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Spatial and temporal variability in the net primary production of alpine grassland on the Tibetan Plateau since 1982

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Abstract: Based on the GIMMS AVHRR NDVI data (8 km spatial resolution) for 1982–2000, the SPOT VEGETATION NDVI data (1 km spatial resolution) for 1998–2009, and observational plant biomass data, the CASA model was used to model changes in alpine grassland net primary production (NPP) on the Tibetan Plateau (TP). This study will help to evaluate the health conditions of the alpine grassland ecosystem, and is of great importance to the promotion of sustainable development of plateau pasture and to the understanding of the function of the national ecological security shelter on the TP. The spatio-temporal characteristics of NPP change were investigated using spatial statistical analysis, separately on the basis of physico-geographical factors (natural zone, altitude, latitude and longitude), river basin, and county-level administrative area. Data processing was carried out using an ENVI 4.8 platform, while an ArcGIS 9.3 and ANUSPLIN platform was used to conduct the spatial analysis and mapping. The primary results are as follows: (1) The NPP of alpine grassland on the TP gradually decreases from the southeast to the northwest, which corresponds to gradients in precipitation and temperature. From 1982 to 2009, the average annual total NPP in the TP alpine grassland was 177.2×10^{12} gC yr^{-1}(yr represents year), while the average annual NPP was 120.8 gC m^{-2} yr^{-1}. (2) The annual NPP in alpine grassland on the TP fluctuates from year to year but shows an overall positive trend ranging from 114.7 gC m^{-2} yr^{-1} in 1982 to 129.9 gC m^{-2} yr^{-1} in 2009, with an overall increase of 13.3%; 32.56% of the total alpine grassland on the TP showed a significant increase in NPP, while only 5.55% showed a significant decrease over this 28-year period. (3) Spatio-temporal characteristics are an important control on annual NPP in alpine grassland: a) NPP increased in most of the natural zones on the TP, only showing a slight decrease in the Ngari montane desert-steppe and desert zone. The positive trend in NPP in the high-cold shrub-meadow zone, high-cold meadow steppe zone and high-cold steppe zone is more significant than that of the high-cold desert zone; b) with increasing altitude, the percentage area with a positive trend in annual NPP follows a trend of

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"increasing-stable-decreasing", while the percentage area with a negative trend in annual NPP follows a trend of "decreasing-stable-increasing", with increasing altitude; c) the variation in annual NPP with latitude and longitude co-varies with the vegetation distribution; d) the variation in annual NPP within the major river basins has a generally positive trend, of which the growth in NPP in the Yellow River Basin is most significant. Results show that, based on changes in NPP trends, vegetation coverage and phonological phenomenon with time, NPP has been declining in certain places successively, while the overall health of the alpine grassland on the TP is improving.

Keywords: Tibetan Plateau; net primary production; CASA model; spatio-temporal patterns; NPP trends

1 Introduction

Grassland ecosystems are a vital component of the terrestrial ecosystem and an important human resource. Net primary production (NPP) refers to the amount of dry organic matter produced by plants per unit time and per unit area, which is a key link in the biogeochemical cycle. NPP is an important index of ecosystem function (Melillo *et al*., 1993; Running *et al*., 2004; Shvidenko *et al*., 2008; Crabtree *et al*., 2009) and a key element in the carbon cycle (Crabtree *et al*., 2009; Piao *et al*., 2011; Zhao and Running, 2010), reflecting the integrated effects of climate change and human activities on terrestrial vegetation. Research into ecosystem NPP, especially on a regional scale, has attracted much scholarly attention and much progress has been made in recent years (Cramer *et al*., 1999; Del *et al*., 2008). The results of many of these studies indicate a generally positive trend in NPP, likely due to a warming climate, increased nitrogen deposition and CO_2 fertilization (Piao *et al*., 2011; Nemani *et al*., 2003). This is in contrast to other studies, which show decreasing trends in NPP and loss of vegetation in some areas due to increased aridity and overgrazing (Zhao and Running, 2010; Zhou *et al*., 2008). However, at present the spatial pattern of NPP change and the direction of change with time remains an understudied topic.

The Tibetan Plateau (TP) alpine grassland covers an area of about 1.525×10^6 km^2, accounting for 59.28% of the total area of the TP, and is one of the most important pastoral areas in China, and indeed Asia as a whole (Zhang *et al*., 2002). Consideration of ecosystem changes in the TP alpine grassland encompasses the ecological and environmental conditions, the social and economic development in local and peripheral areas, and the function and effect of the national ecological security shelter zone (Sun *et al*., 2012). In recent years, there have been many studies into alpine grassland NPP on the TP (Zhou *et al*., 2004; Piao *et al*., 2006; Gao *et al*., 2007a), most of the research focusing on local areas (Zhou *et al*., 2008; Guo *et al*., 2007; Qin *et al*., 2010), but a few studies involved in the entire plateau (Zhou *et al*., 2004; Piao *et al*., 2006; Liu *et al*., 2011). The time scale of these studies ranges from several years (Zhou *et al*., 2004; Liu *et al*., 2011; Zhao, 2011) to 20 years in duration (Piao *et al*., 2006; Qin *et al*., 2010; Du *et al*., 2010). The models used to estimate NPP can be divided into three broad types: 1) the traditional experience model, such as the Chikugo model (Qin *et al*., 2010); 2) the eco-physiological process models, such as TEM (Zhou *et al*., 2004) and BIOME-BGC (Guo *et al*., 2006); and 3) the remote sensing light utilization efficiency models, such as 3-PGS (Liu *et al*., 2011), NPP-EMSC (Zhao, 2011), GLOPEM (Du *et al*., 2010) and CASA (Zhou *et al*., 2008; Piao *et al*., 2006; Gao *et al*., 2007a; Gao *et al*., 2007b; Ke *et al*., 2003). Some NPP estimation models have been revised and improved in the studies of Zhou *et al*. (2004, 2008) and Qin *et al*. (2010). This research has laid a solid foundation for clarifying the patterns and cause of variations in alpine grassland NPP on the TP, and has made an important contribution to the data analysis, model parameter adjustment and ground-based verification of NPP data. However, no research has yet been reported on the systematic analysis of the changing characteristics of alpine grassland NPP on the TP over the past 30 years, from the perspective of regional differentiation.

To accurately reflect the spatio-temporal variation in alpine grassland NPP on the TP over the last 28 years, the GIMMS AVHRR NDVI data and SPOT VEGETATION NDVI data, taken between 1982 and 2009 in this study area, were utilized in this study. Additionally, the CASA model, combined with phytomass sampling plot data from the TP alpine grassland, is used to estimate the NPP on the TP and to analyze the characteristics of the temporal variation. This study is of great significance in ascertaining the health of the alpine grassland ecosystem on the TP, and, by extension, the condition of the national ecological security shelter. The results could provide a scientific basis for sustainable utilization and ecological reconstruction of the TP alpine grassland, and related policy-making activities.

2 Data and data processing

2.1 NDVI data and data processing

The GIMMS AVHRR NDVI and SPOT VEGETATION NDVI datasets were used in this study (Zhang and Liao, 1994; Stow *et al*., 2004; Tucker *et al*., 2005). The Global Inventory Modeling and Mapping Studies (GIMMS) data is derived from imagery obtained from the Advanced Very High Resolution Radiometer (AVHRR) instrument onboard the NOAA satellite series, published by American NASA global monitoring and model research group. The GIMMS AVHRR NDVI data for 1982–2000 is available in the form of half month maximum value composites (MVC), at a spatial resolution of 8 km, while the SPOT VGT NDVI data for 1998–2009 derives from synthesis data covering 10-day periods published by the Flemish Institute for Technological Research in Belgium, at a spatial resolution of 1 km. Both of the NDVI datasets have been corrected for calibration, view geometry, radiation and volcanic aerosols (Xiao and Chen, 1996), but the synthesis NDVI datasets still have systematic errors because of the geometry angle view of the satellite, atmospheric haze, and the synthesis process of NDVI data. In order to further reduce the impacts of these errors, a three-point smoothing method (Xiao and Chen, 1996) was adopted in this study to revise the NDVI values.

