Increasing net primary production in China from 1982 to 1999

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We used a simple process model and satellite data to explore trends in China's terrestrial net primary production (NPP). We found that the country's terrestrial NPP increased by 18.7% from 1982 to 1999. Evidence for this major increase also came from crop yields and forest inventory surveys, and much of it appeared to be the result of a lengthening of the growing season. Plant growth also increased during the middle of the growing season, but to a lesser extent. Historical NPP trends indicate a great deal of spatial heterogeneity, increasing significantly over an area covering 30.8% of China during the past 18 years, but decreasing in areas undergoing rapid urbanization.

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Terrestrial net primary production (NPP) has been the subject of considerable research during the past several decades, because of its important role in the terrestrial carbon cycle and ecosystem processes. NPP varies geographically and over time, and cannot be observed directly at the regional and global scales. Satellite observations of vegetation provide global coverage with high spatial resolution and short revisit intervals, and this method has therefore been used to evaluate the dynamics of terrestrial biosphere production.

Results of satellite-based studies indicate that there has been an increase in plant growth or NPP in the northern high and middle latitudes since the 1980s (Myneni *et al.* 1997, 2001; Cramer *et al.* 2001; Los *et al.* 2001; Tucker *et al.* 2001; Zhou *et al.* 2001; Hicke *et al.* 2002; Lucht *et al.* 2002; Slayback *et al.* 2003). This may help explain the increased carbon sinks in the northern region (Schimel and Sulzman 1995; Schimel *et al.* 2001).

China encompasses a broad range of climates, from tropical to subarctic/alpine and from rainforest to desert, and the vegetation is diverse and species-rich. Investigation of the changes in Chinese NPP could provide useful regional information for global change research. Although there have already been a few such studies (eg Ni 2000; Cao *et al.* 2003), most of these used climate-based approaches, thereby providing potential NPP estimates. Here we use a satellite-based carbon cycle model called CASA (Carnegie–Ames–Stanford Approach) (Potter *et al.* 1993; Field *et al.* 1995), combined with a number of surface observations within China, to explore the trends and spatial patterns of terrestrial NPP in China between 1982 and 1999.

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Methods

The CASA calculates NPP as a function of normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), maximum possible light utilization efficiency (ϵ^*), temperature ($g[t]$) and precipitation ($h[w]$), and is expressed according to the following equation (Potter *et al.* 1993; Field *et al.* 1995):

$$NPP = f(NDVI) \times PAR \times \epsilon^* \times g(t) \times h(w) \quad (1)$$

The NDVI data used for the CASA calculations were from the Global Inventory Monitoring and Modeling Studies (GIMMS) group and were derived from the NOAA/AVHRR Land dataset, at a spatial resolution of 8×8 km^2 and 15-day intervals for the period January 1982 to December 1999 (Tucker *et al.* 2001; Zhou *et al.* 2001). This dataset was mapped to an Albers equal-area projection and corrected for sensor degradation using a technique based on stable desert targets (Los 1998). Corrections were also applied to counter the effects of stratospheric aerosol loadings from the El Chichon and Mount Pinatubo eruptions, which occurred between April 1982 and December 1984 and between June 1991 and December 1993 (Kaufmann *et al.* 2000; Myneni *et al.* 2001; Tucker *et al.* 2001; Zhou *et al.* 2001). Detailed descriptions of calibrations and data processing can be found in Los (1998), Tucker *et al.* (2001), and Slayback *et al.* (2003). These authors found that the corrected dataset could be used to identify long-term trends in vegetation activity. Recent comparison of four AVHRR NDVI datasets indicated that no trends were significant at the 95% level for the GIMMS dataset, either for individual satellites or across the entire time period, and that variations due to satellite drifts and changeover in the GIMMS data are small at latitudes above 40°N (Slayback *et al.* 2003). To further reduce residual atmospheric and bidirectional effects, we produced a monthly NDVI dataset, using the maximum NDVI value for each month (Holben 1986).

The temperature ($g[t]$) and water scalars ($h[w]$) in equation 1 are based on physiological and ecological studies. The former reflects two aspects of the regulation of plant growth by temperature – vegetation acclimation to site-specific seasonal temperature trajectory and limits to acclimation in extreme habitats – and the latter is calculated as a function of the ratio of estimated to potential evapotranspiration (Field *et al.* 1995).

