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ORIGINAL ARTICLE

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Interannual NPP variation and trend of *Picea schrenkiana* forests under changing climate conditions in the Tianshan Mountains, Xinjiang, China

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Abstract The interannual net primary production variation and trends of a *Picea schrenkiana* forest were investigated in the context of historical changes in climate and increased atmospheric CO_2 concentration at four sites in the Tianshan Mountain range, China. Historical changes in climate and atmospheric CO_2 concentration were used as Biome–BGC model drivers to evaluate the spatial patterns and temporal trends of net primary production (NPP). The temporal dynamics of NPP of *P. schrenkiana* forests were different in the western, middle and eastern sites of Tianshan, which showed substantial interannual variation. Climate changes would result in increased NPP at all study sites, but only the change in NPP in the western forest (3.186 gC m^{-2} $year^{-1}$, $P < 0.05$) was statistically significant. Our study also showed a higher increase in the air temperature, precipitation and NPP during 1987–2000 than 1961–1986. Statistical analysis indicates that changes in NPP are positively correlated with annual precipitation ($R = 0.77$–0.92) but that NPP was less sensitive to changes in air temperature. According to the simulation, increases in atmospheric CO_2 increased NPP by improving the water use efficiency. The results of this study show that the Tianshan Mount boreal forest ecosystem is sensitive to historical changes in climate and increasing atmospheric CO_2. The relative impacts of these variations on NPP interact in complex ways and are spatially variable, depending on local conditions and climate gradients.

Keywords BIOME–BGC · Boreal forest · Climate change · Interannual variation · Net primary production (NPP)

Introduction

The Intergovernmental Panel for Climate Change (IPCC) report clearly indicates that warming of the climate system is unequivocal—and very likely due to rapidly increasing atmospheric levels of greenhouse gas (such as CO_2) caused by human activities (IPCC 2007). The climate change in Northwest China shows a considerable similarity to the global situation (Ding et al. 2006): although climate change over the last century (since the end of Little Ice Age) has been dominated by a warm and drought trend, strong signals of climatic shift to a warm, humid pattern have been appearing in the Tianshan Mountain and neighboring regions since 1987 (Shi et al. 2002, 2003). The projection of climate change due to greenhouse effects in Northwest China, as simulated by a regional climate model under $2 \times CO_2$, has indicated that the mean annual temperature will increase 2.7°C, with about a 3.0°C increase in the winter and spring, during the next 100 years. During this same time period, annual precipitation will usually increase by more than 20% in most of Northwest China and by 30% or more in some places (Gao et al. 2003b). Therefore, the effects of climate change on vegetation in this region has been the focus of concern (Chen et al. 2004; Guo et al. 2007; Su et al. 2007; Xie et al. 2007).

Forests, which currently cover approximately 30–40% of the vegetated area of the earth, are essential in determining the state of the global climate system and carbon cycle (Dixon et al. 1994). Boreal forests are of particular importance in both the global climate system, as they expected to undergo the greatest climatically induced change in the twenty-first century (Bonan et al. 1992), and in the world carbon budget, because forests have been suggested as possible sinks for the 'missing

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carbon' (Ciais et al. 1995). The boreal forests of China are mainly distributed in northeastern (Daxingan Mountains) and northwestern China (Altai and Tianshan Mountains) (ECVC 1980). In the study reported here, we have focused on the zonal boreal forests on the northern slopes of Tianshan Mountain.

The Tianshan Mountains form a large, isolated mountain range surrounded by desert basins to the norther and south. The distribution of forest in this mountainous region is limited to areas of sufficient moisture and warmth. The tree line, where the average temperature during the warmest month is 10°C, is 2700 m a.s.l. Areas below 1500 m a.s.l., on the other hand, are generally too dry to support forest vegetation (Zhang and Tang 1989). Boreal spruce forest is the most productive and widespread forest type on the northern slopes of the Tianshan Mountains. It is also one of the most important zonal vegetations in the arid land of the Xinjiang Uygur Autonomous Region, China, accounting for 60.8% of the timber growing stock and 54.0% of forested areas (Zhang and Tang 1989). Therefore, it is also economically important to determine how *Picea schrenkiana* forest ecosystems respond to climate change and increasing CO_2 levels. One line of evidence for projecting the future performance of *P. schrenkiana* forests is how they have responded to the substantial interannual climatic variation in recent decades. Many studies have focused on the growth and production of forests on the Tianshan Mountains during the last decade (Zhang et al. 1980; Sun 1994; Wang and Zhao 2000; Li et al. 2003; Ni 2004), but only a few studies measured past interannual variations and long-term trends of *P. schrenkiana* forest to climate change in this region (Ma et al. 2003; Chen et al. 2004).

Four approaches are commonly used to evaluate the response of forests to climate change in mountain forest areas: forest inventory, standard statistical dendroclimatic analysis, remote sensing method and process-based ecosystem modeling. The forest inventory provides an estimate of the actual biomass accumulation in each period (Fang and Chen 2001). The factors considered in such biomass inventories include forest regrowth following a disturbance, enhanced growth due to climate change, CO_2 fertilization and nitrogen deposition (Dixon et al. 1994). While being very informative, forest inventory cannot distinguish the effects of changing temperature, precipitation and increasing atmospheric CO_2 on growth. Standard statistical dendroclimatic analysis, in contrast, can facilitate the identification of pertinent climatic variables and periods when tree growth was affected by climate change (Yuan and Li 1994; Zhu et al. 2004; Guo et al. 2007). Tree rings provide information on carbon allocation to stem growth, but this information cannot be taken to reflect the growth of a whole forest ecosystem. Recently, there has been increasing interest in estimating vegetation cover and production by normalized difference vegetation index (NDVI) derived from remote sensing images (NOAA/AVHRR) (Luo et al. 2003; Ma et al. 2003; Chen et al. 2004; Xie et al. 2007). This technique provides a high-resolution map of current vegetation in the landscape and integrates well with regional studies.However, NDVI spatial variations result from changes in the surface density of a forest canopy, and the linkage between NDVI and the ground-based growth is not uniform, with variations depending on the terrain and environment. Moreover, the remote sensing method is limited to short-term studies, since most of the remote sensing data were obtained during or after the 1980s. Theoretically, the approach of process-based ecosystem modeling allows the researcher to determine the relative roles of climate and CO_2 on production and avoids many of the limitations already stated for other techniques by integrating ecosystem processes and spatial variations to environmental factors (Cramer et al. 1999).

