VARIATIONS IN VEGETATION NET PRIMARY PRODUCTION IN THE QINGHAI-XIZANG PLATEAU, CHINA, FROM 1982 TO 1999

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Abstract. Vegetation net primary production (NPP) derived from a carbon model (Carnegie–Ames–Stanford Approach, CASA) and its interannual change in the Qinghai-Xizang (Tibetan) Plateau were investigated in this study using 1982–1999 time series data sets of normalized difference vegetation index (NDVI) and paired ground-based information on vegetation, climate, soil, and solar radiation. The 18-year averaged annual NPP over the plateau was 125 g C m^{-2} yr^{-1}, decreasing from the southeast to the northwest, consistent with precipitation and temperature patterns. Total annual NPP was estimated between 0.183 and 0.244 Pg C over the 18 years, with an average of 0.212 Pg C (1 Pg = 10^{15} g). Two distinct periods (1982–1990 and 1991–1999) of NPP variation were observed, separated by a sharp reduction during 1990–1991. From 1982 to 1990, annual NPP did not show a significant trend, while from 1991 to 1999 a marked increase of 0.007 Pg C yr^{-2} was observed. NPP trends for most vegetation types resembled that of the whole plateau. The largest annual NPP increase during 1991–1999 appeared in alpine meadows, accounting for 32.3% of the increment of the whole region. Changes in solar radiation and temperature significantly influenced NPP variation, suggesting that solar radiation may be one of the major factors associated with changes in NPP.

1. Introduction

Vegetation net primary production (NPP) not only serves as a compelling indicator of earth surface system health (Running et al., 2000) but also plays a central role in the terrestrial carbon cycle (Keeling et al., 1996; Field et al., 1998). Therefore, NPP and its response to global change have been a focus of global change research (Cramer et al., 1999), and many studies have been conducted based on historical data sets (e.g., Melillo et al., 1993; Malmström et al., 1997; Peng and Apps, 1999; Schimel et al., 2000; Lucht et al., 2002; Hicke et al., 2002; Cao et al., 2003; Fang et al., 2003; Nemani et al., 2003). These studies have generally concluded that terrestrial photosynthetic activity in the Northern Hemisphere has increased over the past two decades, especially in the high latitudes, owing to elevated temperatures (Hansen et al., 1996; Myneni et al., 1997; IPCC, 2001; Zhou et al., 2001; Tucker et al., 2001; Lucht et al., 2002).

The Qinghai-Xizang Plateau (Tibet), with an average altitude of nearly 5000 m and low temperatures (annual mean temperature over most of the region falling below 0 °C), has been called the “third pole” of the earth. Previous studies have suggested that the temperature fluctuations in the plateau are wider than that of

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other regions in the Northern Hemisphere, indicating its high sensitivity to global change (Lin et al., 1996; Yao et al., 2000). Furthermore, the unique vegetation geography and climate zones of the Plateau, along with low intensity of human disturbance, recommend it as an ideal region for identifying effects of climate change on vegetation activity and its interannual variations; however, very few studies have been performed due primarily to a lack of multiyear field and ground observations (Ni, 2000; Luo et al., 2002). Recently, well-calibrated multiyear satellite data sets and well-documented weather data sets have permitted characterization of year-to-year changes in regional- and global-scale terrestrial production (Malmström et al., 1997; Behrenfeld et al., 2001). Especially, the data set of normalized difference vegetation index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) satellite sensor is useful for identifying vegetation activity dynamics because of its short revisit interval (Tucker et al., 1994, 2001; Zhou et al., 2001, 2003; Lucht et al., 2002; Slayback et al., 2003).

In this study, we investigate the NPP of the Qinghai-Xizang Plateau from 1982 to 1999 using satellite data set and a carbon model, the Carnegie–Ames–Stanford Approach (CASA) (Potter et al., 1993; Field et al., 1995). We aim to (1) explore interannual variations in NPP and its spatial distribution on the plateau, (2) elucidate the relationships between the NPP trends and climatic factors, and (3) identify the changes in NPP by vegetation type.

2. Data and Methods

2.1. STUDY AREA

The Qinghai-Xizang Plateau consists of Qinghai Province and Xizang (Tibet) Autonomous Region (Figure 1), with an area of $192 \times 10^4\,\text{km}^2$, about one-fifth of China's territory. The plateau ranges between 26.5 and 39.5 °N in latitude and between 78.3 and 103.1 °E in longitude. The relatively young Himalayan Tectonic Movement and uplift has made the plateau the youngest and highest highland in the world (Zhao, 1994).

Uplifting of the plateau strengthened the South Asian monsoon, and thus has greatly influenced the climate zones and vegetation distribution on the plateau and adjacent areas (Editorial Committee for Vegetation of China, 1980). Temperature on the plateau is very low, with annual mean temperature of below 0 °C for most areas (but $>10\,^\circ$C in southeastern low altitudes), while solar radiation is extremely high, ranging between 6000 and 9000 MJ $\text{m}^{-2}\,\text{yr}^{-1}$ (Editorial Committee for Physical Geography of China, 1985). Annual precipitation decreases from over 1000 mm on the southeastern border to less 100 mm on the northwestern parts (Zhao, 1994). Such a large climate range from warm to cold and from wet to dry has generated diverse vegetation types, from evergreen broadleaf forest, evergreen coniferous forest,