Additionally, GIMMS AVHRR NDVI and SPOT VGT NDVI datasets are derived from different satellite sensors, so their spectral ranges are slightly different. To reduce the error originating from using two different datasets, correlation analysis was made on the repeating part of GIMMS AVHRR NDVI and SPOT VGT NDVI datasets, with the incorporation of a linear regression equation to interpolate GIMMS NDVI data by using SPOT VGT NDVI data between 2001 and 2009 (Tucker *et al*., 2005).

2.2 The defined scope of the TP alpine grassland

The boundary of the TP is as defined by Zhang *et al*. (2002), while the range of alpine grassland (meadow, steppe, herbaceous wetland, desert grassland and alpine sparse vegetation) is as defined by Zhang (2007)[1]. In order to reduce analytical error and uncertainty, we set the coordinate system of alpine grassland type data and NDVI data as World Geodetic System 1984 (WGS84). Based on the distribution of grassland areas, we extracted all the alpine grassland (meadow (709,675 km^2), steppe (579,375 km^2), herbaceous wetland (39,575 km^2), desert grassland (54,400 km^2) and alpine sparse vegetation (83,550 km^2), totaling 1,466,575 km^2 and accounting for 96.17% of the total TP alpine grassland area) whose area was greater than one pixel of NDVI data (8 km × 8 km) and used this data as the basis for this study.

3 Research methods

3.1 NPP estimation and results validation

(1) The CASA model. The CASA model (Potter *et al*., 1993) was adopted to calculate NPP in this article. The NPP estimation theory of the CASA model is determined by two variables of absorbed photosynthetically active radiation (APAR) and light utilization efficiency (ε).

$$NPP(x, t)=APAR(x, t) * \varepsilon(x, t) \tag{1}$$

where *NPP* is the amount of dry organic matter on the grid cell *x* in time *t*; *APAR* is the fraction of photosynthetically active radiation intercepted by green vegetation on grid cell *x* in time *t*; and *ε* is the light utilization efficiency on grid cell *x* in time *t*.

To allow for the effects of temperature and water stress on *ε*, we calculate it as:

$$\varepsilon(x, t) = \varepsilon_{\max} * T(x, t) * W(x, t) \tag{2}$$

where, ε_{max} is the maximum possible efficiency; *T* accounts for effects of temperature stress on grid cell *x* in time *t*; and *W* accounts for effects of water stress on grid cell *x* in time *t*.

The parameter calculation method the CASA model uses refers to Piao *et al*. (2006), Gao *et al*. (2007a), Potter *et al*. (1993) and Potter (2004), with the monthly maximum possible efficiency of alpine grassland ε_{max} set as 0.56 gC MJ^{-1}, based on Zhou *et al*. (2008).

(2) The NPP estimation. The NPP estimation was carried out as follows: (a) for the NDVI data, we converted the half month MVC data from the GIMMS AVHRR NDVI 1982–2009 TP dataset to GRID data files, and extracted monthly maximum NDVI data using ENVI 4.8 to reduce the cloud impact. We then adopted the method of Sellers *et al*. (1996) to calculate the monthly FPAR (fraction of PAR absorbed by the green vegetation canopy); for meteorological data, we used the spatial interpolation method for monthly meteorological data (monthly precipitation, monthly mean temperature and monthly solar radiation) to obtain grid maps of meteorological elements using ANUSPLIN; we set the coordinate system of all spatial data as WGS84 and set the spatial resolution of all spatial data resampling as 0.05° × 0.05°. (b) The CASA model program is compiled using AML language with ArcGIS 9.3 to

[1]In Zhang (2007), the mapping scale of the data is 1:1 000,000, the actual mapping scale of the data is 1:100,000 and the recognition of different alpine grassland types is based on field investigation data, 1:1 000,000 Vegetation Map of China, 1:500,000 Vegetation Map of Qinghai Province, 1:250,000 Pasture Map of Tibet Autonomous Region and environmental factors of vegetation distribution. In addition, the areas of each type of alpine grassland on the TP are: meadow 739,971 km^2, steppe 601,002 km^2, herbaceous wetland 39,896 km^2, desert grassland 57,268 km^2, and alpine sparse vegetation 86,880 km^2.

model the monthly alpine grassland NPP of the TP. (c) Using the ArcGIS Spatial Analyst module, we quantitatively analyzed the patterns and spatio-temporal characteristics of alpine grassland NPP in the study area.

(3) Results validation and accuracy testing. At present, testing the accuracy of model-predicted results is one of the main difficulties in NPP simulating research. The most commonly used test method applied to simulation results is to compare the measured data with the results predicted by the model. As directly measuring NPP is difficult, we translate plant biomass data into NPP data to eliminate the need for measured NPP data (Gao *et al.*, 2007a; Guo *et al.*, 2006; Gao *et al.*, 2007b; Luo *et al.*, 1999). Using conventional methods (Zhou *et al.*, 2008; Luo *et al.*, 1999), we converted the alpine grassland biomass data measured in the field in August 2004 and August 2006 into alpine grassland NPP. We then compared the observed NPP (biomass converted data) with the model simulation results for the grid cell that includes each observation plot (Figure 1a). After testing for the accuracy of the simulated values (Figure 1b), we found that the simulation values are largely consistent with the measured values (n=52, $p<0.01$). This result shows that the model is adequate for the estimation of alpine grassland NPP on the TP. However, the observed values are converted from the biomass data, which cannot fully represent the true value of NPP, and no measured data from desert grassland and herbaceous wetland is included in this study. Further development of biomass measurement, encompassing all of the alpine grassland types, is required in order to verify and revise the simulation results.

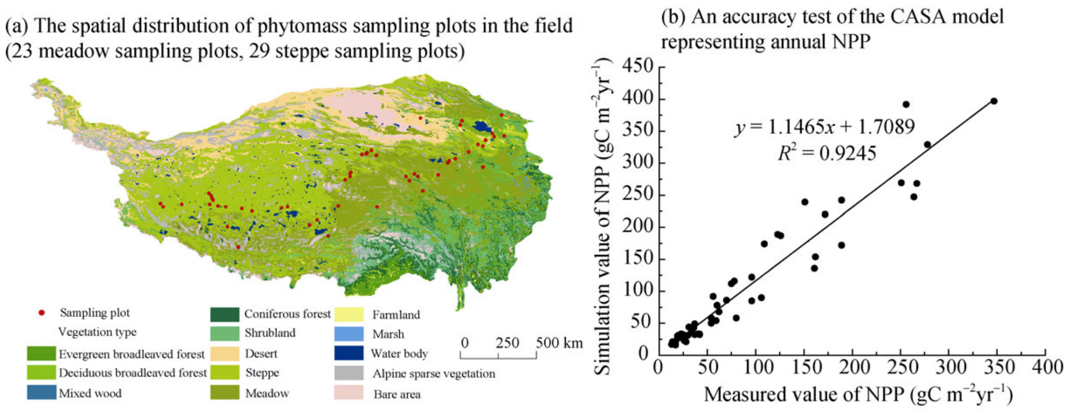


Figure 1 The spatial distribution of phytomass sampling plots in the field (a); and an accuracy test of the CASA model representing annual NPP in alpine grassland on the TP (b)

We extracted the predicted NPP values from the model for specific areas and compared them to results from previous studies (Table 1). The results of this study are identical, within error of the calculation to the previous simulation results based on the CASA model (Piao *et al.*, 2006; Gao *et al.*, 2007a), suggesting these new simulations are reliable. However, there is a considerable discrepancy between the new simulation results and the existing simulation results of other models, such as the TEM model (Zhou *et al.*, 2004) and BIOME-BGC model (Guo *et al.*, 2006), likely a result of the different data sources and spatial distributions of vegetation types in each study. For example, Zhou *et al.* (2004) and Guo *et al.* (2006) used the MODIS data to model NPP, in which the range of alpine grassland did not account for the removal of water bodies and permanent snow and ice, resulting in lower simulated NPP values than those obtained in this study.