Models have been developed to study the responses in terms of net primary productivity (NPP), a key ecosystem variable and the most critical biotic component of the global carbon cycle, which is defined as the difference between gross primary production and the sum of the maintenance and growth respiration components (Cramer et al. 2001). A process-based ecosystem model, BIOME-BGC, simulates the storage and fluxes of water, carbon and nitrogen within the vegetation, litter and soil components of a terrestrial ecosystem and has been used to quantify the effect on NPP under different climate scenarios in oasis areas along the Tianshan Mountains in Xinjiang, China with an arid climate (Gao et al. 2003a). The model parameters were usually derived from published information, but the ability of BIOME-BGC to simulate the NPP of *P. schrenkiana* forests on the Tianshan Mountains has been confirmed using independent field data (Su et al. 2007). Thus, the model can be used as tool to explore the fluctuation of forest growth as a variable of climate change.

The aim of the study reported here was to investigate the evidence of past NPP changes and trends of *P. schrenkiana* forest under the climate change that occurred in recent decades and to assess, using process-based ecosystem model, the historical effect of fluctuations in climate and atmospheric CO_2 on forest production.

Materials and methods

Study sites

The study was undertaken at the middle elevations of the northern slopes of the Tianshan Mountains (Fig. 1). Forests in the region are dominated by *P. schrenkiana*. Some broad-leaved trees and shrubs, such as *Sorbus tianschanica* Rupr., *Salix xerophila* Flod., *Betula tianschanica* Rupr., *B. verrucosa* Ehrh. and *B. microphylla* Bunge, are found in the forest. There is also a dense understorey of *Sabina pseudosabina* (Fisch. et May) (Zhang and Tang 1989). Four sites, Zhaosu (ZS) in western Tianshan, Tianchi (TC) and Xiaoquzi (XQZ) in

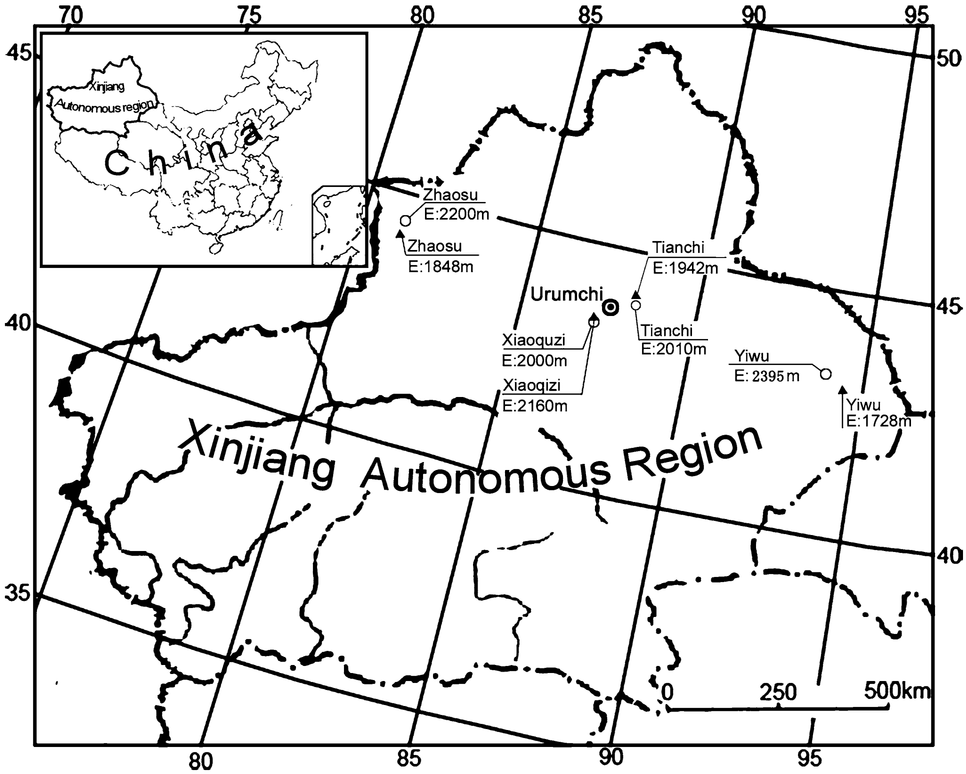

Fig. 1 Study sites of *Picea schrenkiana* forests in the Xinjiang Uygur Autonomous Region, China. *Open circle* Plot sites, *filled triangle* meteorological stations, *E* elevation of sites

Table 1 General stand characteristics of the four forest sites on the north slopes of the Tianshan Mountains, Xinjiang Uygur Autonomous Region, China

Study site	Code	Species[a]	Density (ha^{-1}) Mean (min–max)	DBH (cm)[b]	Height (m)	Soil type[c]	Soil texture (%)			Soil depth (m)
							Sand	Silt	Clay	
Zhaosu	ZS	*P.* spp.	1123(700–2200)	17.9 ± 9.6	11.0 ± 5.6	MLGS	19.79	66.21	14.00	1.50
Xiaoquzi	XQZ	*P.* spp.	1269(825–1700)	17.1 ± 8.7	13.5 ± 5.5	MTGS	26.17	51.67	22.16	0.85
Tianchi	TC	*P.* spp.	1975(1050–3450)	15.6 ± 9.0	11.4 ± 5.7	MTGS	26.17	51.67	22.16	0.85
Yiwu	YW	*P.* spp. *L.* spp.	1583(975–3250)	17.5 ± 9.8	11.9 ± 5.6	MCGS	28.18	50.62	21.20	1.00

[a] *P.* spp. *Picea schrenkiana* var. *tianschanica*; *L.* spp., *Larix sibirica*

[b] DBH is diameter at breast height (cm); DBH and height are expressed in mean ± 1 SD

[c] MLGS, Mountain leaching gray-cinnamon forest soil; MTGS, mountain typical gray-cinnamon forest soili; MCGS, mountain carbonate gray-cinnamon forest soil

middle Tianshan, and Yiwu (YW) in eastern Tianshan, were selected for this study (Table 1). These sites have different climatic conditions in the various regions of the northern slopes of the Tianshan Mountain.