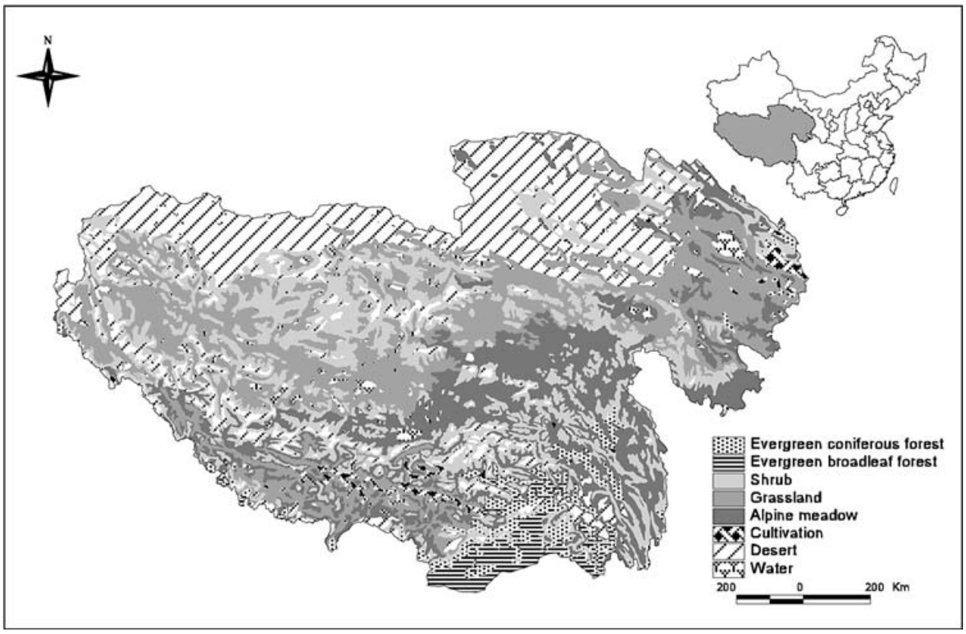

Figure 1. Vegetation map of the Qinghai-Xizang Plateau derived from ground observations (based on *Institute of Geography, Chinese Academy of Sciences*, 1996).

shrub, alpine meadow, and grassland to desert from southeastern to northwestern parts (Figure 1).

2.2. CASA MODEL

Theoretically, NPP can be estimated using the variables of the absorbed photosynthetically active radiation (APAR) and the efficiency by which radiation is converted to plant biomass (ε) (Monteith, 1977). CASA calculates APAR as the product of photosynthetically active radiation (PAR) and the fraction of APAR (fAPAR). The parameter ε represents a function of the maximum light-use efficiency variable (ε^*), as well as temperature (T_ε) and moisture (W_ε) scalars that represent climate stresses on vegetation light-use efficiency. NPP for a location (x) and time (t) is calculated as

$$\mathrm{NPP}(x,t) = \mathrm{fAPAR}(x,t) \times \mathrm{PAR}(x,t) \times \varepsilon^*(x,t) \times T_\varepsilon(x,t) \times W_\varepsilon(x,t) \qquad (1)$$

where fAPAR relates closely to NDVI, and is defined as a combination of red and near-infrared surface reflectance of the canopy (Sellers et al., 1995). The CASA uses NDVI as a proxy for fAPAR. For the detailed algorithm of the CASA model, see Potter et al. (1993) and Field et al. (1995).

In order to quantify change rate of NPP, we regressed annual NPP versus year [$\mathrm{NPP} = m + b(\mathrm{year}) + e$; m and b are regression coefficients, and e is the residual error]. The slope of the regression, b, is the mean increase amount of annual NPP, and its ratio to average NPP over the study period is defined as mean increase rate of annual NPP.

2.3. DATA SETS

NDVI data set used in this study was produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group using the AVHRR/NOAA series satellites (NOAA 7, 9, 11 and 14), and is available from 1982 to 1999, with a spatial resolution of 8 km × 8 km and a semimonthly temporal resolution. The processing of the data set includes improved navigation, calibration for sensor degradation and correction for stratospheric volcanic aerosols for El Chichon and Mount Pinatubo eruptions in April 1984 and June 1991 (Zhou et al., 2001; Slayback et al., 2003).

Nonetheless, interannual signals of vegetation reflectance are subtle and therefore subject to non-vegetation effects. Many factors, unrelated to vegetation structures, can introduce extraneous variability in NDVI both in space and time, and can easily be misidentified as real NDVI variability (Gutman, 1999). In the AVHRR time series, the major problems are with the continuous changes in sensor sensitivity (calibration problems) and with satellite orbital drift and changeover. Properties of both surface and atmosphere are spatially and temporally variable and quantitative characteristics of atmospheric constituents and surface are insufficient (Gutman, 1999). Accordingly, successful removal of non-vegetation effects remains a challenge. The quality of this NDVI data set has been assessed by Tucker et al. (2001) and Zhou et al. (2001, 2003). They found that the data set could be used to identify the long-term trends in vegetation activity. Recent comparison among four AVHRR NDVI data sets has also indicated that variations due to satellite drifts and changeover are small in this data set, especially in high latitudes (Slayback et al., 2003).

Some of these non-vegetated effects can be minimized, to a large extent, by processing and analyzing only the monthly maximum NDVI value composites (MVC) (Holben, 1986; Tucker et al., 1994). We used these maximum values as monthly NDVI in this study. To further eliminate the impacts of bare and sparsely vegetated regions, only grid cells with annual mean NDVI of >0.1 unit during the 18 years were used in this study. As a result, the total study area in this study was 170×10^4 km^2.

The monthly NDVI values were then converted to geographic projection at $0.1^\circ \times 0.1^\circ$ resolution from the original Albers equal area projection using bilinear interpolation in ARC/INFO 7.1.1 software.

The meteorological data used in this study included monthly mean temperature, monthly precipitation, and monthly solar radiation. These data sets, with a spatial resolution of 0.1°, were obtained from Fang et al. (2001a, 2003). Soil texture and vegetation data were acquired by digitizing the soil texture map of China (Deng, 1986) and vegetation map of China (CAS, Institute of Geography, 1996), respectively.