Mean monthly temperatures and precipitation values at 0.1° x 0.1° resolution used in this study were produced from monthly temperature and precipitation measurements from 680 widely distributed climate stations across China (Piao *et al.* 2003). Some errors may have occurred in the Tibetan Plateau, because of the limited number of meteorological stations in this region. Solar radiation data were derived from the 1980–1999 solar radiation database of China (Fang *et al.* 2001a). Information on soil texture was obtained by digitizing a soil texture map of China (ISSCAS 1986), and vegetation type was obtained from a digitized vegetation map of China (Institute of Geography 1996).

Results

Over the past 18 years, China's NPP increased from 1.34 PgC/yr (1PgC = 10^{15} gC) in the early 1980s (the average of the period 1982–1984) to 1.59PgC/yr by the end of the 1990s (average of 1997–1999), giving a total increase of 18.7%, or an annual mean rate of increase of 1.04%. The average annual NPP was 1.44 PgC (SD = 0.097) and the average rate of increase was 0.153 PgC/yr^2 ($r^2 = 0.71$, $p < 0.001$) (Figure 1a and Table 1).

Interannual variations in NPP generally mirrored those in NDVI (Figure 1b), and corresponded closely with changes in temperature (Figure 1c). Over the past 20 years, temperatures rose substantially (0.062°C/yr, r^2 = 0.56, $p < 0.001$) (Figure 1c). Precipitation did not show a significant trend ($r^2 = 0.04$, $p = 0.46$) (Figure 1d). NPP was anomalously high in 1990 and 1998 and low in 1992 (Figure 1a), and these anomalies are strongly associated with changes in climate. High NPP in 1990 and 1998 was coupled with warm temperatures (Figure 1c) and high precipitation (Figure 1d), while a marked decrease in NPP in 1992 was associated with cool temperatures and low precipitation.

The clear NPP trend seen at the country scale was supported by historical changes in biome-level NPP over the past 18 years. Based on the vegetation map of China (IGCAS 1996) and biome classifications used in the CASA, China's vegetation was divided into 11 types. The NPP for all vegetation types except deciduous needle-leaf forests indicated a significant increase over the past 18 years (R = 0.53 to 0.83, p = 0.07 to 0.02) (Table 1). The absence of a clear increase in NPP for the deciduous needle-leaf forests in the northernmost part of northeast China was probably related to a heavy forest fire in 1987 and continuous logging in that region (Zhou 1997).

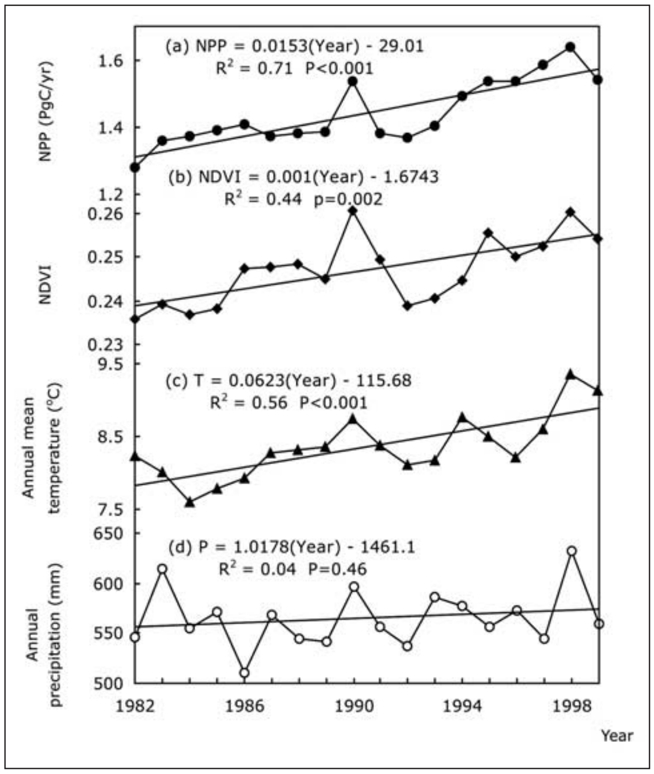

Figure 1. *Interannual changes in (a) total terrestrial net primary production (NPP, PgC/yr) in China; (b) area-weighted mean normalized difference vegetation index (NDVI); (c) annual mean temperature (°C), and (d) annual precipitation (mm).*

The elevated NPP rates by vegetation type were qualitatively similar to those for the country as a whole (Table 1). The largest increase in NPP occurred in broadleaf and needle-leaf mixed forests, located in northeast China, in areas with abundant precipitation; here there was an annual increase of 4.22 gC/m^2/yr, while the smallest increase was seen in deserts (0.30 gC/m^2/yr) (Table 1). The mean rate of increase of NPP for most vegetation types was close to 1% per year, which supports the annual mean rate of increase of 1.04% for the all of China (Figure 1a). The values for the relative change suggest that the widest variations in NPP occur in deciduous needle-leaf forests (CV = 13.1%) and deserts (CV = 11.7%) (Table 1).