The process-based ecosystem model

The BIOME-BGC model, a multi-biome generalization of the FOREST-BGC model (Running and Coughlan 1988), is a general ecosystem process model designed to simulate daily biogeochemical and hydrologic processes from stand to global scales (Running and Hunt 1993; White et al. 2000; Thornton et al. 2002). Details of the model are presented elsewhere and the model has been successfully applied over a range of diverse biomes, spatial scales and climate regimes, including boreal forests of the Tianshan Mountains (e.g. Churkina and Running 1998; Churkina et al. 2003; Gao et al. 2003a; Hanson et al. 2004; Law et al. 2004; Kang et al. 2006; Schmid et al. 2006; Kimball et al. 2007; Su et al. 2007). Version 4.1.1 of the BIOME-BGC model was used in this study.

Model parameterization

The major input variables for the model include climate, vegetation ecophysiological parameters and site condition parameters. In this study, non-site-specific ecophysiological parameters for *P. schrenkiana* forests [taken from data gathered on-site when available; otherwise, species-specific values were used from a recent literature synthesis (White et al. 2000)]. For details on the parameters, see Su et al. (2007). This parameterization reflects an important model assumption that the four *P. schrenkiana* forests have the same physiology and remain constant throughout all the simulation. Site-specific parameters, such as soil texture (clay, silt and sand content) and effective soil depth, were obtained from field data (Table 1).

The standard daily meteorological input file for BIOME-BGC was generated by a microclimate simulation model, MT-CLIM (version 4.3; www.forestry.umt.edu/ntsg) (Kimball et al. 1997; Thornton and Running 1999; Thornton et al. 2000). The original climate records (including daily minimum and maximum air temperature and precipitation over the period 1961–2000) from meteorological stations near the sites were obtained from the China National Climatic Data Center (NCDC) (Fig. 1). A coefficient adjusting the daylight average temperature (TEMCF), which was set to 0.45 in the original MT-CLIM model, was set to −0.11, −0.12, −0.12,and −0.07 for ZS, TC, XQZ, and YW, respectively, based on the daily temperature observations in those areas. The XQZ and TC stations are centrally located in the study region and fall within the elevation range of the plots under study, so the weather data could be used without interpolation. MT-CLIM initialized the flat surface conditions of the two sites to the same elevation as the original station data to compute the variables not present in standard weather station records for the BIOME-BGC model. However, the ZS and YW stations are some distance from the study sites (about 10 and 25 km, respectively), which may have introduced some uncertainty into the climate data used for the simulations. Therefore, the daily data were adjusted for site conditions using MT-CLIM based on the elevation, longitude and latitude. Here, the precipitation pattern and lapse rates for the minimum and maximum air temperature were estimated using data obtained from earlier studies on the climate conditions of the Tianshan Mountains (Wei and Hu 1990; Zhou 1995; Yang et al. 2006).

Simulation experiments

Two simulations with BIOME-BGC were performed: one considered climate and CO_2 changes together, and the other considered only climate change. These two runs were compared to determine the effect of CO_2 fertilization on NPP. All analyses were based on the run combining climate and CO_2 changes.

In both cases, the model was first run until a steady-state condition was achieved for each forest site (the spin-up run). Throughout this process, the 40-year climate record was repeated as often as necessary. Atmospheric CO_2 concentrations were set to 294.8 ppmv throughout the spin-up run, thereby approximating levels at the end of the nineteenth century (Churkina et al. 2003). Next, taking the spin-up endpoint as an initial condition, the effect of climate change was simulated under historical daily climate data from 1961 to 2000. The same parameters were used in the two stages of the simulation. The runs with both climate and CO_2 changes used the historical CO_2 and daily climate data from 1961 to 2000 as inputs. Here, historical records of atmospheric CO_2 concentrations at the Mauna Loa Observatory were used (Keeling and Whorf 2002). The atmospheric CO_2 level has increased by 16.3% (from 317.2 to 368.8 ppmv) over the study period.

Data analysis

1. For each of the four sites, we applied simple linear regression to explore possible trends of the two climate parameters (the mean annual temperature and total annual precipitation) and simulated NPP during the 40-years period. Because recent research suggests that a climatic shift from warm–dry to warm–wet occurred in 1987 in the middle and west regions of Northwest China (Shi et al. 2002, 2003), we additionally split our data in two different time spans: 1961–1986 and 1987–2000. Essentially, we were interested in noting whether the findings of Shi et al. are consistent with those of our study. For both the time spans, again, a simple linear regression was applied to our climate.
2. Annual mean temperature and annual precipitation were used together with the simulated NPP to examine the patterns of interannual variability in the productivity of *P. schrenkiana* forests in relation to some potential climatic predictors using lagged cross-correlation analysis with SPSS for Windows ver. 11.0 statistical software (SPSS, Chicago, IL). The time lags (0, 1 and 2 years), which were suggested for the cross-correlation analyses, were thought to incorporate both immediate physiological alterations and delayed biogeochemical adjustments of *P. schrenkiana* forest ecosystems due to variable climate.
3. The net CO_2 fertilization effect on growths for the time period 1961–2000 was calculated as the difference in NPP between the two experiments (climate with CO_2 and climate only). Then, annual mean temperature, annual precipitation and water-use efficiency [WUE, defined as the ratio between annual NPP and annual total evapotranspiration (mm year^{-1})] were used to examine how these factors influence the strength of the CO_2 fertilization effect that governs the activity of forest ecosystem.