Table 1 Comparison of average annual NPP (of alpine grassland) results from this paper with those from related studies

Region	Related research					Average NPP of this study/gC m^{-2} yr^{-1}*
	Satellite data	Period	Model	Author	Average NPP /gC m^{-2} yr^{-1}	
TP	MODIS	2002–2004	TEM	Zhou *et al*. (2004)	103.8	126.84
TP	AVHRR	1982–1999	CASA	Piao *et al*. (2006)	127.5	125.21
Northern Tibet	AVHRR	1981–2004	CASA	Gao *et al*. (2007a)	47.7	43.22
Three River Sources	MODIS	2000–2004	BIOME-BGC	Guo *et al*. (2006)	82.04	127.57
Huangnan Prefecture	AVHRR	1981–2000	GLOPEM	Du *et al*. (2010)	71.51	363.02

*The duration of data, on which the simulations are based, considered in our study is as follows: Northern Tibet, 1982–2004; Huangnan Prefecture, 1982–2000. The duration of data in other regions is the same as the period in the related research study.

3.2 Regional differentiation analysis of NPP

The spatio-temporal characteristics of NPP change were analyzed by employing the tools of GIS and the methods of spatial statistics, separately on the basis of physico-geographical factors (natural zone, altitude, latitude and longitude), river basin, and county-level administrative area. The brief data preprocessing steps for spatial statistics are as follows: 1) the boundary of each natural zone is based on the map of physico-geographical regions of the TP (Zheng, 1996). 2) Based on the SRTM DEM data, the range of altitude on the TP is divided into eight elevation zones (less than 3000 m, 3000–3500 m, 3500–4000 m, 4000–4500 m, 4500–5000 m, 5000–5500 m, 5500–6000 m, and more than 6000 m), at 500 m intervals; the range of latitude is divided into 12 divisions with an interval of one-degree (south of 29ºN, 29º–30ºN, 30º–31ºN, 31º–32ºN, 32º–33ºN, 33º–34ºN, 34º–35ºN, 35º–36ºN, 36º–37ºN, 37º–38ºN, 38º–39ºN, and north of 39ºN); the range of longitude is divided into 13 divisions with an interval of two degrees (west of 80ºE, 80º–82ºE, 82º–84ºE, 84º–86ºE, 86º–88ºE, 88º–90ºE, 90º–92ºE, 92º–94ºE, 94º–96ºE, 96º–98ºE, 98º–100ºE, 100º–102ºE, and east of 102ºE). 3) Using SRTM DEM data, the boundaries of each river basin on the TP are determined by the watershed boundary extraction method (Zhang *et al*., 2005). 4) In order to analyze the regional differentiation in the area percentage of change in alpine grassland NPP on the TP, the data is analyzed in the context of natural zone, elevation, latitude and longitude, river basin, and county-level administrative area, at various significance levels.

4 Results and discussion

4.1 Distribution and trends in NPP on the TP

(1) Characteristics of NPP distribution

Between 1982 and 2009, the distribution of average annual NPP in alpine grassland on the TP gradually decreases from southeast to northwest (Figure 2). This distribution is strongly correlated with the regional spatial distribution of precipitation and temperature. During the period 1982–2009, the average annual NPP in alpine grassland, as estimated by the CASA model, was 120.8 gC m^{-2} yr^{-1}, of which steppe accounts for 55.9 gC m^{-2} yr^{-1}, meadow accounts for 188.7 gC m^{-2} yr^{-1}, herbaceous wetland accounts for 147.2 gC m^{-2} yr^{-1}, desert grassland accounts for 41.1 gC m^{-2} yr^{-1} and alpine sparse vegetation accounts for 34.5 gC m^{-2} yr^{-1}; the average annual total NPP in alpine grassland amounted to 177.2×10^{12} gC yr^{-1}, of which steppe accounts for 32.4×10^{12} gC yr^{-1}, meadow accounts for 133.9×10^{12} gC yr^{-1} and herbaceous wetland accounts for 5.8×10^{12} gC yr^{-1}. The average annual NPP of meadow-type grassland is three times greater than that of steppe grassland, being 75.6% and 18.3% of the alpine grassland total NPP, respectively, despite the area of land covered by steppe being only marginally smaller than that covered by meadow-type grassland.

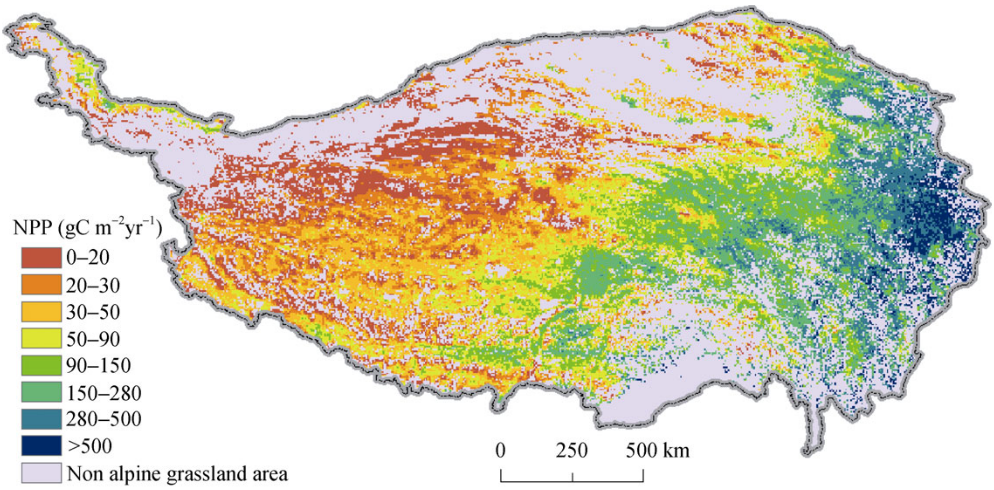


Figure 2 Distribution of average annual NPP in alpine grassland on the TP from 1982 to 2009

The average annual NPP in alpine grassland on the TP was between 47.7 gC m^{-2} yr^{-1} and 127.5 gC m^{-2} yr^{-1} according to the results from related research studies, while the simulated NPP results from this study yield values of 120.8 gC m^{-2} yr^{-1}. The large difference between these results is closely correlated with the study area and the duration of the study. Even though different study areas may be classified as belonging to the same type of alpine grassland, (e.g., meadow), the different specific habitats, ecological community type and growth condition of the alpine grassland in different areas can lead to a large difference in NPP. Furthermore, different study periods, even within the same area, can lead to differences in average annual NPP due to temporal variation in the weather conditions from year to year.