TABLE I
Annual NPP for different vegetation types in the Qinghai-Xizang Plateau

Vegetation type	Area (10^5 km^2)	NPP (g C m^{-2} yr^{-1})	SD	Total NPP (Tg C)
Evergreen broadleaf forest	4.44	525	191	23.33
Evergreen coniferous forest	5.94	247	128	14.67
Shrubs	43.92	110	90	48.14
Desert	25.88	44	52	11.40
Grassland	49.44	89	75	44.15
Alpine Meadow	37.61	178	83	66.86
Cultivation	2.40	167	77	4.02
Total	169.63	125	122	212.57

SD: standard deviation.

3. Results

3.1. GEOGRAPHIC DISTRIBUTION OF NPP

Averaged annual NPP over the plateau and NPP values for each vegetation type during 1982–1999 are shown in Table I. The 18-year averaged total annual NPP and mean annual NPP per area were 0.212 Pg C yr^{-1} and 125 g C m^{-2} yr^{-1} (Table I).

Alpine grassland, meadow and shrub are the three dominant biome types, with forests limited to the southeastern areas (Figure 1). The largest mean NPP appeared in evergreen broadleaf forest (525 g C m^{-2} yr^{-1}), followed by evergreen coniferous forest (247 g C m^{-2} yr^{-1}), meadow (178 g C m^{-2} yr^{-1}), cultivated land (167 g C m^{-2} yr^{-1}), shrubs (110 g C m^{-2} yr^{-1}), and grassland (89 g C m^{-2} yr^{-1}), with deserts having the smallest mean (44 g C m^{-2} yr^{-1}). Total forest NPP accounted for only 17.9% of the plateau's total, while alpine meadows composed the largest portion of the total, accounting for 31.4% (Table I).

NPP clearly decreased from southeastern to northwestern areas (Figure 2A), consistent with the changes in the vegetation zone (Figure 1) and precipitation and temperature patterns (Figure 2B and C). In the southeast, subtropical evergreen broadleaf forest had large NPP, ranging from 500 to 1000 g C m^{-2} yr^{-1}, while in the northwest, vegetation is very sparse due to very limited precipitation (Figure 2B) and its NPP seldom exceeded 10 g C m^{-2} yr^{-1}. NPP in the eastern areas generally varied from 200 to 400 g C m^{-2} yr^{-1}, and was typically below 100 g C m^{-2} yr^{-1} in the western areas.

3.2. NPP TRENDS

Figure 3 illustrates the interannual variations in annual NPP, annual average NDVI, annual precipitation, annual mean temperature, and annual solar radiation in the plateau between 1982 and 1999. Annual NPP varied between 0.183 and 0.244 Pg C yr^{-1} with a coefficient of variation of 7.9% and an increase rate of 0.7% yr^{-1} in the study period.

Although overall NPP increased in the plateau over the past two decades ($R = 0.45$, $p = 0.06$), two distinct periods of NPP variation were identified: 1982–1990

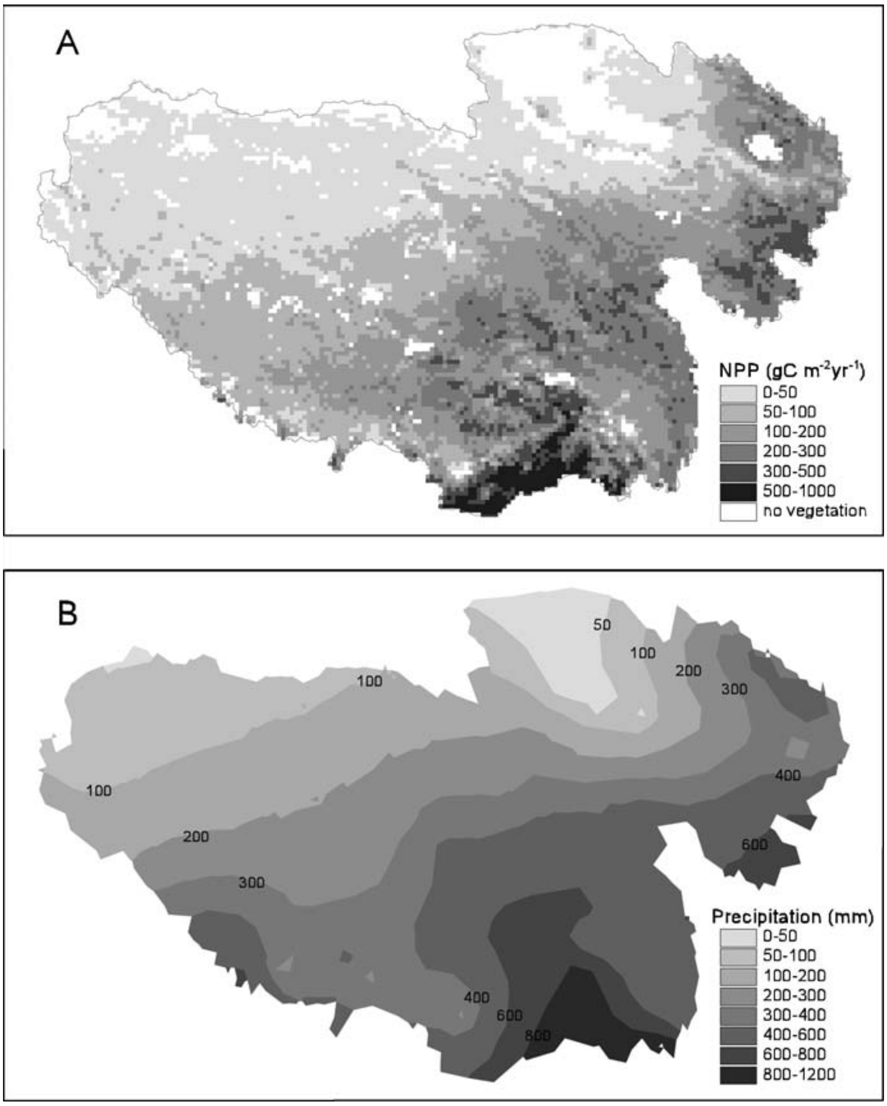

Figure 2. Spatial patterns of (A) 18-year averaged annual NPP derived from the CASA, (B) annual precipitation, and (C) annual mean temperature in the Qinghai-Xizang Plateau.