Results

Climate analysis

During the period between 1961 and 2000, the mean changes of the temperature were +0.021°C year^{-1}

($P < 0.05$) at the ZS and YW sites. However, the warming trends in terms of annual means at XQZ and TC (both +0.008°C year^{-1}) were not statistically significant (Table 2). There was also a trend towards a higher increase in the air temperature during 1987–2000 than 1961–1986.

Precipitation change was a very complicated parameter at the four study sites during 1961–2000 (Table 2). Although the average annual precipitation decreased by 0.72 mm year^{-1} at ZS, increased by 2.12 mm year^{-1} at XQZ and increased by 1.36 mm year^{-1} at TC, the linear trend test results showed that the trends over time were weak and statistically insignificant. Only the trend in YW was significant (+2.333 mm year^{-1}, $P = 0.019$).

Trends in NPP

Based on the BIOME-BGC simulations, we estimated the NPP of four *P. schrenkiana* forest ecosystems on the northern slopes of the Tianshan Mountains during the period 1961–2000 (Table 2). ZS in the west had the highest annual NPP (mean 595.9 ± 11.0 g C m^{-2} year^{-1}, range 479.9–757.6 gC m^{-2} year^{-1}), followed by XQZ (mean 510.4 ± 22.6 gC m^{-2} year^{-1}, range 151.2–718.6 gC m^{-2} year^{-1}) and TC (mean 518.3 ± 27.5 gC m^{-2} year^{-1}, range 71.4–775.2 gC m^{-2} year^{-1}); YW, the cool and dry eastern site, has the lowest NPP (mean 327.7 ± 15.4 gC m^{-2} year^{-1}, range 123.2–594.4 gC m^{-2} year^{-1}).

The annual NPP showed substantial interannual variations, with very different temporal patterns for each site (Fig. 2). Higher NPP occurred in 1964, 1980 and 1998 at most of the sites, declining sharply in 1976 and 1997. Linear trend analysis revealed that NPP in the period 1961–2000 increased by an average of 0.351 gC m^{-2} year^{-1} at ZS, 2.139 gC m^{-2} year^{-1} at XQZ, 1.977 gC m^{-2} year^{-1} at TC and 3.186 gC m^{-2} year^{-1} at YW. The increase in NPP was only significant at YW ($P < 0.05$). Again, we found a higher increase in the NPP during 1987–2000 than during 1961–1986 (Table 2).

Influence of climate fluctuation on NPP

In the west (ZS), middle (XQZ, TC) and east (YW) of the Tianshan Mountains, different climate-driven processes regulated forest production over the period 1961–2000 (Fig. 2). Annual mean temperature and precipitation were the major climatic factors governing the NPP of the *P. schrenkiana* forest (Table 3). The weakly positive zero-lag correlations between temperature and NPP in the ZS and YW forests indicated an immediate response to warmer temperatures through the enhancement of plant production. The central sites, XQZ and TC, however, displayed significantly negative zero-lag correlations. Interestingly, almost all of the NPP values

Table 2 Trends in precipitation, temperature and NPP in four study sites within a given time span

Study site	Trend in[a]	1961–2000			1961–1986			1987–2000		
		Mean (± 1 SD)	Change (±1 SD)	*P*	Mean (± 1 SD)	Change (± 1 SD)	*P*	Mean (± 1 SD)	Change (± 1 SD)	*P*
ZS	T	2.3 ± 0.6	0.021 ± 0.051	0.012	2.2 ± 0.5	0.018 ± 0.082	0.257	2.6 ± 0.4	0.038 ± 0.135	0.310
	P	657.7 ± 111.9	−0.719 ± 9.778	0.644	659.1 ± 102.5	−2.818 ± 13..614	0.302	656.4 ± 142.2	5.991 ± 30.067	0.578
	NPP	595.9 ± 69.6	0.351 ± 6.116	0.715	588.9 ± 72.4	−1.409 ± 9.754	0.469	609.0 ± 65.1	1.328 ± 16.755	0.769
XQZ	T	2.3 ± 0.6	0.008 ± 0.057	0.362	2.2 ± 0.5	−0.005 ± 0.092	0.778	2.4 ± 0.7	0.041 ± 0.138	0.293
	P	540.1 ± 101.2	2.125 ± 8.589	0.126	515.7 ± 127.0	−1.085 ± 12.569	0.664	582.8 ± 110.7	−0.307 ± 30.936	0.971
	NPP	510.4 ± 142.9	2.139 ± 12.327	0.279	488.2 ± 128.5	0.359 ±17.479	0.918	551.7 ± 162.8	−2.991 ± 41.903	0.794
TC	T	2.1 ± 0.6	0.008 ± 0.057	0.357	2.0 ± 0.5	−0.013 ± 0.092	0.476	2.3 ± 0.7	0.042 ± 0.146	0.307
	P	533.2 ± 119.5	1.356 ± 10.423	0.416	524.4 ± 127.0	3.716 ± 16.822	0.271	554.5 ± 114.9	−12.836 ± 28.669	0.122
	NPP	518.3 ± 173.9	1.977 ± 15.103	0.413	504.8 ± 187.6	4.772 ± 25.072	0.341	543.4 ± 146.7	−15.266 ± 34.131	0.120
YW	T	1.2 ± 0.6	0.021 ± 0.051	0.014	1.0 ± 0.5	−0.009 ± 0.087	0.587	1.7 ± 0.4	0.042 ± 0.109	0.180
	P	417.0 ± 73.9	2.333 ± 6.015	0.019	397.6 ± 60.7	0.730 ± 8.230	0.655	457.8 ± 88.7	9.285 ± 22.484	0.151
	NPP	327.7 ± 111.9	3.186 ± 7.912	0.015	301.7 ± 79.0	1.319 ± 10.693	0.535	376.0 ± 112.2	6.732 ± 28.081	0.387

