing Service System (CMDSS, http://cdc.nmic.cn). These meteorological gridded datasets were generated by

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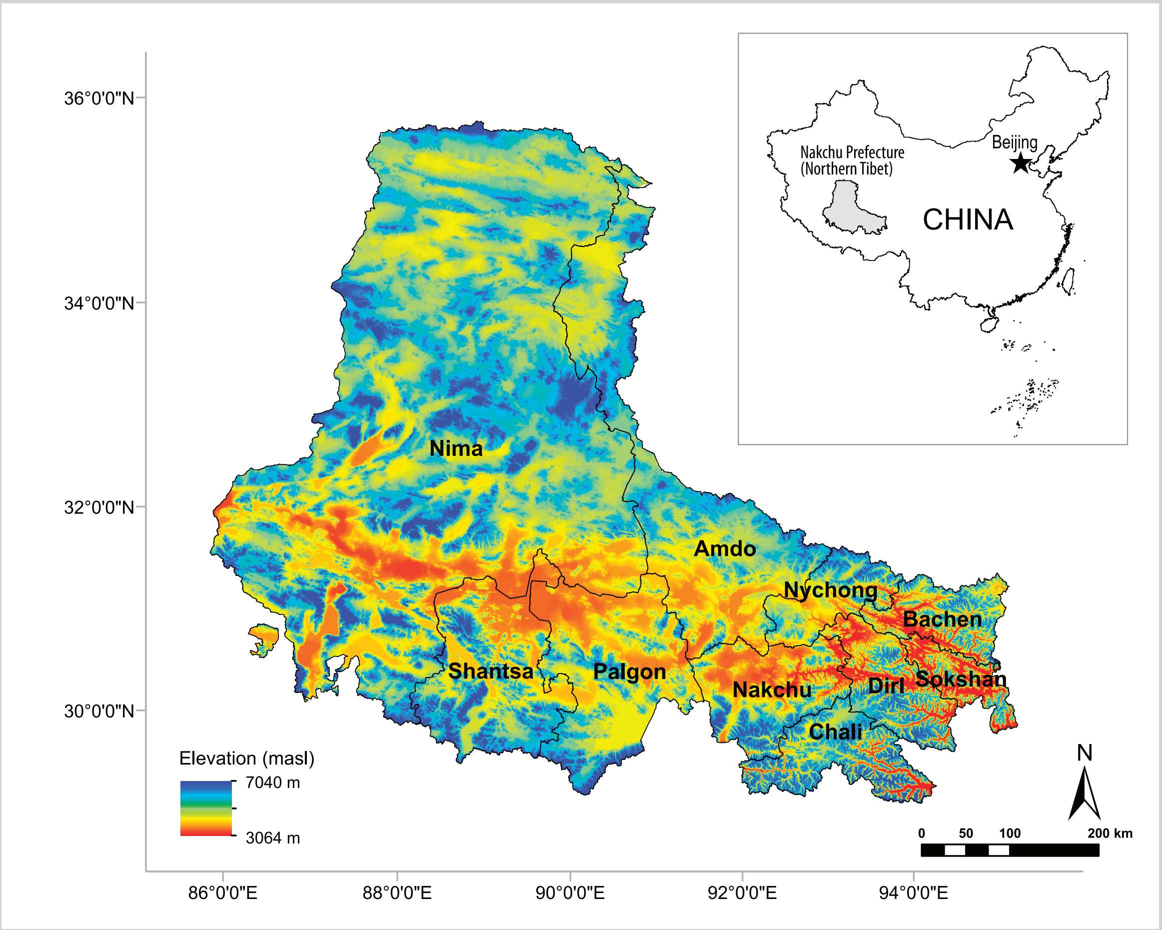
FIGURE 1 Topography (elevation in masl), geographical location, and counties of northern Tibet (Nakchu Prefecture). (Map by Xiaoke Zhang)



the Thin Plate Spline method using ANUSPLIN software; the data sources include mean monthly temperature and monthly precipitation data from more than 2400 well-distributed climate stations across China, as well as digital elevation model data (Shi et al 2014). Thus, both region and altitude effects were considered in these climate datasets, and a goodness of fit of the interpolated values was validated by CMDSSS (Shi et al 2014). To match a spatial resolution of 250 m × 250 m, the meteorological gridded datasets were downscaled by ordinary kriging spatial interpolation using the ArcGIS 10.0 software (Zhou and Zhang 2014). In addition, the growing season temperature (GST) and growing season precipitation (GSP) were defined as the average air temperature and the accumulated precipitation during the growing season of alpine grasslands from May to September (Cao et al 2004; Zhao et al 2006) (Figure 2).