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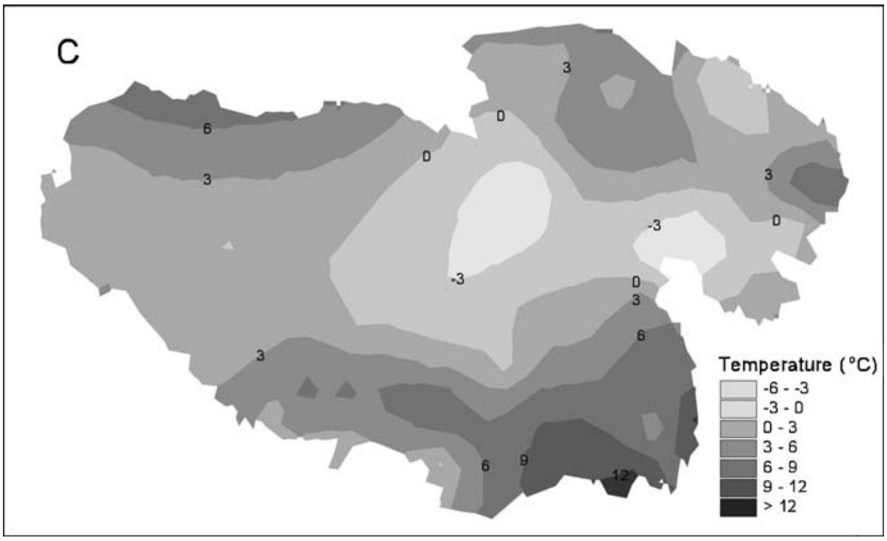

Figure 2. (*Continued*)

and 1991–1999, separated by a rapid reduction from 1990 to 1991, most likely due to the Mt. Pinatubo eruption in June 1991. This eruption has led to a great stratospheric aerosol increase and solar radiation decrease in the Northern Hemisphere (Stowe et al., 1992; Minnis et al., 1993). This solar radiation decrease was also documented in the plateau; 1991 was the year of the lowest solar radiation during the 18 years (Figure 3e).

In general, variations in annual NPP were associated with those in temperature and precipitation of the current year (for example, in 1998 and 1999). However, the NPP continuously increased in 1997, despite lower temperature, precipitation, and solar radiation. This likely resulted from higher temperature and precipitation in the preceding year (1996) because in some cases vegetation activity has been documented to lag behind climate variations at a large scale (Braswell et al., 1997; Los et al. 2001; Piao et al., 2003).

From 1982 to 1990, annual NPP did not show a significant trend ($R = -0.16$, $p = 0.67$), despite marked increase in average temperature and NDVI ($R = 0.66$, $p = 0.05$ and $R = 0.79$, $p = 0.01$). This may have resulted from a significant decrease in solar radiation during this period ($R = -0.89$, $p = 0.001$). During 1991–1999, the plateau NPP increased dramatically from 0.183 Pg C in 1991 to 0.244 Pg C in 1999, with an annual increase of 0.007 Pg C yr^{-1} ($R = 0.89$, $p = 0.001$). This increase coincided with climatic variations: from 1991 to 1999, temperature (Figure 3c), precipitation (Figure 3d), and solar radiation (Figure 3e) all tended to increase ($R = 0.61$, $p = 0.08$; $R = 0.45$, $p = 0.30$, and $R = 0.52$, $p = 0.15$, respectively).

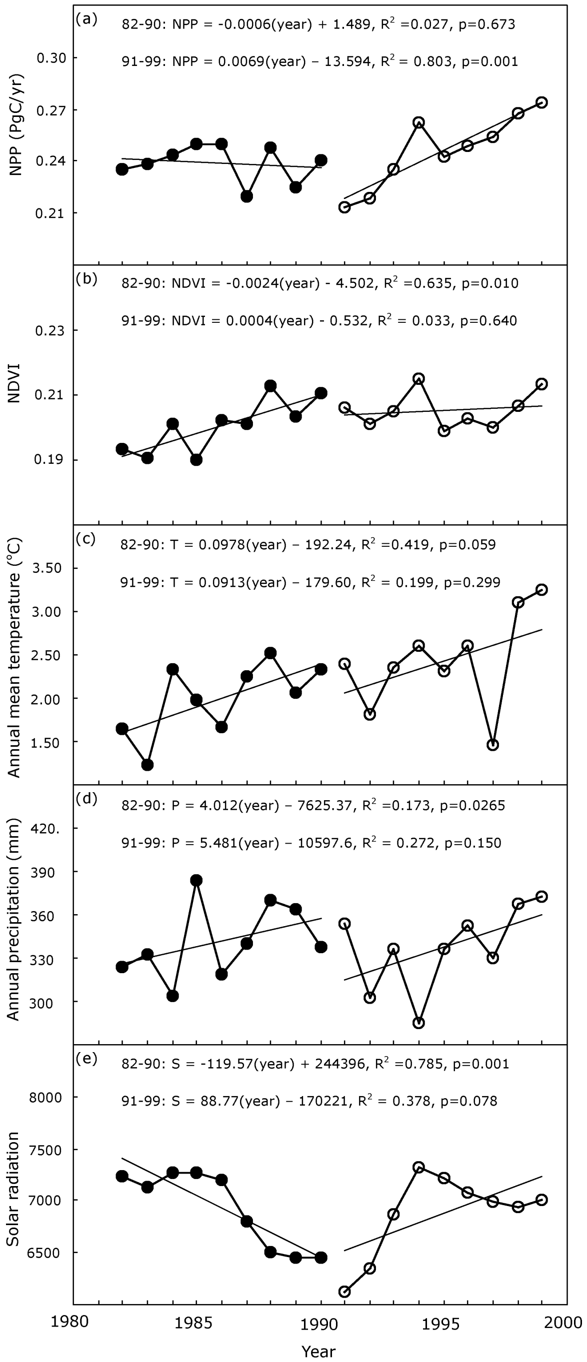

Figure 3. Interannual changes in (a) total net primary production (NPP, Pg C yr^{-1}), (b) area-weighted normalized difference vegetation index (NDVI), (c) annual mean temperature (°C), (d) annual precipitation (mm), and (e) solar radiation (MJ m^{-2} yr^{-1}) over the period 1982–1999 in the Qinghai-Xizang Plateau.