Note that the change and standard deviation (SD) are given per year. All trend changes presented refer to changes in regression values rather than actual values to avoid unreasonable findings caused by randomly high starting or ending values. The slope parameters of the linear regression runs indicate the direction (increasing or decreasing) as well as the magnitude of climate change and productivity parameters within a given time span. The NPP were estimated by a process-based model, BIOME-BGC

[a] T , Annual temperature (°C); P, annual precipitation (mm); NPP, net primary production (gC m^{-2} year^{-1})

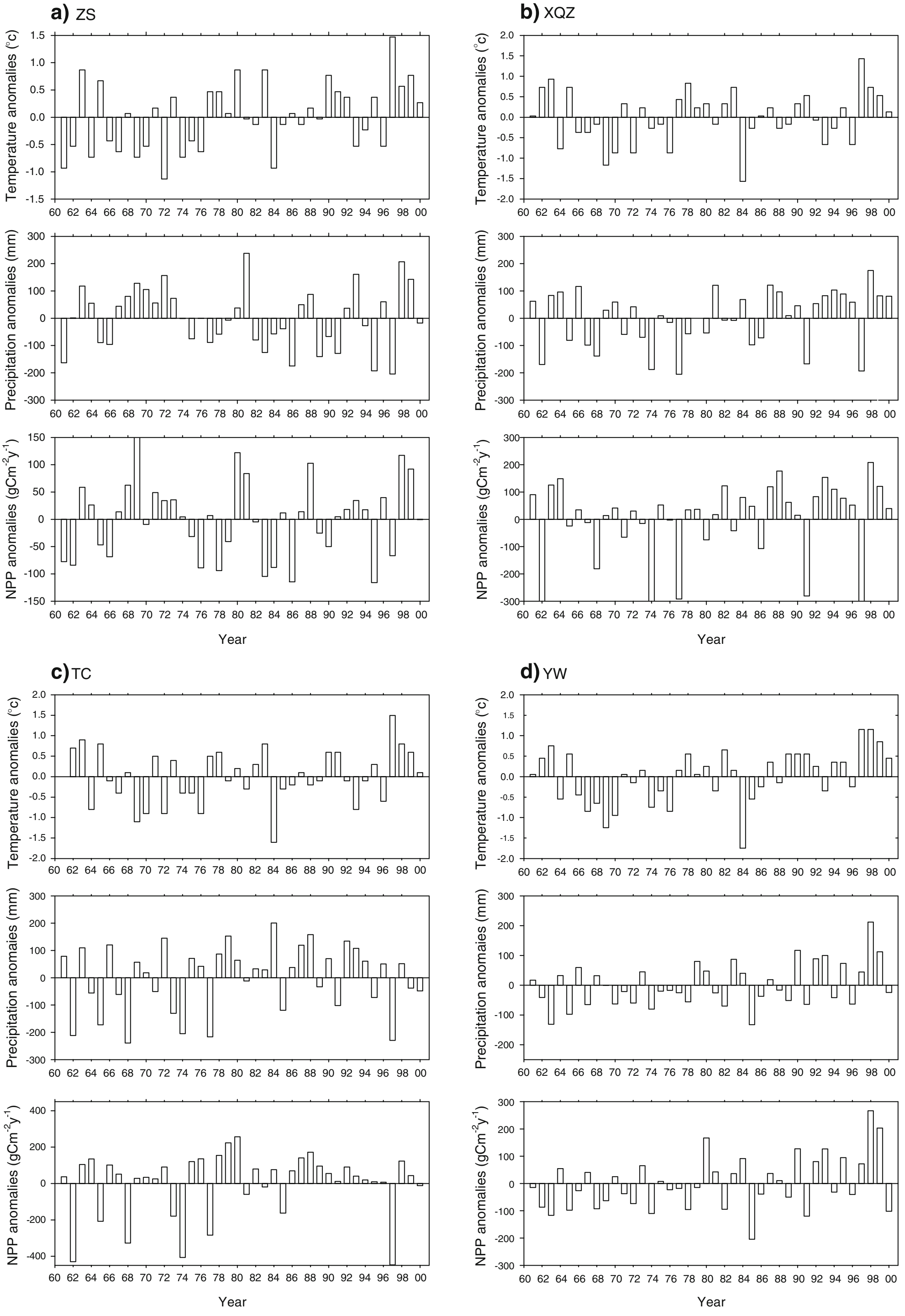

Fig. 2 Effects of interannual variations in temperature (°C) and precipitation (mm) on net primary production (*NPP*, gC m^{-2} $year^{-1}$) at the four study sites over the period 1961–2000. **a** Zhaosu (*ZS*), **b** Xiaoquzi (*XQZ*), **c** Tianchi (*TC*), **d** Yiwu (*YW*)

Table 3 The lagged correlations (*R* values) of annual NPP versus temperature and precipitation at the four forest sites

Study site	Precipitation			Temperature		
	0-Lag	1-year Lag	2-year Lag	0-Lag	1-year Lag	2-year Lag
ZS	0.774**	0.275	−0.246	0.036	0.174	0.112
XQZ	0.882**	−0.011	−0.256	−0.324*	0.308	0.209
TC	0.851**	−0.073	−0.228	−0.322*	0.372	−0.014
YW	0.832**	0.124	−0.130	0.159	0.454	0.189

*Correlation is significant at the $\alpha < 0.05$ level (single-tailed); **correlation is significant at the $\alpha < 0.01$ level (single-tailed)