(2) Spatial and temporal trends in NPP data

The annual NPP in alpine grassland on the TP fluctuates from year to year, but has a generally positive trend, increasing from 114.7 gC m^{-2} yr^{-1} in 1982 to 129.9 gC m^{-2} yr^{-1} in 2009 (Figure 3). This represents an average overall increase of 13.3% and an average annual growth rate of 0.46%. Over the last 30 years, the minimum and maximum values of average annual NPP in alpine grassland were 112.6 gC m^{-2} yr^{-1} and 129.9 gC m^{-2} yr^{-1}, respectively. During the years 1987, 1995 and 2003, alpine grassland average annual NPP was lower than normal, with values of 112.6 gC m^{-2} yr^{-1}, 113.7 gC m^{-2} yr^{-1} and 118.2 gC m^{-2} yr^{-1}, respectively. A close covariance between average annual NPP and climatic conditions is observed on the TP; the general positive trend in alpine grassland NPP is in accordance with the positive trend in average annual temperature, while the three troughs in NPP values outlined above correspond to significantly decreased rainfall in the preceding years, 1986, 1994 and

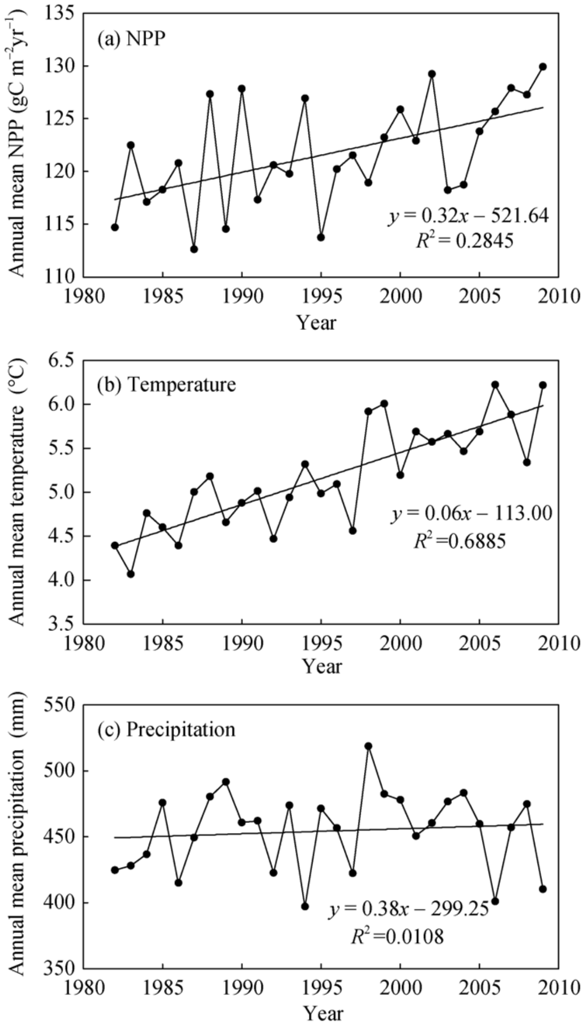


Figure 3 Fluctuations in annual NPP in alpine grassland (a), temperature (b) and precipitation on the TP (c) from 1982 to 2009

2002. This suggests that the combined effects of precipitation and temperature are responsible for the annual variations in NPP on the TP.

With respect to spatial trends, the relative change in alpine grassland NPP on the TP is not evenly distributed across the plateau, with a larger amplitude of change in the east, where there are 5 times more areas with increasing NPP values than with decreasing NPP values (Figure 4). The relative amplitude of increase and decrease in NPP is larger in the east of the TP than in the middle and west, which is related to the specific ecological community types and the spatial distribution of alpine grassland productivity in these regions. The amplitude of NPP change is greater on the eastern side of the TP, due to higher productivity in this region, while both the NPP fluctuations and the level of productivity are smaller in the middle and western regions of the TP. From the perspective of the significance level of changes in NPP, the change in the east is also greater than that in the middle and western regions of the TP. Spatial analysis shows: at the $p<0.1$ level, the proportion of alpine grassland showing a significantly positive trend in NPP is 39.11% of the total, with an increase of 20.3×10^{12} gC, while the proportion of alpine grassland showing a significantly negative trend in NPP accounts for 7.62%, with a decrease in NPP of 3.9×10^{12} gC, and 53.27% of the alpine grassland area showed no significant change in NPP. By contrast, at the $p<0.05$ level, the proportion of alpine grassland showing a significant positive trend in NPP accounts for 32.56% of the total, with an increase in NPP of 18.0×10^{12} gC, the proportion showing a negative trend is 5.55% of the total, with a decrease in NPP of 3.3×10^{12} gC, and no significant change in NPP was recorded to be 61.89% of the total grassland area. The analysis of grassland coverage over the same period shows that the alpine grassland coverage on the TP is generally increasing. Across the plateau, the proportion of alpine grassland that showed an increase in area represents 46.85% of the total, while the proportion of grassland that showed a decrease in coverage is 14.29%, and the area with no obvious change during this interval represents 38.86% of the total (Ding *et al.*, 2010). The growing season for grassland appears to have extended between 1999 and 2009 by 8 days every 10 years. The area of grassland with an extended growing season is 45.56% of the total, while the area with a shorter growing season represents 14.59% of the total, and 39.85% of grassland areas showed no significant change in growing season duration. The spatio-temporal data suggests that the expansion in the growing season has predominantly occurred in the east of the TP, while a shortening of the growing season has occurred in the west (Ding *et al.*, 2012). Therefore, in terms of spatio-temporal variation in grassland NPP, coverage and growing season, the regional differentiation is obvious on the TP that the overall health of the alpine grassland is improving, while grassland in some areas continued to degenerate between 1982 and 2009.

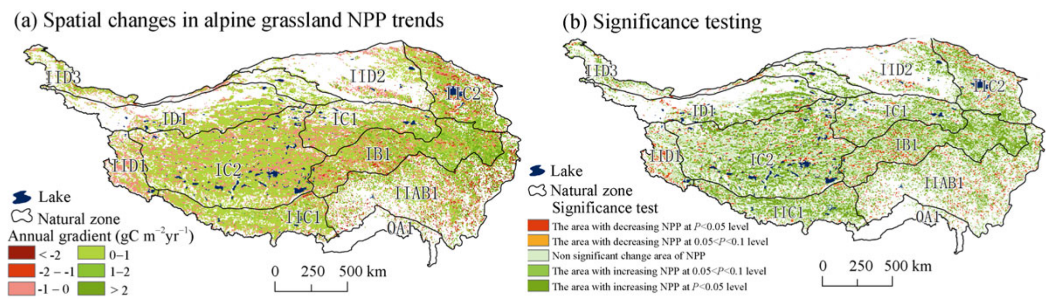


Figure 4 Spatial changes in alpine grassland NPP trends on the TP from 1982 to 2009 (a); and significance testing of this data (b)

Note: The boundary of each natural zone is based on the map of physico-geographical regions of the TP (Zheng, 1996). The names of the natural zones are as follows: IB1 = Golog-Nagqu high-cold shrub-meadow zone; IC1 = Southern Qinghai high-cold meadow steppe zone; IC2 = Qangtang high-cold steppe zone; ID1 = Kunlun high-cold desert zone; IIAB1 = Western Sichuan-eastern Tibet montane coniferous forest zone; IIC1 = Southern Tibet montane shrub-steppe zone; IIC2 = Eastern Qinghai-Qilian montane steppe zone; IID1 = Ngari montane desert-steppe and desert zone; IID2 = Qaidam montane desert zone; IID3 = Northern slopes of Kunlun montane desert zone; 0A1 = Southern slopes of Himalaya montane evergreen broad-leaved forest zone.