Grassland classification data for northern Tibet were obtained from the Grassland Resources of the Tibet Autonomous Region (Su et al 1994). These consisted of 5 classes from the southeast to northwest—alpine meadow, alpine meadow steppe, alpine steppe, alpine desert steppe, and alpine desert—and 14 groups (Figure 3). Groups include medium grasses, short grasses, short sedges, tall sedges, forbs, subshrub sagebrush, and subshrub. The dominant groups belong to *Cyperaceae* and *Gramineae*, with *Leguminosae* and others occurring as the subdominants.

Statistical analyses

To minimize the influence of soil on vegetation in sparsely vegetated regions, we chose areas with a multiyear average NDVI greater than 0.1 (Yang and Piao 2006). Pearson's correlation coefficient was used to reveal the long-term variations of alpine grassland NDVI. It is a correlation coefficient between the alpine grassland mean growing season NDVI x_i and the natural sequence 1, 2, 3 … , t, at a given time n. A positive or negative value of R_{xy} predicts a linear increasing or decreasing trend of alpine grassland NDVI within the given time. If R_{xy} passes a significance test ($P < 0.05$), it shows a "significant"

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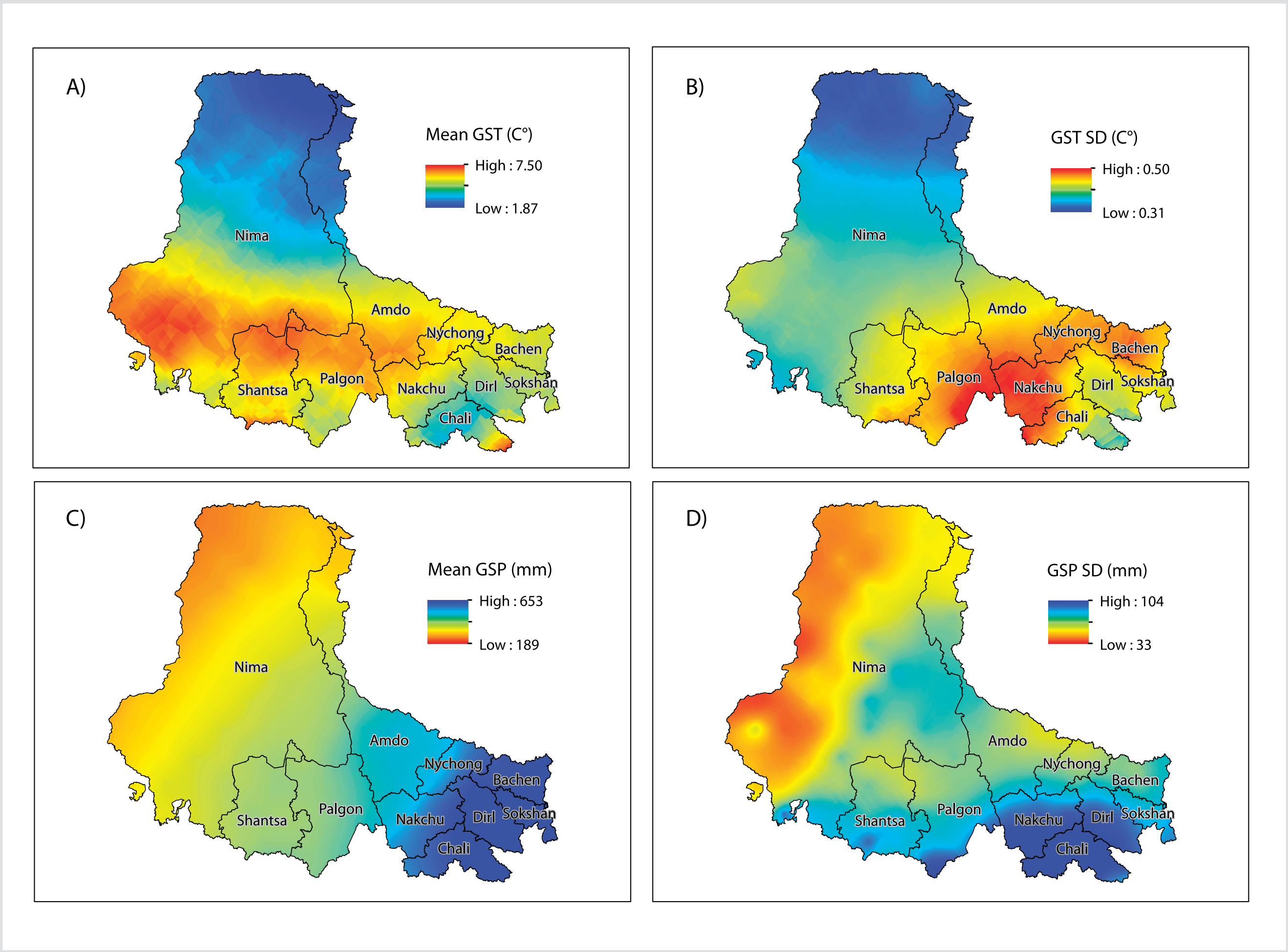
FIGURE 2 Spatial distributions of average values (A, C) with standard deviations (B, D) of growing season temperature (GST) and growing season precipitation (GSP) from 2000 to 2013 in northern Tibet.