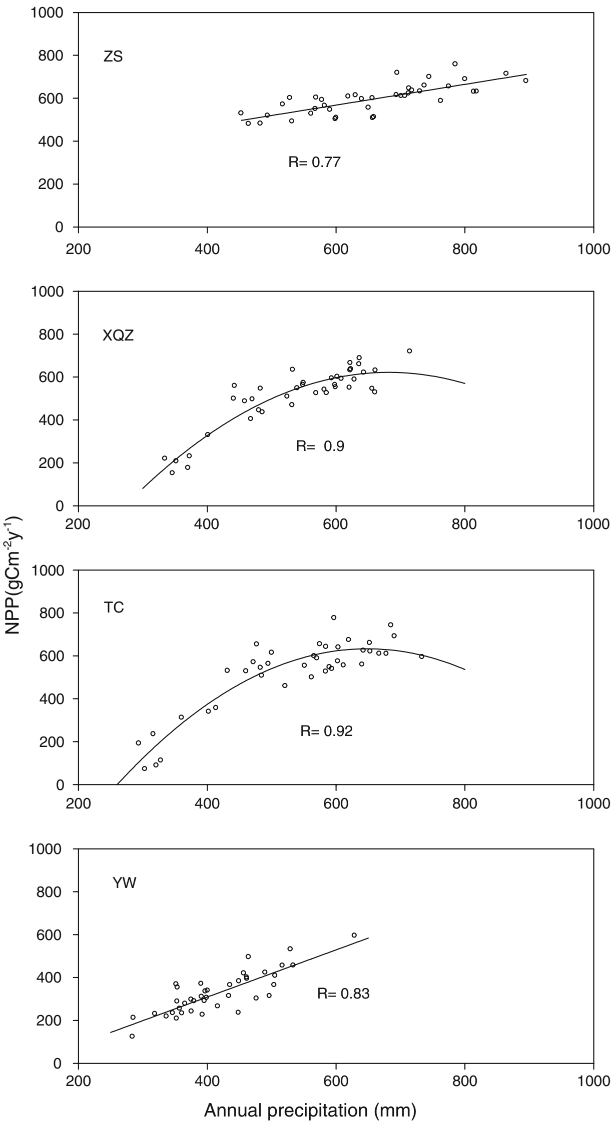

Fig. 3 The response of net primary production (*NPP*, gC m^{-2} $year^{-1}$) to precipitation (*P*, mm) in the four forest sites over the period 1961–2000

were positively correlated with the 1- or 2-year lagged temperature.

Strongly positive zero-lag correlations were found between NPP and annual precipitation at all four sites. This indicated a direct and immediate enhancement of forest production following an increase in precipitation, which on some occasions persisted into the next year (see the 1-year lagged correlations). However, negative correlations between growth and precipitation were found in the 2-year lagged data at all four sites.

These results revealed that the effects of precipitation on the NPP were greater at the dry sites (XQZ, TC, and YW) than at the wet site (western Tianshan, ZS) (Fig. 3). The correlations between precipitation and NPP were strong at the dry sites (*R* in the range 0.83–0.92, $P < 0.001$) with relatively steep slopes. The correlation in ZS, the wet area, was weaker ($R = 0.77$, $P < 0.01$), and the slope was relatively shallow. These results suggest that a small decrease in precipitation at the dry sites could lead to a large decrease in growth, while a similar decrease in precipitation at the wet site might not affect growth to any major extent. It is interesting to note that NPP tended to decrease when annual precipitation was greater than 648.4 mm at TC and 681.8 mm at XQZ. However, the NPP of the other two sites was positively correlated with annual precipitation at all levels.

The effect of CO_2 fertilization on NPP

Climate variability coupled with CO_2 fertilization generally resulted in a higher annual NPP than did climate variability without CO_2 fertilization (Fig. 4). The strength of the CO_2 fertilization effect for the *P. schrenkiana* forests showed site-to-site variations, with a mean 21.03 ± 2.40 gC m^{-2} $year^{-1}$ (or 3.82 ± 0.47%) for ZS, 22.02 ± 2.20 gC m^{-2} $year^{-1}$ (or 5.27 ± 0.71%) for XQZ, 9.43 ± 1.61 gC m^{-2} $year^{-1}$ (or 4.30 ± 1.81%) for TC and 7.74 ± 1.04 gC m^{-2} $year^{-1}$ (or 3.05 ± 0.55%) for YW in the period 1961–2000.

The net effect of CO_2 fertilization on NPP showed great temporal and spatial variations and did not show a monotonic increase in magnitude as atmospheric CO_2 concentration increased from 317.2 to 368.8 ppmv during the study period (Fig. 4). Other environmental factors, however, could also play a part in the observed trends (Table 4). Correlation analysis suggested that both temperature and precipitation can influence the strength of the CO_2 fertilization effect. The results of our analysis further indicated that interannual variations in the CO_2 fertilization effect were strongly correlated with inter-annual WUE.

Fig. 4 Effect of CO_2 on net primary production *(NPP*, gC m^{-2} $year^{-1}$) of *P. schrenkiana* forests in the four forest sites over the period of 1961–2000. *Solid lines* indicate the changing trends