TABLE II

Mean increase amount of annual NPP (Tg C yr^{-2}) (*S*), mean increase rate of annual NPP (% yr^{-1}) (*B*), and coefficients of correlation between NPP and year (*R*) for different vegetation types during 1982–1990, 1991–1999, and 1982–1999 ($R = 0.667$ for significantly positive correlation when $n = 9$ and $df = 7$; $R = 0.468$ for significantly positive correlation when $n = 18$ and $df = 16$)

	1982–1990			1991–1999			1982–1999		
Vegetation type	*S*	*B*	*R*	*S*	*B*	*R*	*S*	*B*	*R*
Evergreen broadleaf forest	−0.273	−1.14	−0.28	1.024	4.49	0.88	0.001	0.00	0.00
Evergreen coniferous forest	0.020	0.14	0.04	0.708	4.81	0.86	0.098	0.67	0.29
Shrub	−0.303	−0.64	−0.32	1.637	3.34	0.87	0.302	0.62	0.4
Desert	0.082	0.74	0.34	0.354	3.05	0.79	0.093	0.81	0.50
Grassland	0.311	0.73	0.41	0.837	1.83	0.56	0.406	0.91	0.61
Alpine meadow	−0.544	−0.83	−0.38	2.246	3.29	0.83	0.426	0.64	0.39
Cultivation	0.062	1.66	0.43	0.115	2.69	0.83	0.069	1.73	0.77

3.3. NPP TRENDS BY VEGETATION TYPE

NPP trends for different vegetation types allow us to better understand the pattern of NPP change. Similar to the change in annual NPP over the 18 years, annual NPP for most vegetation types increased significantly from 1991 to 1999, and lacked any pronounced trend between 1982 and 1990 (Table II).

The annual NPP trends differed among vegetation types. From 1982 to 1990, annual NPP for evergreen broadleaf forests, shrubs, and meadows decreased sharply, while that for the remainders it increased (Table II). Among the seven vegetation types, agricultural areas showed the largest annual mean increase rate (1.6% yr^{-1}). To figure out the possible mechanisms that cause increase or decrease in annual NPP, we calculated coefficients of correlation between annual mean NDVI, annual precipitation, annual mean temperature, annual solar radiation, and year for each vegetation type during periods of the study (Table III). The results showed that solar radiation decreased significantly and that other climatic variables all increased for all vegetation types, suggesting that these climate parameters could not explain increased NPP for the three vegetation types and decreased NPP for the rests. This raised a question to be answered.

From 1991 to 1999, annual NPP tended to increase for all vegetation types except grasslands. The largest annual NPP increase (2.25 Tg C yr^{-2}) was observed in alpine meadows, accounting for 32.3% of the plateau total increase. Shrubs and evergreen broadleaf forest increased by 1.64 and 1.02 Tg C yr^{-2}, respectively. Evergreen coniferous forest had the largest annual mean increase rate (4.81% yr^{-1}), followed by evergreen broadleaf forest (4.49% yr^{-1}).

TABLE III

Coefficients of correlation between annual mean NDVI, annual precipitation (*P*), annual mean temperature (*T*), annual solar radiation (SOL), and year for each vegetation type during 1982–1990, 1991–1999, and 1982–1999 ($R = 0.667$ for significantly positive correlation, $n = 9$, $df = 7$; $R = 0.468$ for significantly positive correlation, $n = 18$, $df = 16$)

	1982–1990				1991–1999				1982–1999			
Vegetation type	NDVI	*P*	*T*	SOL	NDVI	*P*	*T*	SOL	NDVI	*P*	*T*	SOL
Evergreen broadleaf forest	0.86	0.54	0.38	−0.81	0.67	0.37	0.64	0.63	0.34	0.45	0.56	−0.25
Evergreen coniferous forest	0.82	0.62	0.42	−0.89	0.71	0.33	0.49	0.66	0.52	0.34	0.5	−0.22
Shrub	0.70	0.33	0.64	−0.88	0.08	0.48	0.38	0.61	0.47	0.15	0.55	−0.18
Desert	0.62	0.29	0.71	−0.84	0.05	0.48	0.6	0.52	0.50	0.12	0.72	−0.05
Grassland	0.71	0.20	0.66	−0.86	−0.15	0.6	0.45	0.57	0.44	0.05	0.63	0.01
Alpine meadow	0.77	0.42	0.55	−0.9	0.23	0.42	0.36	0.66	0.53	0.07	0.49	−0.14
Cultivation	0.90	0.75	0.77	−0.79	0.71	0.6	0.58	0.65	0.82	0.56*	0.62	−0.02

4. Discussion

Large-scale vegetation production cannot be measured directly. Therefore, estimating terrestrial vegetation production by ecological models has become an indispensable technique (Cramer et al., 1999). A number of different models have been used to estimate NPP at large spatial scales, but few studies have investigated NPP in the Qinghai-Xizang Plateau, due to limited field and ground observations. Recently, Luo et al. (2002) calculated annual NPP in the plateau based on an empirical statistical model. According to their simulation, annual NPP of natural vegetation in the plateau was 0.285 Pg C, approximating our estimation of 0.212 ± 0.017 Pg C (including areas under cultivation). In addition, Ni (2000) estimated annual NPP for different vegetation types on the plateau using the Biome3 model. This model estimated forest NPP between 220 and 810 g C m^{-2} yr^{-1}, and other vegetation types below 200 g C m^{-2} yr^{-1}.