ascending or descending trend (Piao and Fang 2001; Gao et al 2009):

$$R_{xy} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(i - \bar{t})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (i - \bar{t})^2}}. \quad (1)$$

Using bivariate analysis, Pearson's correlation coefficients were computed at the 95% confidence level ($P = 0.05$) and the 99% confidence level ($P = 0.01$) to test the strength of the linear association between datasets (precipitation, temperature) and NDVI. The statistical analyses were conducted using ArcGIS 10.0, ENVI 4.8, SPSS 17.0, and Origin 9.0.

Results

Temporal patterns of NDVI in northern Tibet

The average annual NDVI of all the alpine grasslands in northern Tibet generally increased slightly from 2000 to 2013 (Figure 4A). The average annual NDVI values showed annual variations ranging from 0.112 to 0.492 across all alpine grassland groups and years (Table 1). The maximum annual average NDVI value was 0.477 (for the tall sedges group in the meadow subclass in the alpine meadow class), and the minimum annual average NDVI value was 0.117 (for the subshrub group in the alpine desert class) (Table 1).

The different alpine grassland classes and groups show different variation trends in the period 2000–2013 (Table 1). Alpine meadow and alpine steppe were the main types of grassland and included a number of different groups. In the meadow subclass of alpine meadow, the NDVI of tall sedges presented a significant decreasing trend ($P < 0.05$), the NDVI of forbs a significant increasing trend ($P < 0.05$), and the variations in NDVI of subshrub, short sedges, and medium grasses were not significant. For swamp meadow and salinized meadow, the NDVI of short sedges in salinized meadow increased significantly ($P < 0.01$), but that variation of short sedges in swamp meadow was not