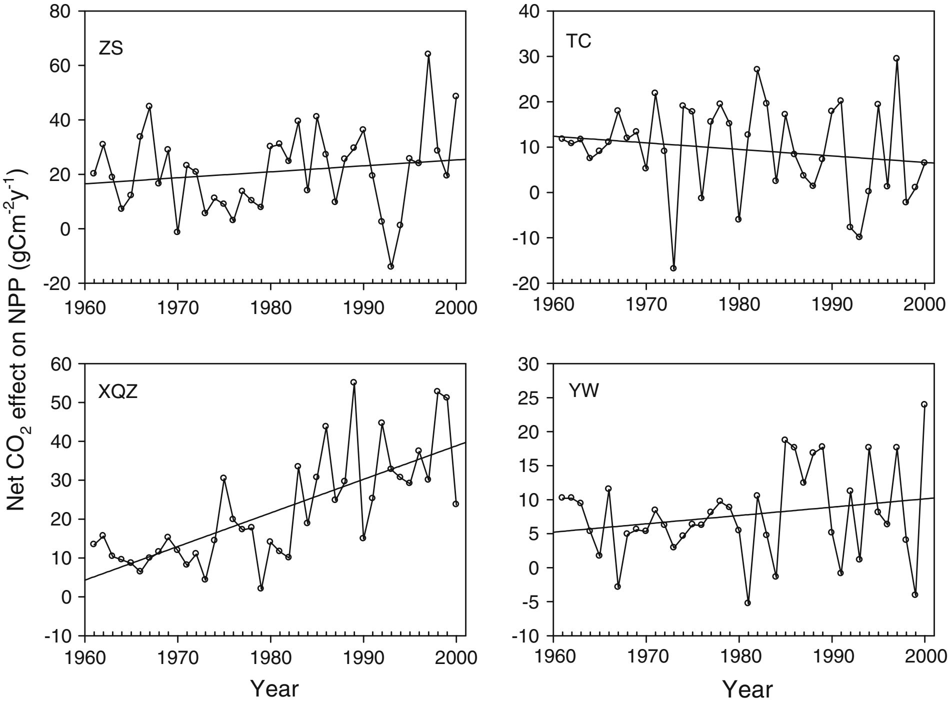

Table 4 Correlative coefficients between precipitation, temperature, water use efficient changes (ΔWUE) and net CO_2 effect on the NPP of *P. schrenkiana* forests

Study site	T	P	ΔWUE
ZS	0.340*	−0.282	0.943**
XQZ	0.260	0.216	0.922**
TC	0.309	−0.306	0.873**
YW	0.262	−0.217	0.861**

*Correlation is significant at the $\alpha < 0.05$ level (single-tailed); **correlation is significant at the $\alpha < 0.01$ level (single-tailed)
T , Annual temperature (°C); P, annual precipitation (mm); NPP, net primary production (gC m^{-2} $year^{-1}$)

Discussion

Interannual climate change

Based on our analysis of the temperature records from four meteorological stations in the Tianshan Mountains, there was a trend for annual mean air temperature to increase at all four sites. This result is in agreement with observed trends for Xinjiang as a whole (Su et al. 2003; Xu and Wei 2004). Both local and provincial data show that (1) most of the temperature increase occurred during the last two decades of the twentieth century, and (2) in many places the degree of warming was well above the global average.

Annual precipitation at the four sites showed significant variation over the years studied. Our results suggest that any long-term, monotonic trend was weak and statistically insignificant in all regions except for site YW. These results are consistent with those of Song and Zhang (2003) and Chen et al. (2004) who found that mean precipitation displayed a slight upward trend towards the end of the twentieth century in the Tianshan Mountains. Even combining their analysis with our own, it is still too early to conclude that there has been a systematic, monotonic, regional trend in precipitation or temperature in Tianshan Mountains over the past 40 years. Consequently, we conclude that the results of our study do not support the conclusion of Shi et al. (2002, 2003) that a climatic shift from warm–dry to warm–wet occurred in 1987 in Northwest China.

Trends in NPP

Based on the climate and CO_2 concentration information for the period 1991–2000, the BIOME-BGC estimations of mean NPP were similar to those previously published estimates of productivity on the north slopes of the Tianshan Mountains (Wang and Zhao 2000; Ni 2004). Despite the uniform physiognomy of forest cover in these regions, our simulations also suggest that the NPP decreased from west to east, responding strongly to the rainfall and temperature gradient (Sun 1994; Wang and Zhao 2000).

Our analysis of the BIOME-BGC simulations revealed an increase in the NPP of *P. schrenkiana* forests in the Tianshan Mountains and also showed that the forest NPP has changed even more in the latter two decades of the twentieth century in response to significant temperature changes. Evidence for a substantial increase in productivity can also be found using forest inventory surveys. The total growing stock and standing volume per hectare of Xinjiang forests have increased enormously in recent decades according to forest inventory data (Fang and Chen 2001; Li et al. 2003). Depending on the regional scale, results of satellite-based studies indicate that forest growth and vegetation production have increased on the northern slopes of the Tianshan Mountains since the early 1980s (Ma et al. 2003; Chen et al. 2004), which is consistent with the trends in plant growth or NPP in the northern high and middle latitudes at the same time (Myneni et al. 1997; Hicke et al. 2002; Fang et al. 2003; Nemani et al. 2003; Slayback et al. 2003; Cao et al. 2004; Kimball et al. 2007). This may partially explain the increased carbon sinks in the northern region (Schimel et al. 2001). In comparing our work with other studies, our most striking result is the sustained climate signal and favorable growth response from the 1980s to the present. This suggests that the NPP trends estimated from the three approaches are comparable. We also evaluated the results of our model and were able to identify key information gaps that can be filled by appropriate observational and research programs.

Changes in NPP due to climate change and CO_2

Recent climate changes have enhanced plant growth in the northern mid-latitudes and high latitudes, and multiple mechanisms (e.g. climate changes, CO_2 fertilization, nitrogen deposition, forest regrowth and management) have promoted increases in NPP (Nemani et al. 2003; Hyvönen et al. 2007). In the temperate and boreal zones, nutrient availability is the main limiting factor, but in large parts of Northwest China, forest growth is primarily limited by temperature (high latitudes) or water availability (arid, semi-arid) (Zhang and Tang 1989). Given the focus of this study on estimating the NPP of *P. schrenkiana* forests at an ecosystem level, we only discuss here the relationship between climate variables, atmospheric CO_2 concentration and NPP; NPP variability associated with other factors is beyond the scope of our study.