Previous observational and NPP modeling studies have documented substantial evidence that terrestrial photosynthetic activity has increased over the past two to three decades in the middle- and high latitudes in the Northern Hemisphere (Fang et al., 2001b, 2003; Pacala et al., 2001; Hicke et al., 2002; Cao et al., 2003). Recently developed satellite-based NDVI data sets for the period of 1982–1999 also indicate consistent trends of NDVI increase (Myneni et al., 1997; Zhou et al., 2001; Tucker et al., 2001; Piao et al., 2003; Slayback et al., 2003). However, this increase has been found to differ greatly in the magnitude and spatial distribution (Table IV). For example, with use of a satellite-based model, Nemani et al. (2003) reported that the global NPP increased by 6.17% (3.4 Pg C) over the past 18 years (or 0.34% yr^{-1}), while this value was 10% during the 1980s (1.2% yr^{-1}) based on Malmström et al.

TABLE IV
NDVI-based NPP estimates in Tibet and other regions and the global

Region	Period	NPP ($Pg\,C\,yr^{-1}$)	Trend ($Pg\,C\,yr^{-2}$)	Relative trend ($\%\,yr^{-1}$)	Reference
Global	1982–1999	55.9*	0.19	0.34	Nemani et al. (2003)
	1982–1990	56.4	0.69	1.2	Malmström et al. (1997)
	1983–1991	55	0.1–0.24**	0.18–0.44	Ichii et al. (2001)
North America	1982–1998	6.2	0.03	0.47	Hicke et al. (2002)
China	1982–1999	1.4	0.015	1.03	Fang et al. (2003)
Amazon Basin	1982–1999	–	–	>1	Nemani et al. (2003)
Tibet	1982–1990	0.21	−0.0006	−0.29	This study
	1991–1999	0.22	0.0069	3.12	This study
	1982–1999	0.21	0.0014	0.66	This study

Dashes depict no estimates.
*Estimated from NPP trend and relative NPP trend.
**Estimated from mean NPP and relative NPP trend.

(1997) and Potter et al. (1999). Fang et al. (2003) suggested that terrestrial NPP in China increased at a total rate of 18.5%, or 1.03% annually over the period 1982–1999, which is larger than that in North America (0.47% yr^{-1}) (Hicke et al., 2002). In this study, we found that the NPP had increased by an annual rate of 0.7% in the Qinghai-Xizang Plateau from 1982 to 1999, with a smaller rate than that over China. Moreover, the NPP trends in the plateau over the two decades were divided into two distinguished periods: without any clear trend from 1982 to 1990 ($R = -0.16$, $P = 0.67$) and significant increase from 1991 to 1999 ($R = 0.89$, $P = 0.001$). This suggests that vegetation growth on the plateau in the 1990s has been much enhanced compared to that in 1980s, consistent with the trend in the northern latitudes indicated by Schimel et al. (2001).

Terrestrial vegetation production is quite sensitive to climate changes (Dai et al., 1993). It is well known that temperature, precipitation, and solar radiation are the dominant controllers of plant photosynthesis (Dai et al., 1993; Peng and Apps, 1999; Nemani et al., 2003). To determine the effects of climatic variables on the NPP trends at the regional scale, we calculated the correlations between total NPP and solar radiation, temperature and annual precipitation. We found solar radiation correlated most strongly with NPP ($R = 0.59$, $p = 0.01$), followed by temperature ($R = 0.44$, $p = 0.07$) and precipitation ($R = 0.15$, $p = 0.54$). This suggests that changes in solar radiation may play a critical role in NPP variation and support the conclusions of Nemani et al. (2003). Previous studies have reported that surface solar radiation significantly declined during 1960–1990 in the United States (Liepert, 2002) and China (Cha, 1995; Li et al., 1998). However, such radiation was found to increase since the early 1990s in China (Zhang et al., 1999), which the results presented in this study support.

Mechanisms other than climate, such as CO_2 fertilization, N deposition and land-use change that affect NDVI may also play roles in the increasing NPP trend (Schimel et al., 2001). However, these factors were not quantified in our study because they are not directly modeled in the CASA.

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References

Asner, G. P.: 2000, 'Contribution of multi-view angle remote sensing to land-surface and biogeochemical research', *Remote Sens. Environ.* **18**, 137–162.

Behrenfeld, M. J., Randerson, J. T., McClain, C. R., Feldman, G. C., Los, S. O., Tucker, C. J., Falkowski, P. G., Field, C. B., Frouin, R., Esaias, W. E., Kolber, D. D., and Pollack, N. H.: 2001, 'Biospheric primary production during an ENSO transition', *Science* **291**, 2594–2597.

Braswell, H., Schimel, S., Linder, E., and Moore III: 1997, 'The response of global terrestrial ecosystems to interannual temperature variability', *Science* **278**, 868–872.

Cao, M. K., Prince, S. D., Li, K. R., Tao, B., Small, J., and Shao, X. M.: 2003, 'Response of terrestrial carbon uptake to climate interannual variability in China', *Global Change Biol.* **9**, 536–546.

Cha, L. S.: 1995, 'Research on the variation of solar radiation in northwest China', *Arid Land Geogr.* **18**, 8–13.

Cramer, W., Kicklighter, D. W., Bondeau, A., Moore, B., Churkina, C., Nemry, B., Ruimy, A., and Schloss, A. L.: 1999, 'Comparing global models of terrestrial net primary productivity (NPP): Overview and key results', *Global Change Biol.* **5**(Suppl. 1), 1–15.

Deng, Q.: 1986, 'Map of soil texture of China', in Institute of Soil Science, Academia Sinica (ed.), *The Soil Atlas of China*, Cartographic Publishing House, Beijing, pp. 23–24.