Approximately 92% of the counties on the TP have a greater area of alpine grassland with NPP increases than the area showing decreases, significant at the $p<0.1$ level (Figure 5). Approximately 79% of the counties on the TP had no significant change in alpine grassland NPP in more than 40% of their areas, significant at the $p<0.1$ level (Figure 6). Therefore, the alpine grassland NPP on the TP is still in a relatively stable state. The difference between areas that show increasing and decreasing alpine grassland NPP is higher in the eastern and southern parts of the TP, where the difference is >20%, while the difference between increasing and decreasing NPP is lower in the central and western regions. The regions that show a negative difference are predominantly distributed in Cele and Minfeng in Xinjiang, Zhada and Gaer in Tibet, Deqing in Yunnan, and Litang in Sichuan. Previous research into Tibetan NPP variability suggests that the areas with decreasing NPP are predominantly in southwest Ngari, whereas a significant increasing trend in NPP is found in Lhasa, Nyingchi, northern Qamdo and Nagqu (Du *et al.*, 2008). Hence, the results of our study are consistent with previous research findings. As northern Tibet is one of the most important pastoral areas on the TP, the change in grassland NPP here has attracted the attention of many academics in recent years. Research indicates that between 1981 and 2004, the annual NPP in alpine grassland in northern Tibet fluctuated greatly, including two large negative fluctuations in 1987 and 1994, and overall showed a negative trend in NPP (Gao *et al*., 2007b). However, our study shows that the annual NPP in alpine grassland in northern Tibet shows a positive trend with an average increase of 13.41% between 1982 and 2009, albeit with pronounced minima during 1987, 1989, 1995 and 2006 (Figure 7). The different findings of these two studies in terms of NPP values and trends, is likely due to the different study periods and types of land cover in each study, e.g., in the study of Gao *et al.* (2007b), the data were

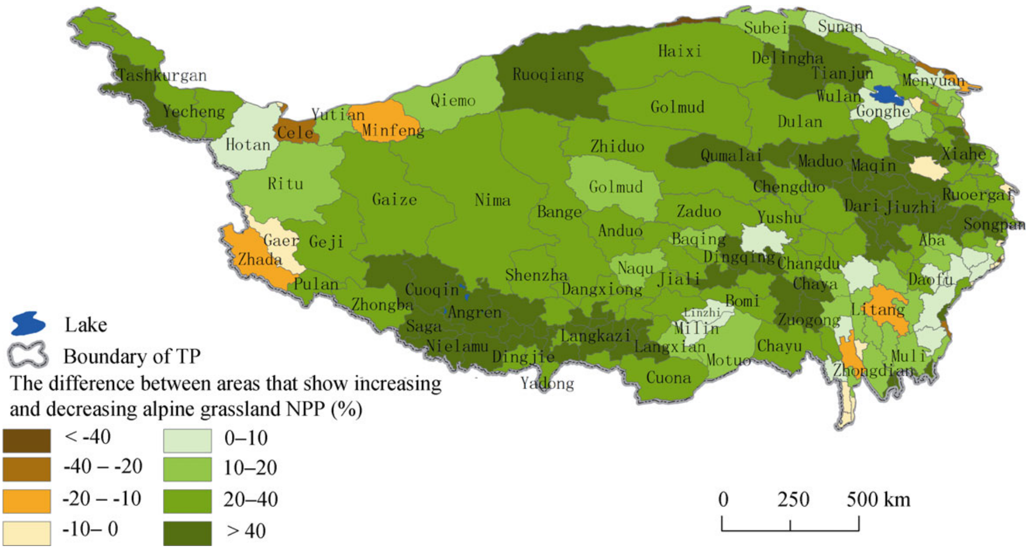


Figure 5 Spatial distribution in difference between areal percentage increasing and decreasing of alpine grassland NPP in counties on the TP

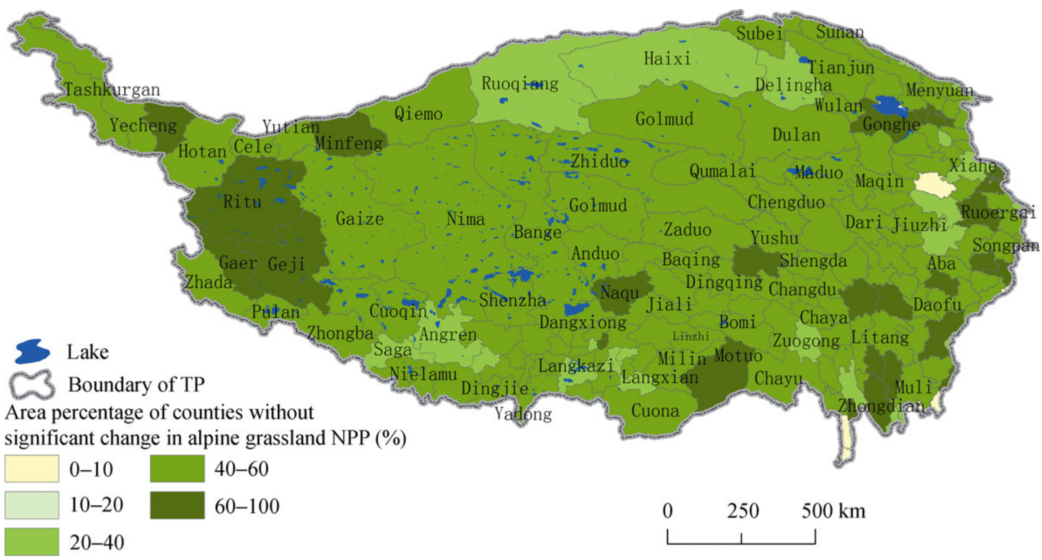


Figure 6 Spatial distribution in area percentage of counties on the TP without significant change in alpine grassland NPP

reported only up until 2004, but a decline in annual NPP occurred between 2000 and 2006, with a significant increase between 2006 and 2009. Furthermore, with respect to types of land cover, Gao *et al.* (2007b) did not eliminate the non-vegetated areas such as glaciers, bare land and open water, which our study did take account of.

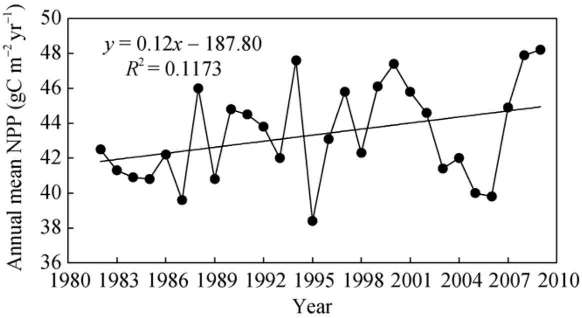


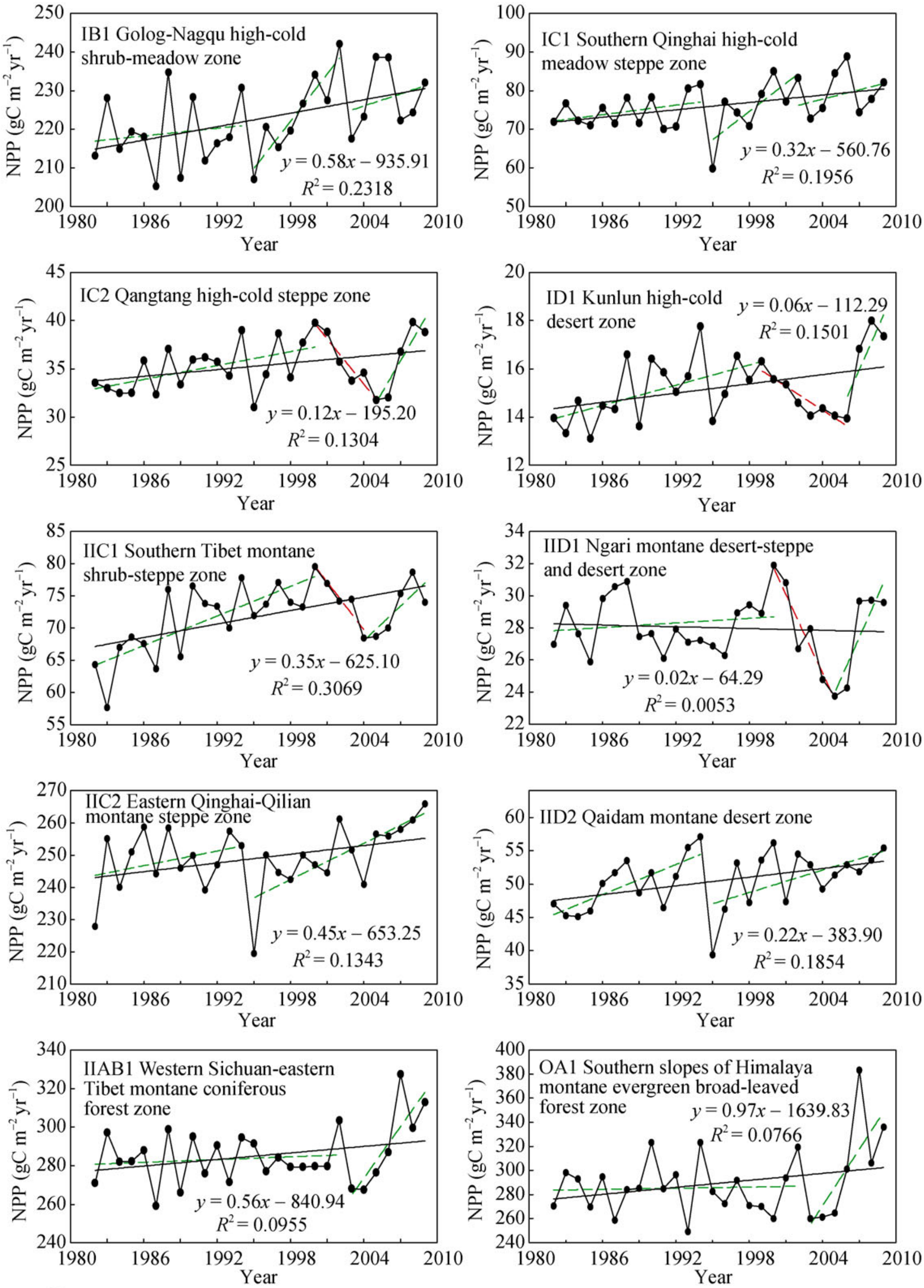
Figure 7 Trend in annual NPP in alpine grassland in northern Tibet from 1982 to 2009