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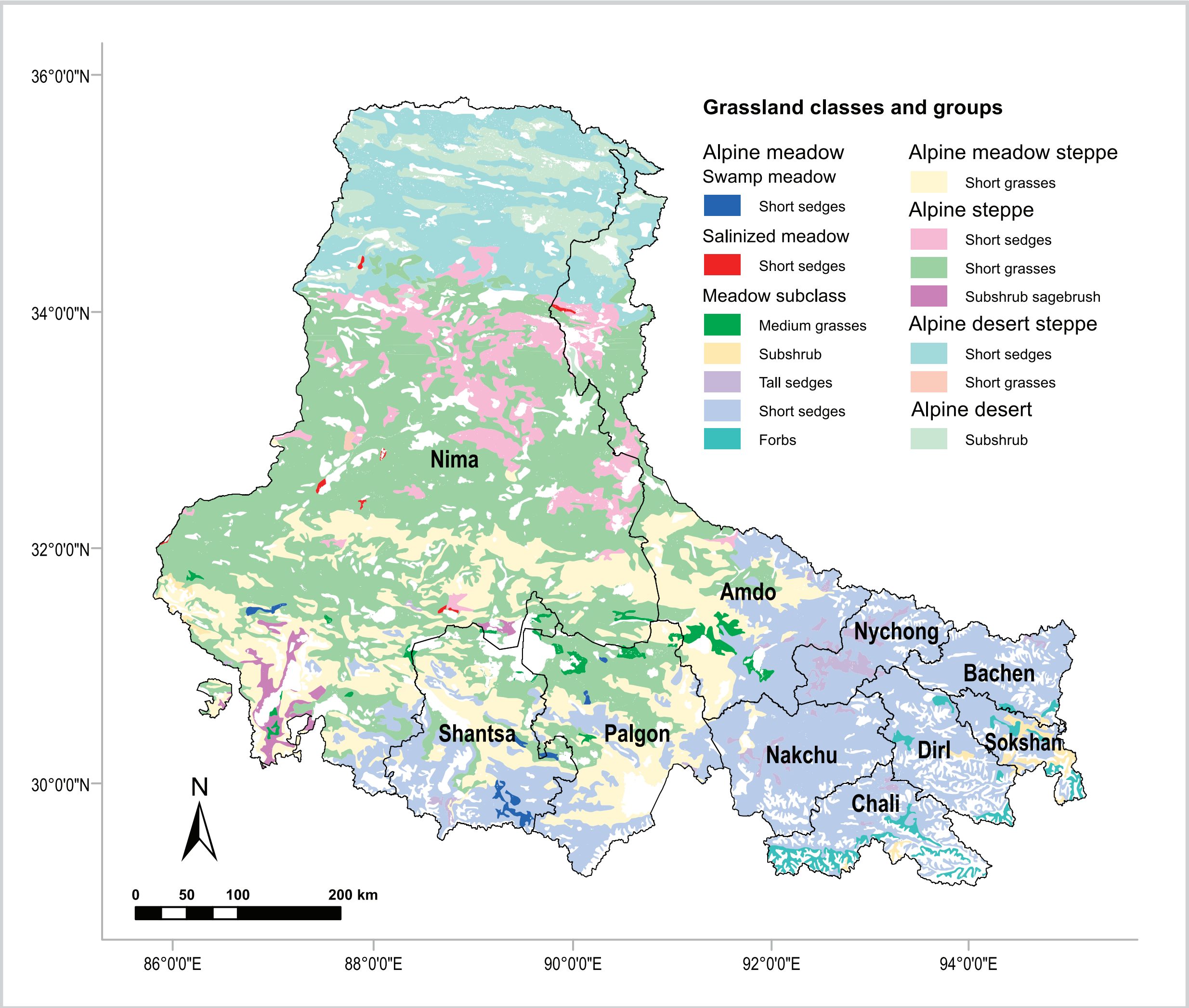
FIGURE 3 Spatial distribution of alpine grassland classifications and groups in northern Tibet.