Editorial Committee for Physical Geography of China: 1985, Physical Geography of China: Climate, Science Press, Beijing.

Editorial Committee for Vegetation of China: 1980, *Vegetation of China*, Science Press, Beijing.

Fang, J. Y., Piao, S. L., Tang, Z. Y., Peng, C. H., and Ji, W.: 2001a, 'Relationship between interannual variability in net primary production and precipitation', *Science* **293**, 1723a.

Fang, J. Y., Chen, A. P., Peng, C. H., Zhao, S. Q., and Ci, L. J., 2001b, 'Changes in forest biomass carbon storage in China between 1949 and 1998', *Science* **292,** 2320–2322.

Fang, J. Y., Piao, S. L., Field, C. B., Pan, Y. D., Guo, Q. H., Zhou, L. M., Peng, C. H., and Tao, S.: 2003, 'Increasing net primary production in China from 1982 to 1999', *Front. Ecol. Environ.* **1**(6), 293–297.

Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P.: 1998, 'Primary production of the biosphere: Integrating terrestrial and oceanic components', *Science* **281**, 237–240.

Field, C. B., Randerson, J. T., and Malmström, C. M.: 1995, 'Global net primary production: Combing ecology and remote sensing', *Remote Sens. Environ.* **51**, 74–88.

Gutman, G.: 1999, 'On the use of long-term global data of land reflectances and vegetation indices derived from the advanced very high resolution radiometer', *J. Geophys. Res.* **104**, 6241–6255.

Hansen, J., Ruedy, R., Sato, M., and Reynolds, R.: 1996, 'Global surface air temperature in 1995: Return to pre-Pinatubo level', *Geophys. Res. Lett.* **23**, 1665–1668.

Hicke, J. A., Asner, G. P., Randerson, J. T., Tucker, C., Los, S., Birdsey, R., Jenkins, J. C., Field, C., and Holland, E.: 2002, 'Satellite-derived increases in net primary productivity across North America, 1982–1998', *Geophys. Res. Lett.* **29**, doi: 10.1029/2001GL013578.

Holben, B. N.: 1986, 'Characteristics of Maximum Value Composite images from temporal AVHRR data', *Int. J. Remote Sens.* **7**, 1417–1434.

Ichii, K., Matsui, Y., Yamaguchi, Y., and Ogawa, K.: 2001, 'Comparison of global net primary production trends obtained from satellite-based normalized difference vegetation index and carbon cycle model', *Global Biogeochem. Cycles* **15**, 351–363.

Institute of Geography, Chinese Academy of Sciences: 1986, *Digitized Vegetation Map of China*, National Laboratory for GIS and Remote Sensing, Beijing.

Intergovernmental Panel on Climate Change (IPCC): 2001, *Climate Change 2001: Impact, Adaptation, and Vulnerability*, Cambridge University Press, Cambridge.

Keeling, C. D., Chin, J. F. S., and Whorf, T. P.: 1996, 'Increased activity of northern vegetation inferred from atmospheric CO_2 measurements', *Nature* **382,** 146–149.

Li, X. W., Li, W. L., and Zhou, X. Y.: 1998, 'Analysis of the solar radiation variation of China in recent 30 years', *Quart. J. Appl. Meteorol.* **9**, 24–31.

Li, W. H., Wang, Q. J., Luo, T. X., Luo, J., Zhang, X. Z., and Lin, Z. H.: 1998, 'Biomass and productivity of ecosystems in Qinghai-Xizang Plateau', in Li, W. H. and Zhou, X. M. (eds.), *Ecosystems of Qinghai-Xizang Plateau and Approach for Their Sustainable Management*, Guangdong Science and Technology Press, Guangzhou, pp. 183–250.

Liepert, B. G.: 2002, 'Observed reductions of surface solar radiation at sites in the United States and worldwide', *Geophys. Res. Lett.* **29**, article no. 1421.

Lin, Z. Y. and Zhao, X. Y.: 1996, 'Spatial characteristics of changes in temperature and precipitation of the Qinghai-Xizang (Tibet) plateau', *Sci. China Ser. D Earth Sci.* **39**, 442–448.

Los, S. O., Collatz, G. J., Bounoua, L., Sellers, P. J., and Tucker, C. J.: 2001, 'Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation', *J. Clim.* **14**, 1535–1549.

Lucht, W., Prentice, L. C., Myneni, R. B., Sitch, S., Friedlingstein, P., Cramer, W., Bousquet, P., Buermann, W., and Smith, B.: 2002, 'Climatic control of the high-latitude vegetation greening trend and Pinatubo effect', *Science* **296,** 1687–1689.

Luo, T. X., Li, W. H., and Zhu, H. Z.: 2002, 'Estimated biomass and productivity of natural vegetation on the Tibetan Plateau', *Ecol. Appl.* **12**(4), 980–997.

Malmström, C. M., Thompson, M. V., Juday, G. P., Los, S. O., Randerson, J. T., and Field, C. B.: 1997, 'Interannual variation in global-scale net primary production: Testing model estimates', *Global Biogeochem. Cycles* **11**: 367–392.

Melillo, J. M., McGuire, A. D., Kicklighter, D. W., Moore, B., Vorosmarty, C. J., and Schloss, A. L.: 1993, 'Global climate change and terrestrial net primary production', *Nature* **363**, 34–240.

Minnis, P., Harrison, E. F., Stowe, L. L., Gibson, G. G., Denn, F. M., Doelling, D. R., and Smith, W. L.: 1993, 'Radiative climate forcing by the mount Pinatubo eruption', *Science* **259**, 1411–1415.

Monteith, J. L.: 1977, 'Climate and efficiency of crop production in Britain [J]', *Trans. R. Soc. Lond. Ser. B* **281**, 271–294.