4.2 Physico-geographical controls on NPP trends

(1) The characteristics of NPP change divided by natural zone

During the period 1982–2009, variations in annual alpine grassland NPP on the TP varies significantly between different natural zones (Figure 8). NPP is seen to increase in the majority of natural zones on the TP, and only shows a slight decrease of 0.02 gC m^{-2} yr^{-1} in the Ngari montane desert-steppe and desert zone. The maximum growth rate is approximately 0.58 gC m^{-2} yr^{-1} in the Golog-Nagqu high-cold shrub-meadow zone. The growth rates are reduced successively in the Qangtang high-cold steppe zone, the Kunlun high-cold desert zone, the Qaidam montane desert zone and the Northern slopes of Kunlun montane desert zone. These results indicate that the general positive trend in NPP in the meadow zone and shrub zone, distributed in the eastern and southern regions of the TP, are more significant than that of the alpine steppe zone in the western and northern regions.

The trends in annual alpine grassland NPP are very similar in natural zones which belong to either the same temperature zone (Figure 8) (e.g., the Plateau Subfrigid Zone (I), the Plateau Temperate Zone (II)) or the same regional type (e.g., the Humid Region (IIA), the Semi-humid Region (IIB), the Semi-arid Region (IIC)). These trends can be divided into five types: “stable-increasing-stable”, “stable-decreasing-increasing”, “stable-slowly increasing”, “stable-sharply increasing” and “continuously slowly increasing”. Specifically, the Golog- Nagqu high-cold shrub-meadow zone (IB1) and the Southern Qinghai high-cold meadow steppe zone (IC1) have an NPP trend which can be described as “stable” between 1982–1994, then “increasing” between 1995 and 2002, and “stable” again between 2003 and 2009. The Qangtang high-cold steppe zone (IC2), Kunlun high-cold desert zone (ID1), Southern Tibet montane shrub-steppe zone (IIC1) and Ngari montane desert-steppe and desert zone (IID1) have an NPP trend which can be described as “stable” between 1982 and 1999, “decreasing” between 2000 and 2005, and “increasing” between 2006 and 2009. The Eastern Qinghai-Qilian montane steppe zone (IIC2) and Qaidam montane desert zone (IID2) have an NPP trend which can be described as “stable” between 1982 and 1994, and “slowly increasing” between 1995 and 2009. By contrast, the northern slopes of the Kunlun montane desert zone (IID3) have an NPP trend which can be described as “continuously slowly increasing” between 1982 and 2009. As the natural zones above nearly all belong to semi-arid or arid regions, the inflection points in the trends largely fall on drought years, when precipitation decreased significantly, e.g., 1994, 2002 and 2006. By comparison, the trend in



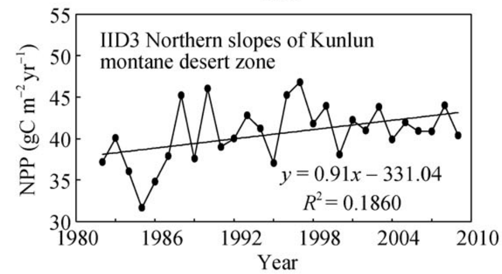


Figure 8 The annual alpine NPP in each natural zone on the TP from 1982 to 2009

NPP in the Western Sichuan-eastern Tibet montane coniferous forest zone (IIAB1) and the Southern slopes of Himalaya montane evergreen broad-leaved forest zone (0A1), situated in humid or semi-humid regions, is completely different from those observed for the semi-arid and arid zones, with fluctuating values prior to 2002, then a short period of decreasing NPP values followed by a sharp rise post-2004.

In all of the natural zones, apart from the Ngari montane desert-steppe and desert zone where decrease was equal to increase, the area of increased grassland NPP is greater than the area of decreased NPP (Figure 9). However, different natural zones have different levels of change in NPP decrease or increase by area, significant at the $p<0.1$ level. The largest percentage of NPP decrease by area is 19.18% in the Ngari montane desert-steppe and desert zone, while the smallest decrease occurred in the Southern Tibet montane shrub-steppe zone, with a value of 4.81%. The opposite trend is found when considering NPP increase by area; the greatest increase is found in the Southern Tibet montane shrub-steppe zone, at 51.54%, while the smallest is found in the Ngari montane desert-steppe and desert zone, at 19.54%. The pattern of NPP increase in the Southern Tibet montane shrub-steppe zone is likely to be closely related to climate change and human activities in this region. Recently, a variety of ecological protection measures were implemented to protect the environment in the valleys of this region, combined with a generally warm and humid climate, ideal for plant growth. The decrease observed in NPP in the Ngari montane desert-steppe and desert zone may be related to climate change. Zhang *et al*. (2013) found that the climate in northwest Tibet became warmer and dryer between 1970 and 2010, with a significant increase in temperatures, reduced precipitation and increased evaporation.

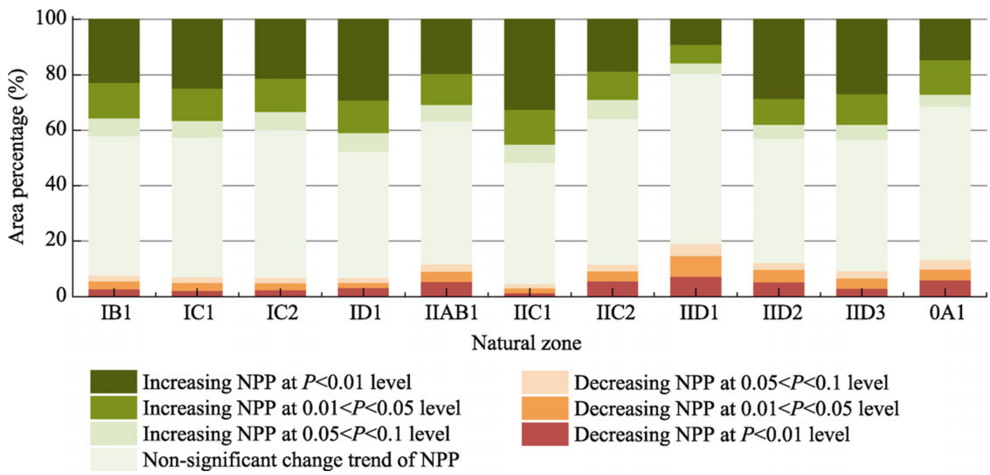


Figure 9 Percentage of change in alpine grassland NPP by area in each natural zone on the TP, at various significance levels