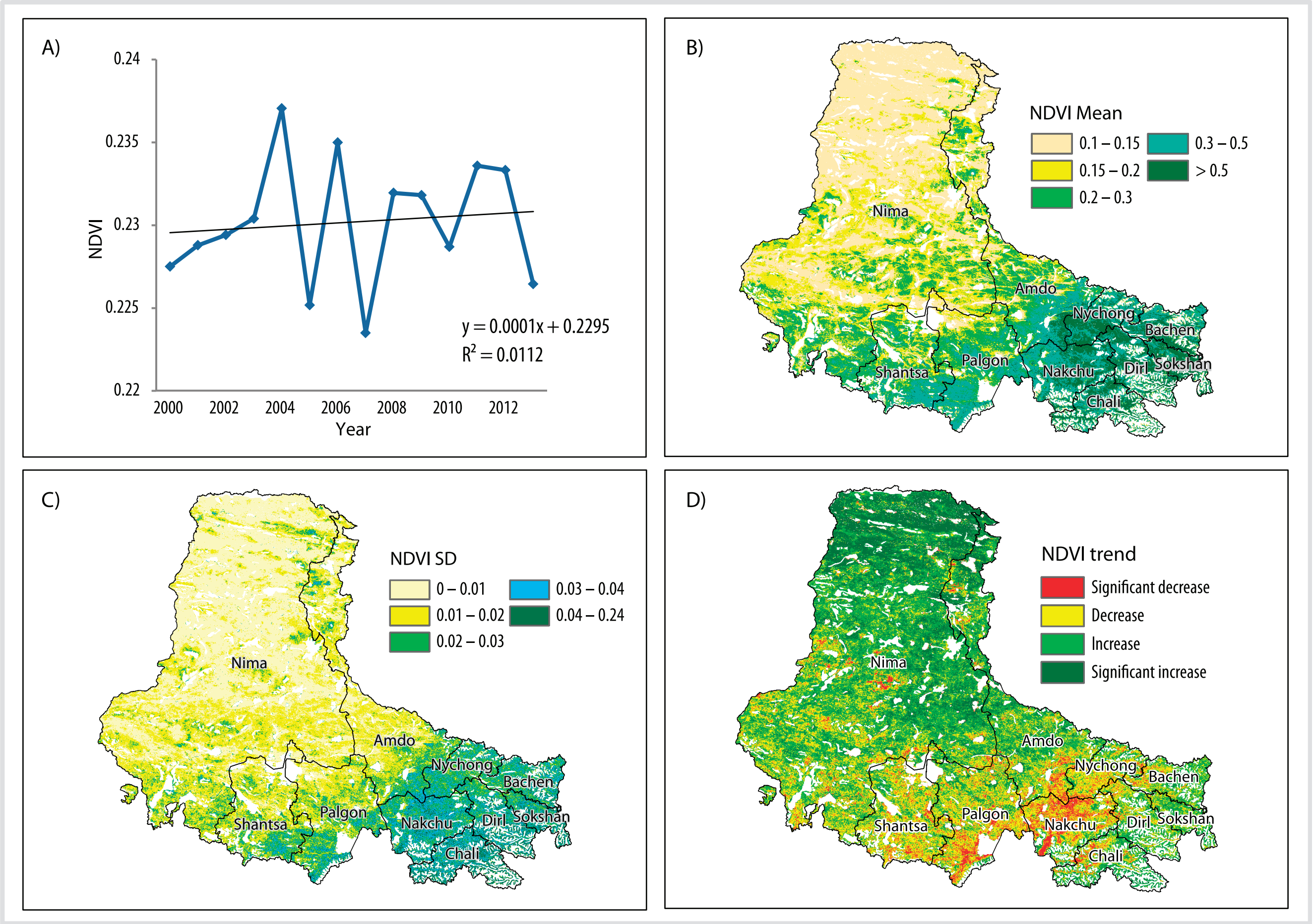
obvious. The NDVI of alpine steppe showed a different pattern, with only the NDVI of short sedges showing a significant increase with a variation coefficient of 0.597 ($P < 0.05$), while the NDVI of the other two groups of alpine steppe, including subshrub sagebrush and short grass, remained largely unchanged (Table 1).

Alpine meadow steppe is the transitional alpine grassland type between alpine meadow and alpine steppe, and the NDVI of short grasses changed little in the period 2000–2013, with a minor variation coefficient of −0.159 (Table 1). For alpine desert, the variation coefficient of subshrub was 0.860, representing a significant ascending trend ($P < 0.01$). The NDVI of short sedges in alpine desert steppe was similar to that of subshrub of alpine desert: It increased significantly, with a variation coefficient of 0.767 ($P < 0.01$), but the NDVI of short grasses in alpine desert steppe remained largely unchanged (Table 1).