Myneni, R. B., Keeling, C. D., Tucker, C. J., Asrar, G., and Nemani, R. R.: 1997, 'Increased plant growth in the northern high latitudes from 1981–1991', *Nature* **386**, 698–702.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W.: 2003, 'Climate-driven increases in global terrestrial net primary production from 1982 to 1999', *Science* **300**, 1560–1563.

Ni, J.: 2000, 'A simulation of biomes on the Tibetan plateau and their responses to global climate change', *Mt. Res. Dev.* **20**, 80–99.

Pacala, S. W., Hurtt, G. C., Baker, D., Peylin, P., Houghton, R. A., Birdsey, R. A., Heath, L., Sundquist, E. T., Stallard, R. F., Ciais, P., Moorcroft, P., Caspersen, J. P., Shevliakova, E., Moore, B., Kohlmaier, G., Holland, E., Gloor, M., Harmon, M. E., Fan, S. M., Sarmiento, J. L., Goodale, C. L., Schimel, D., and Field, C. B.: 2001, 'Consistent land- and atmosphere-based US carbon sink estimates', *Science* **292**, 2316–2320.

Peng, C. H. and Apps, M. J.: 1999, 'Modelling the response of net primary productivity (NPP) of boreal forest ecosystems to changes in climate and fire disturbance regimes', *Ecol. Model.* **122**, 225–238.

Piao, S. L., Fang, J. Y., Zhou, L. M., Guo, Q. H., Henderson, M., Ji, W., Li, Y., and Tao, S.: 2003, 'Interannual variations of monthly and seasonal NDVI in China from 1982 to 1999', *J. Geophys. Res. Atmos.* **108**, doi: 10.1029/2002JD002848.

Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., and Klooster, S. A.: 1993, 'Terrestrial ecosystem production: A process model based on global satellite and surface data', *Global Biogeochem. Cycles* **7**, 811–841.

Potter, C. S., Klooster, S., and Brooks, V.: 1999, 'Interannual variability in terrestrial net primary production: Exploration of trends and controls on regional to global scales', *Ecosystems* **2**, 36–48.

Running, S. W., Thornton, P. E., Nemani, R., and Glassy, J.: 2000, 'Global terrestrial gross and net primary productivity from the earth observing system', in Sala, O. E., Jackson, R. B., Mooney, H. A. and Howarth, R. W. (eds.), *Methods in Ecosystem Science*, Springer, New York, pp. 44–57.

Schimel, D. S., House, J. I., Hibbard, K. A., Bousquet, P., Ciais, P., Peylin, P., Braswell, B. H., Apps, M. J., Baker, D., Bondeau, A., Canadell, J., Churkina, G., Cramer, W., Denning, A. S., Field, C. B., Friedlingstein, P., Goodale, C., Heimann, M., Houghton, R. A., Melillo, J. M., Moore, B., Murdiyarso, D., Noble, I., Pacala, S. W., Prentice, I. C., Raupach, M. R., Rayner, P. J., Scholes, R. J., Steffen, W. L., and Wirth, C.: 2001, 'Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems', *Nature* **414**, 169–172.

Schimel, D., Melillo, J., Tian, H. Q., McGuire, A. D., Kicklighter, D. M., Kittel, T., Rosenbloom, N., Running, S., Thornton, P., Ojima, D., Parton, W., Kelly, R., Sykes, M., Neilson, R., and Rizzo, B.: 2000, 'Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the united states', *Science* **287**, 2004–2006.

Sellers, P. J., Meeson, B. W., Hall, F. G., Asrar, G., Murphy, R. E., Schiffer, R. A., Brethrton, F. P., Dickinson, R. E., Ellingson, R. G., Filed, C. B., Huemmrich, K. F., Justice, C. O., Melack, J. M., Roulet, N. T., Schimel, D. S., and Try, P. D.: 1995, 'Remote sensing of the land surface for studies of global change: Models–algorithms–experiments', *Remote Sens. Environ.* **51**, 3–26.

Slayback, D., Pinzon, J., Los, S., and Tucker, C.: 2003, 'Northern Hemisphere photosynthetic trends 1982–1999', *Global Change Biol.* **9**, 1–15.

Stowe, L. L., Garey, R. M., and Pellegrino, P. P.: 1992, 'Monitoring the MT. Pinatubo aerosol layer with NOAA/11AVHRR data', *Geophys. Res. Lett.* **19**, 159–162.

Tucker, C. J., Newcomb, W. W., and Dregne, A. E.: 1994, 'AVHRR data sets for determination of desert spatial extent', *Int. J. Remote Sens.* 15, 3547–3566.

Tucker, C. J., Slayback, D. A., Pinzon, J. E., Los, S. O., Myneni, R. B., and Taylor, M. G.: 2001, 'Higher northern latitude NDVI and growing season trends from 1982 to 1999', *Int. J. Biometeorol.* **45**, 184–190.

Yao, T. D., Liu, X. D., Wang, N. L., and Shi, Y. F.: 2000, 'Amplitude of climatic changes in Qinghai-Tibetan Plateau', *Chin. Sci. Bull.* **45**, 1236–1243.

Zhang, X. F., Chen, D., Fu, X. J., and Zheng, Y. H.: 1999, 'Analysis of the regularity and forming reasons of the solar radiation variation of Henan in recent 40 years', *Meteorol. Month.* **25**, 21–25.

Zhao, S. Q.: 1994, *Geography of China: Environment, Resources, Population and Development*, Willey, New York.

Zhou, L. M., Kaufmann, R. K., Tian, Y., Myneni, R. B., and Tucker, C. J.: 2003, 'Relation between interannual variations in satellite measures of northern forest greenness and climate between 1982 and 1999', *J. Geophys. Res. Atmos.* **108**(D1), doi: 10.1029/2002JD002510.

Zhou, L. M., Tucker, C. J., Kaufmann, R. K., Slayback, D., Shabanov, N. V., and Myneni, R. B.: 2001, 'Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999', *J. Geophys. Res. Atmos.* **106**(D17), 20069–20083.

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