(2) Changes in NPP trend with altitude and latitude/longitude

Trends in alpine grassland NPP are significantly affected by altitude. As altitude increases, the percentage of total area with an increasing trend in annual NPP displays an “increasing-stable-decreasing” trend, significant at the $p<0.1$ level (Figure 10). At an altitude of 3.5 km or less, the percentage of total area with an increase in NPP increases as the altitude increases; at altitudes between 3.5–6 km, the percentage of areas with NPP increases is fairly

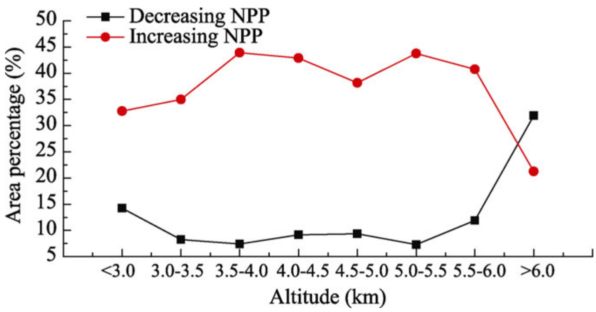


Figure 10 The effect of altitude on percentage changes in areal extent of alpine grassland NPP increases and decreases on the TP

stable with increasing altitude; at altitudes greater than 6 km, the percentage of areas with increases in NPP declines sharply. Conversely, the percentage of total area with a decreasing trend in annual NPP displays a "decreasing-stable-increasing" trend with increasing altitude (Figure 10). At an altitude of 3.5 km or less, the percentage of total area with a decrease in NPP decreases as the altitude increases; at altitudes between 3.5–5.5 km, the percentage of areas with NPP decreases is fairly stable with increasing altitude; at altitudes greater than 5.5 km, the percentage of areas with decreases in NPP increases sharply. Additionally, with the exception of regions at altitudes greater than 6 km, the percentage of the total area on the TP with an increasing trend in NPP, is greater than that of areas showing NPP decreases at the equivalent altitude, suggesting that grassland productivity overall has improved over the study period.

Changes in alpine grassland NPP on the TP exhibit both east-west trending (longitudinal) and north-south trending (latitudinal) variation. As the percentage of total area with a decreasing trend in annual NPP fluctuates by only 10% with longitude, the trends seen in the difference between areal percentages in NPP increase and decrease are predominantly controlled by the percentage area with an increasing trend in NPP (Figure 11a). The ratio of areal percentage in NPP increase to areal percentage in NPP decrease varies between 2:1 and 10.4:1. To the west of 92ºE, the difference between areal percentages in NPP increase and decrease fluctuates greatly. From west to east, the percentage of areas with an increasing trend in annual NPP follows a "decreasing-increasing-decreasing" trend, while the percentage of areas with a decreasing trend follows a "decreasing-increasing" trend (Figure 11a). The maximum difference between areas with increasing and decreasing NPP is reached in the region of 86º–88ºE, where the ratio of area with increasing NPP to area with decreasing NPP is over 10. To the east of 92ºE, the difference and the ratio between increasing and decreasing trends in NPP show no obvious changes. With respect to latitudinal variation, again the difference between areas of increasing and decreasing NPP is predominantly controlled by changes in the percentage area of NPP increases, with a ratio of area with increasing NPP to area with decreasing NPP that varies between 1.5:1 and 6.4:1 (Figure 11b). South of 38ºN, from south to north, the percentage of areas that shows an NPP increase fluctuates, with an overall negative trend, while the percentage of areas that shows an NPP decrease displays no obvious change. To the north of 38ºN, the percentage of areas that shows an increasing trend in NPP shows a significant decline, whilst the percentage of areas showing a decreasing trend in NPP shows a significant increase. The variations in annual NPP with latitude and longitude, as described above, have a close relationship with the distribution of vegetation and environmental conditions on the plateau. In western and northern regions of the TP, which have overall adverse growth conditions and poor adaptability to climatic or human-induced change, the spatial differences in NPP change are significant. While in the eastern and southern regions of the TP, where growth conditions are more favorable, the spatial difference in NPP changes is small.

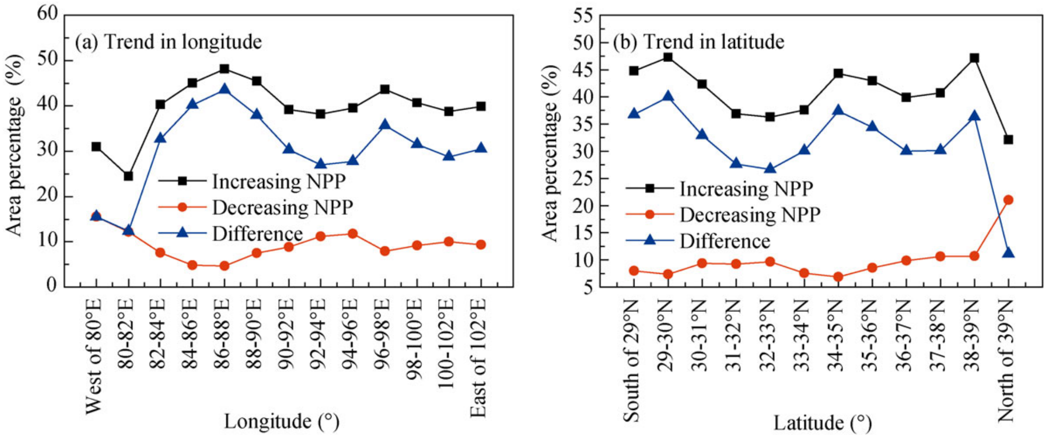


Figure 11 The effect of longitude(a) and latitude (b) on percentage changes in areal extent of alpine grassland NPP increases and decreases on the TP

4.3 Trends in NPP change between different major river basins

The TP is the source of China's major rivers, and even some rivers further afield in Asia. The source areas of these rivers contain large tracts of alpine grassland, which play an important role in both water conservation and animal husbandry. The average annual NPP of alpine grassland in the major TP river basins all display positive trends with time, in which the growth rate in the Yellow River Basin is most significant at 0.74 gC m^{-2} yr^{-1}, while that in the Yangtze River Basin is the smallest at 0.33 gC m^{-2} yr^{-1} (Figure 12). Whilst, the average annual NPP in the Yellow River Basin is also the highest in the region, at 257.84 gC m^{-2} yr^{-1}, while the Yarlung Zangbo River Basin showed the lowest levels of average annual NPP, at 103.48 gC m^{-2} yr^{-1}. The results are largely consistent with those of Guo *et al.* (2006), which suggested that greater vegetation growth occurs in the source region of the Yellow River than in the Yangtze River source region and that the average annual NPP in the southeast of the source region of the Yellow River is approximately 250 gC m^{-2} yr^{-1}.

Trends in NPP change in each major river basin on the TP can be divided into three stages, 1982–1994, 1995–2002 and 2003–2009, based on the low precipitation years, 1995 and 2002, (Figure 12). During the first stage, NPP increased significantly in the Yarlung Zangbo River Basin, decreased slightly in the Lancang River Basin, and showed a minor positive, but fluctuating trend in the remainder of the basins. During the second and third stages, the major river basins follow a significant positive trend in NPP, with the exception of the slow rise in the Yarlung Zangbo River Basin in the second stage and of the Yellow River Basin in the third stage.