Spatial patterns of NDVI in northern Tibet

The distribution of mean annual NDVI in alpine grassland in northern Tibet gradually decreased from the southeast to the northwest (Figure 4B–4D) and was generally consistent with the regional spatial distribution of temperature and precipitation (Figure 2). During the period 2000–2013, the average annual NDVI for all alpine grasslands in northern Tibet was 0.232, reached 0.859 in the southeast, and decreased to 0.100 in the northwest (Figure 4B). For the eastern parts, including Chali, Dirl, Sokshan, Nyrong, and Bachen counties, the NDVI of alpine grassland was higher than for the other areas, with the multiyear average values greater than 0.500. The middle areas, including Nakchu, south of Amdo and Palgon counties, ranked second, with a multiyear average NDVI from 0.300 to 0.500. The western parts, which cover Shansta and the south of Nima counties, were third with a multiyear average NDVI from 0.200 to 0.300. The vast

FIGURE 4 (A) Annual variation trend of the annual average NDVI from 2000 to 2013 in northern Tibet, and spatial distributions of annual average values (B) with standard deviations (C), and interannual variation trends (D) of alpine grassland NDVI in the growing season.



northern parts of Nima and Amdo counties presented the lowest multiyear average NDVI, that is, less than 0.200 (Figure 4B).

The NDVIs of most alpine grasslands did not present significant variations during the period 2000–2013, accounting for 77.50% of alpine grasslands in this region (Figure 4D). The remaining 22.50% exhibited a significant variation, of which 16.44% showed a significant increasing trend that was mainly distributed in the northwest of northern Tibet, and 6.06% showed a significant decreasing trend that was mainly distributed in the southeast of northern Tibet. Especially in Nakchu County, the significant decrease was in an area of 4326.5 km^2 and covered most of the total significant decreasing area in northern Tibet (Figure 4D).

Relationship between NDVI and climatic factors in northern Tibet

The NDVI variations of all alpine grasslands in northern Tibet were positively correlated with both GST and GSP ($P < 0.01$; Table 2). Nevertheless, alpine grassland classifications showed different correlation patterns with GST and GSP. The NDVI variation of alpine meadow was positively correlated with GSP ($P < 0.01$), the NDVI variations of alpine steppe and alpine desert were positively correlated with GST ($P < 0.05$), and the NDVI variations of alpine meadow steppe were significantly negatively correlated with GST ($P < 0.05$). No correlations were found between the NDVI variations of alpine desert steppe and GST or GSP ($P > 0.05$) (Table 2).

The correlation coefficients between growing season NDVI and climatic variables also differed for the different alpine grassland groups (Table 2). The interannual dynamic in the NDVI of subshrub and forbs in the meadow subclass, short sedges of the alpine desert steppe, and subshrub of the alpine desert were generally consistent with the variation in GST, and all exhibited significant positive correlation with GST ($P < 0.05$). By contrast, the NDVI variations of short grasses in the alpine meadow steppe and subshrub sagebrush in the alpine steppe were found to be negatively correlated with

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TABLE 1 NDVI values and annual variation coefficients of alpine grassland classes and groups from 2000 to 2013 in northern Tibet. $*P < 0.05$, $**P < 0.01$.

Alpine grassland types			Area ($\times 10^3$ km^2)	Average	Maximum	Minimum	Variation coefficient
Alpine meadow	Meadow subclass	Subshrub	1.78	0.469	0.489	0.457	0.425
		Tall sedges	3.23	0.477	0.492	0.449	–0.557*
		Short sedges	70.49	0.427	0.449	0.403	–0.379
		Forbs	3.29	0.213	0.218	0.204	0.573*
		Medium grass	2.66	0.401	0.415	0.384	0.107
	Swamp meadow	Short sedges	0.93	0.354	0.373	0.335	–0.325
	Salinized meadow	Short sedges	0.29	0.153	0.165	0.143	0.847**
Alpine meadow steppe		Short grass	48.84	0.228	0.235	0.216	–0.159
Alpine steppe		Subshrub sagebrush	2.32	0.195	0.207	0.184	–0.164
		Short sedges	16.31	0.145	0.151	0.138	0.597*
		Short grass	105.63	0.166	0.172	0.161	0.364
Alpine desert steppe		Short grass	32.04	0.123	0.131	0.113	–0.044
		Short sedges	0.29	0.125	0.134	0.118	0.767**
Alpine desert		Subshrub	0.14	0.117	0.122	0.112	0.860**

GST ($P < 0.05$). The other groups were not significantly related to GST. No significant correlations were found between the NDVI variations of any grassland group and GSP ($P > 0.05$) (Table 2).