It is well established that temperature and precipitation are dominant controlling factors of plant photosynthesis, and the interaction of their effects on general growth patterns has been obtained from long-term experiments (Lieth 1975). Our analysis suggests that precipitation is an important factor affecting the growth of *P. schrenkiana*, accounting for at least 70% of the total variance in NPP at all four study sites (Fig. 3). In other words, an increase in precipitation in the future will tend to alleviate the moisture stress for forest growth and have, therefore, a positive effect on the NPP of *P. schrenkiana* forests in the Tianshan Mountain region (Su et al. 2007). These results are in general agreement with those from other *P. schrenkiana* studies in which growth-ring evidence at Xinjiang showed that precipitation is critical to growth (e.g. Yuan et al. 2000; Yuan et al. 2001; Zhu et al. 2004; Guo et al. 2007). These results are also in agreement with those from studies of water-limited regions by Nemani et al. (2003) and Mohamed et al. (2004), which showed that increasing precipitation will dramatically increase the simulated NPP in the future. Our analysis also indicated a negative correlation between NPP and 2-year lagged precipitation for all four sites (Table 3). The lagged correlations provide a possible explanation for a delayed negative impact of precipitation on forest production: the NPP was positively related with the current year rainfall, but rainfall did not influence or had a negative relation with lagged the 2-year NPP.

In contrast, the results from our study suggest that temperature had relatively little effect on the NPP of *P. schrenkiana* forests. In other words, the precipitation increase had a greater influence than the temperature changes on *P. schrenkiana* forest productivity in the Tianshan Mountains (Su et al. 2007). This result is consistent with the analysis of Hunt and Running (1992), who suggested that the temperature effect in BIOME-BGC simulation is small. Almost all of the NPP, however, showed positive 1- and 2-year lagged correlations with the temperature. This was difficult to explain as being simply a composite effect of the forest ecosystem. The following mechanism, however, may provide an explanation for this result. Warm temperatures result in an increase of biomass input to the soil pool, while precipitation increases soil moisture and facilitates the transformation of organic matter into readily available inorganic nutrients (mainly phosphorous and nitrogen). Warm temperatures therefore benefit forest growth, but only after a certain delay (Tian et al. 1998). Consequently, in the BIOME-BGC model, the interaction of temperature, precipitation and nutrients in terms of their effects on forest general growth patterns seems to be well estimated (Su et al. 2007). Elevated temperatures may increase NPP through metabolically enhanced photosynthesis and by prolonging the growing season as well as increasing nutrient availability through higher rates of decomposition. Elevated temperatures, however, may also decrease NPP by decreasing soil moisture and enhancing plant respiration (Churkina and Running 1998; Thornton et al. 2002). Our results suggest that the positive effects of the temperature increase more than just compensate for the negative effects on the NPP of the *P. schrenkiana* forest at the ZS and YW sites. Without an increase in precipitation, increases in temperature may limit the production of *P. schrenkiana* forests at the XQZ and TC sites. This proposal is in agreement with other *P. schrenkiana* studies, which have determined that lower production may be attributed to a temperature-induced increase in water stress in these water-deficient environments (Yuan and Li 1994, 1995; Zhu et al. 2004). It has been suggested that the effects of temperature on productivity may be dependent on local conditions (Nemani et al. 2003; Mohamed et al. 2004).

The rise in atmospheric CO_2 concentration is one of the best documented global atmospheric changes of the past half century, and enormous research efforts have been undertaken to understand how plants and ecosystems will respond to it (Ainsworth and Long 2005). The results of our study suggest that the increasing CO_2 concentration had a comparatively small positive effect on the NPP of *P. schrenkiana* forests (range 3.05–5.27%). This positive response resulted primarily from the higher rates of photosynthesis due to the direct effect of CO_2 fertilization, but also to a reduction in stomatal conductance and transpiration and improved WUE in the simulation. This result is in agreement with that of Chen et al. (2000), who reported a similar decrease in isotopic discrimination and increase in WUE over the same period using historical records of *P. schrenkiana* tree rings. Our result is also consistent with the simulation results of Xiao et al. (1998), Ni (2002) and Su et al. (2007), who both reported that an increase in atmospheric CO_2 concentration had no significant effect on the NPP of the boreal forests in China. Similarly, Melillo et al. (1993) found that increasing simulated atmospheric CO_2 levels did not change the NPP of the boreal woodland and boreal forest as predicted by the terrestrial ecosystem model (TEM).

Our analysis also indicated that interannual climate variability could alter the effect of CO_2 fertilization on the production of *P. schrenkiana* forests, which show that different ecosystems respond to increased levels of CO_2 quite differently depending on environmental factors (Fig. 4). In particular, we found that the effect of CO_2 fertilization on the forests in the Tianshan Mountains depended strongly on temperature (Table 4). The simultaneous elevation of CO_2 and temperature had been observed to have a positive effect in most tree organs (Aranjuelo et al. 2005). This positive interaction between CO_2 and temperature could be explained by an increase in the photosynthetic thermal optimum due to changes in the Rubisco kinetic properties (Long 1991). Therefore, these results emphasize the importance of resource interactions and feedback in the analysis of forest response to rising CO_2 concentrations (Hanson et al. 2005).

Conclusion

The climate data reported here shown that the annual mean temperature increased significantly and precipitation varied greatly at all four sites in the Tianshan Mountain range between 1961 and 2000. The NPP of the *P. schrenkiana* forests exhibited a substantial year-to-year variation, and most production variations did not show any significant trends due to the dominance of high frequencies. Thus, NPP estimates based on a single year's measurement must be treated cautiously in view of the temporal and spatial variations in climate. Our sensitivity analysis suggested that the NPP is sensitive to temperature and rainfall changes and that precipitation appears to be a determinant of production of *P. schrenkiana* forests. The results show that the most striking feature of the climate and NPP record is continuing temperature and rainfall changes and a favorable growth response from the 1980s to the present in the Tianshan Mountains. They also reveal that the recent increase in atmospheric CO_2 may already have had impacts on the production of *P. schrenkiana* forests. Our analysis indicates that climate change and CO_2 fertilization explain most of the NPP variation observed in *P. schrenkiana* forests.

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