The percentage of areas with an increasing trend in average annual NPP of alpine grassland is higher than the percentage with a decreasing trend ($p<0.1$) in the major river basins of the TP; however, different river basins have differing proportions of increasing or decreasing NPP trends by area (Figure 13). The basins with the highest percentage of increase in NPP, in decreasing order, are: the Yarlung Zangbo River Basin (46.89%), the Yellow

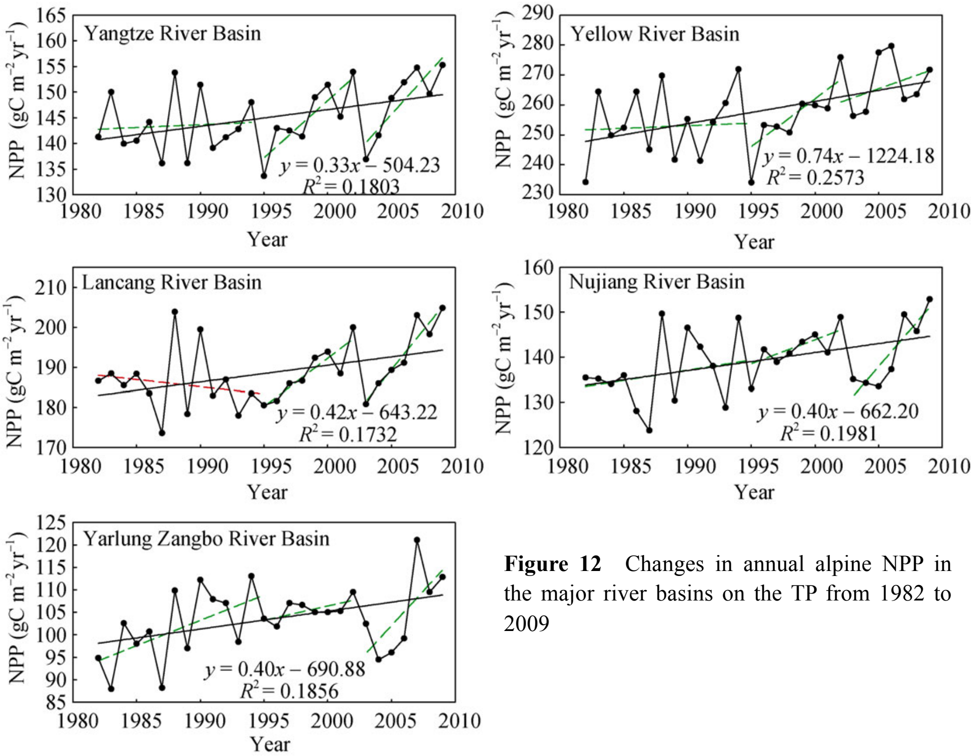


Figure 12 Changes in annual alpine NPP in the major river basins on the TP from 1982 to 2009

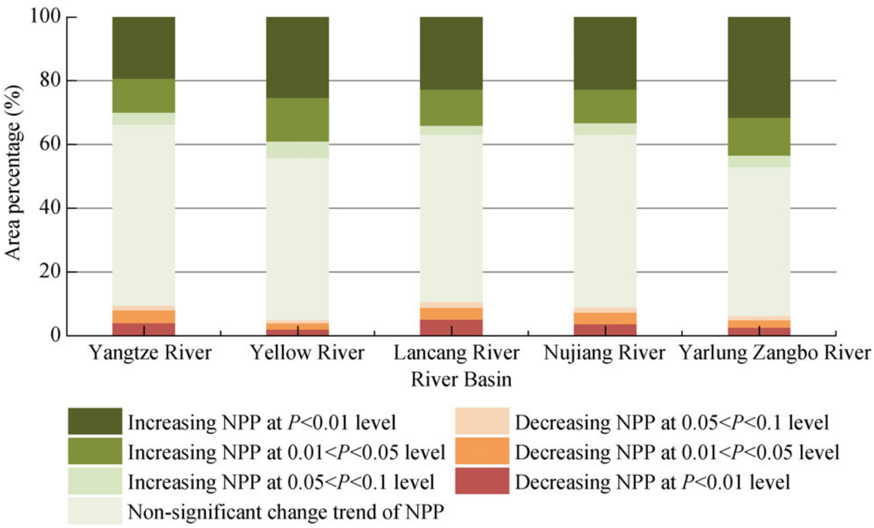


Figure 13 The percentage changes in alpine grassland NPP, by area, in major river basins on the TP, at various significance levels

River Basin (43.97%), the Lancang River Basin (36.80%), the Nujiang River Basin (36.71%), and the Yangtze River Basin (33.66%). The basins with the highest percentage of decrease in NPP, in decreasing order, are: the Lancang River Basin (10.75%), the Yangtze River Basin (9.63%), the Nujiang River Basin (9.06%), the Yarlung Zangbo River Basin (6.32%), and the Yellow River Basin (5.15%). With respect to the status of grassland productivity, the Yarlung Zangbo River Basin and the Yellow River Basin show significant improvements, while the Yangtze River Basin shows only a relatively weak improvement. The change in NPP on the TP with time is affected not only by precipitation and temperature, but also by human activities. In the past few years, a series of ecological protection measures and construction projects have been implemented by the government in the source region of the Yangtze River, the Yellow River and the Lancang River and Yarlung Zangbo River Basin (EPBOQP, 2003; SCIO, 2003; EPCTNREB, 2007; PGQP, 2009), which have improved the ecological and environmental conditions in these areas and, to some extent, improved the grassland productivity (Shao *et al.*, 2012).

5 Conclusions

(1) The average annual total NPP in alpine grassland on the TP is 177.2×10^{12} gC yr^{-1}, with an average annual NPP of 120.8 gC m^{-2} yr^{-1} from 1982–2009. The NPP of alpine grassland on the TP gradually decreases from the southeast to the northwest.

(2) During 1982–2009, the average annual NPP had a positive, but fluctuating, trend from 114.7 gC m^{-2} yr^{-1} in 1982 to 129.9 gC m^{-2} yr^{-1} in 2009, with a range of 112.6–129.9 gC m^{-2} yr^{-1}, and representing an overall increase of 13.3%. The NPP increase of 32.56% to 39.11% of the total alpine grassland on the TP showed a significant positive trend with time, with increases of 18.0×10^{12}–20.3×10^{12} gC, while 5.55% to 7.62% of the total alpine grassland showed a significant negative trend in NPP with time, with decreases of 3.3×10^{12}–3.9×10^{12} gC. The NPP had no significant change in the alpine grassland area occupied 53.27% to 61.89%. Vegetation coverage (Ding *et al.*, 2010), growing season (Ding *et al.*, 2012), with the spatio-temporal variation in NPP show that some areas of the TP show a worsening trend, meanwhile the overall health of the alpine grassland is improving.

(3) During the study period, the spatial characteristics in average annual alpine grassland NPP change on the TP are as follows:

(a) The annual NPP increased in most natural zones on the TP except in the Ngari montane desert-steppe and desert zone. The positive trend in NPP in the high-cold shrub-meadow zone, high-cold meadow steppe zone and high-cold steppe zone, is stronger than that in the high-cold desert zone. The variation in annual NPP with altitude is significant; areas with an increasing trend in NPP are characterized by an "increasing-stable-decreasing" trend with increasing altitude, while those areas with a decreasing trend in NPP are characterized by a "decreasing-stable-increasing" trend. Changes in average annual NPP with longitude and latitude are predominantly affected by the distribution of vegetation and specific environmental conditions.

(b) The average annual NPP in the Yellow River Basin, Yangtze River Basin, Lancang River Basin, Yarlung Zangbo River Basin and Nujiang River Basin follows a positive trend with time. The increasing trend in NPP in the Yellow River Basin is most significant, which is likely due to the effects both of climate change and of the implementation of ecological protection and construction projects in this river basin.

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