Discussion

NDVI variation in northern Tibet

The NDVI of alpine grasslands generally appeared to have an increasing trend in northern Tibet during the period 2000–2013 (Figure 4A). This seems to confirm the findings of studies on NDVI time series over the whole Tibetan Plateau during the last two decades, which demonstrated a positive trend during the growing season (Mao et al 2007; Xu et al 2008; Zhao et al 2009).

NDVI variations in the growing season differed for the various alpine grassland classes and groups. The NDVI dynamics of alpine meadow and alpine meadow steppe exhibited interannual fluctuations and a decreasing trend, whereas alpine steppe, alpine desert steppe, and alpine desert present an increasing trend (Table 1). These results seem to contradict recent studies that found that the net primary production of alpine meadow and alpine steppe increased and that of the alpine desert decreased from 1982 to 2010 in alpine grassland over the whole Tibetan Plateau (Ding et al 2010; Zhang et al 2014b); they are also inconsistent with a study that found that the NDVI of alpine meadow and alpine desert decreased and that of alpine steppe increased from 1981 to 2001 in northern Tibet (Zhang et al 2007). These inconsistent results may be due to the different location and the time between our study and the others. The variation between alpine grassland groups is difficult to compare with other studies because no related research has focused on alpine grassland groups on the Tibetan Plateau until now. A comparison with NDVI dynamics in other mountain and alpine regions shows that they also exhibited different variations among different types of alpine ecosystems (Agrawal et al 2003; Dirnböck et al 2003; Alcaraz-Segura et al 2008; Gomez-Giraldez et al 2014).

With regard to the spatial distribution of the NDVI interannual variations, 77.50% of the alpine grasslands in northern Tibet did not present significant variations from 2000 to 2013; 22.50% of alpine grasslands exhibited significant variations, with 16.44% showing a significantly increasing trend and 6.06% a significantly decreasing one (Figure 4D). This is generally in agreement with previous reports that found that areas with no or little change in NDVI accounted for 77.27% of the total area of northern Tibet, whereas areas that showed significantly decreasing

TABLE 2 Pearson's correlation coefficients (r) between the NDVI of alpine grassland classifications and groups and climate factors, including growing season temperature (GST) and growing season precipitation (GSP). $*P < 0.05$, $**P < 0.01$.

Alpine grassland types			GST	GSP
Alpine meadow	Meadow subclass	Subshrub	0.635*	−0.028
		Tall sedges	−0.332	0.107
		Short sedges	−0.113	−0.047
		Forbs	0.761**	−0.307
		Medium grasses	−0.337	−0.012
	Swamp meadow	Short sedges	−0.486	0.278
	Salinized meadow	Short sedges	0.338	0.436
	Total		**−0.022**	**0.701****
Alpine meadow steppe		Short grasses	−0.659*	0.177
Alpine steppe		Subshrub sagebrush	−0.646*	0.365
		Short sedges	0.352	0.002
		Short grasses	−0.105	−0.052
		Total	0.890**	0.114
Alpine desert steppe		Short grasses	−0.317	0.084
		Short sedges	0.552*	0.167
		Total	−0.121	−0.170
Alpine desert		Subshrub	0.650*	0.296
Total alpine grassland			**0.443****	**0.824****

and increasing NDVI values accounted for 22.73% (Zhang et al 2007). Nevertheless, the area distribution of significant variations in NDVI differ between the two studies: while ours shows that a significantly increasing area was distributed in the northwest and a significantly decreasing area was distributed in the southeast, Zhang et al (2007) found that both significantly increasing and decreasing areas were distributed in the southeast.

The driving force of NDVI variation in northern Tibet

The dominant climatic factor influencing NDVI was not the same for different alpine grassland classes. The GSP was the key factor that influenced the NDVI variations of alpine meadow, while the GST was the key factor that influenced the NDVI variations of alpine meadow steppe, alpine steppe, and alpine desert (Table 2). Ding et al (2007) also found a good relationship between NDVI and precipitation in alpine meadow and a small effect of precipitation on vegetation in the desert area. However, Chen et al (2012) considered that the limiting factor was precipitation west of the 450-mm rainfall line, whereas east of the 450-mm rainfall line, temperature was the dominating factor for vegetation growth from 1982–1999. According to Sun et al (2013), in general, over the entire Tibetan Plateau both precipitation and temperature affects NDVI, but precipitation is the main climatic factor that affects the vegetation cover.

For different alpine grassland groups, the increasing temperature contributing to humid weather is a favorable condition for grassland growth (Table 2); by contrast, warming trends in arid conditions or conditions of insufficient rainfall lead to drought, which does not allow vegetation cover to increase (Xu et al 2008). The short grasses in alpine meadow steppe and subshrub sagebrush of the alpine steppe in these regions are sensitive to precipitation and vulnerable to climate warming, and the warm-dry climate decreases the alpine grassland NDVI (Chen et al 2014; Qin et al 2014). By contrast, in our study subshrub and forbs in alpine meadow exhibited a significant positive correlation with GST. The reason is that in a water-sufficient condition, rising temperatures can cause a continuous advancing trend (Zhang et al 2013) and increase the photosynthetic rate as well as prolong the growth season and improve nutrient utilization (Piao et al 2006; Sardans et al 2008). Therefore, the driving force of NDVI variations for northern Tibet is quite different among alpine grassland types and times.

Some alpine grassland groups, such as the tall sedges and short sedges of the alpine meadow as well as short grass and short sedges of the alpine steppe—the main

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species in alpine meadow and alpine steppe—did not exhibit a significant correlation with temperature and precipitation. Perhaps anthropogenic activities (land use changes, overgrazing) and some grassland policy measures might have interactively altered the alpine grassland ecosystems in the plateau, either improving or deteriorating grassland conditions (Zhang et al 2014a). Further ecoclimatological factors such as solar radiation, soil water content, and snow melt were not explored in this study but may also account for the variability in grassland growth (Alcaraz-Segura et al 2008; Zhong et al 2010; Gomez-Giraldez et al 2014). In addition, the time coverage of approximately 14 yr was relatively short. In future, rising trends for precipitation and temperature may continue in northern Tibet, and the aridity indices could show a decreasing trend, which could boost vegetation growth (Gao et al 2014). Therefore, further analysis is imperative to better understand the driving forces of NDVI variation.

Conclusions

This study assessed the temporal and spatial changes in alpine grassland NDVIs and analyzed the relationship between NDVI variations and climatic factors. In general, the NDVI appeared to show a slightly increasing trend in alpine grassland and the annual average NDVI values for alpine grassland ranged from 0.112 to 0.492 across all alpine grassland groups and years. The NDVI variations of forbs in the meadow subclass, short sedges in salinized meadow, alpine steppe, and alpine desert steppe, and subshrub in alpine desert presented significant increasing trends, while the NDVI variations for tall sedges in the meadow subclass presented a significant decreasing trend. The other groups presented little variation in trends.

The NDVIs of alpine grassland in northern Tibet clearly decreased from the southeastern to the northwestern areas and were consistent with the changes in the vegetation zone and climate patterns. The alpine grasslands with a significant variation of mean growing season NDVI accounted for 22.50% of the total grasslands in northern Tibet, with 16.44% showing a significantly ascending trend and only 6.06% indicating a significantly descending trend. The other 77.50% of alpine grasslands had insignificantly descending or ascending NDVI values.

For the entire alpine grassland of northern Tibet, both temperature and precipitation were the key factors that controlled the NDVI variations, but precipitation played a more critical role. For different alpine grassland classifications and groups, the driving force influencing NDVI was complicated and varied. Precipitation was the key factor that influenced the NDVI variations of alpine meadow, while temperature was the key factor that influenced the NDVI variations of alpine meadow steppe, alpine steppe, and alpine desert. Temperature was also the key factor that controlled the NDVI of some alpine grassland groups, including subshrub and forbs in the meadow subclass, short sedges of alpine desert steppe, and subshrub of alpine desert, short grasses in alpine meadow steppe, and subshrub sagebrush of alpine steppe. In addition, some groups exhibited no correlation with temperature and precipitation. Therefore, to improve our understanding of ecosystems in the region and better relate them to acquired meteorological data in the study region, a more detailed analysis between vegetation growth and climate change is still needed.

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