Well-documented food-yield statistics and nationwide forest inventory observations provide a way to validate the results obtained from CASA. We compared the

Table 1. Total area, annual mean NPP and its coefficient of variation (CV), annual NPP trend and its coefficient of correlation (R), and mean rate of increase of annual NPP for 11 biomes in China from 1982 to 1999

Vegetation type	*Total area* ($\times 10^6$ha)	*Mean NPP* (gC/m^2)	*CV* (%)	*Trend* (gC/m^2/yr^2)	R	P *value*	*Mean rate of increase* (%)
Evergreen broadleaf forests	27.99	418.3	8.4	3.51	0.53	0.023	0.86
Deciduous broadleaf forests	22.93	244.6	7.1	2.24	0.69	0.002	0.78
Broadleaf and needle-leaf mixed forests	3.36	296.0	11.0	4.22	0.69	0.002	0.90
Evergreen needle-leaf forests	57.94	245.5	9.2	2.78	0.65	0.003	1.00
Deciduous needle-leaf forests	12.19	285.3	13.1	1.40	0.20	0.427	0.71
Broadleaf shrubs	22.28	222.2	8.4	2.01	0.57	0.013	0.92
Temperate grasslands	113.63	135.8	7.9	1.49	0.74	0.000	0.90
Savannas	155.68	218.4	7.4	2.19	0.73	0.001	0.93
Alpine meadows and tundra	159.01	137.0	8.3	1.32	0.62	0.006	0.82
Desert	197.46	18.0	11.7	0.30	0.74	0.000	1.74
Cultivation	167.01	170.6	8.3	2.20	0.83	0.000	1.16
China	**939.5**	**153.5**	**6.8**	**1.63**	**0.84**	**0.000**	**1.04**

CASA-derived annual NPP and the rate of increase for cultivated crops with those estimated from China's food yields (ECCAY 2000) (Figure 2). Surprisingly, the trend seen for total food yield (3.89 TgC/yr^2; Tg = 10^{12} g) was very close to that of CASA-derived crop NPP (3.68 TgC/yr^2), although the magnitude of the former was smaller than that of the latter because food yield was only a portion of total NPP for food crops. This supports the conclusion that the large NPP increase is based in China's terrestrial ecosystems.

Evidence for the substantial increase in NPP can also be found using forest inventory surveys. Fang *et al.* (1996) reported that, at the provincial level in China, total forest production (y, TgC/yr) was closely related to total forest biomass (x, TgC), expressed as $y = 0.1007x + 2.323$ ($r^2 = 0.92$, $p < 0.0001$). Using this expression and inventory-based forest biomass estimates from the periods 1977–1981 and 1994–1998 (Fang *et al.* 2001b), the country forest NPP total increased from 443 TgC/yr during the period 1977–1981 to 481 TgC/yr during the period 1994–98, with an increase rate of 2.31 TgC/yr^2. This is about two thirds of the CASA-derived NPP figure (3.42 TgC/yr^2, calculated from Table 1) for all the forest types. The CASA-derived NPP was based on all forests across the country, and should be greater than that estimated from the inventory data, because only living biomass accumulation was included in the inventory-based NPP. This suggests that the NPP trends estimated from the two approaches are comparable.

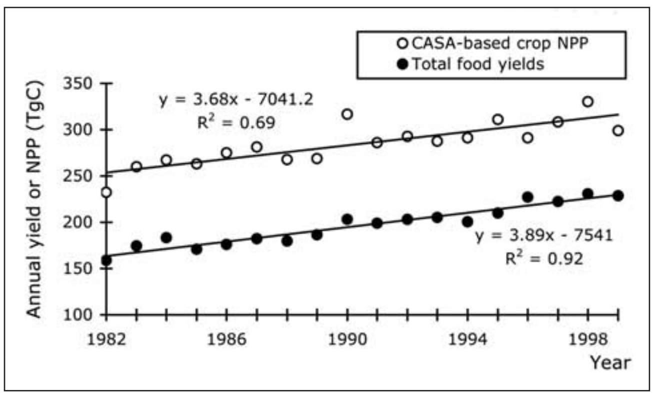

Figure 2. *Changes in total food yields (bottom) and CASA-based cultivation NPP (top) in China from 1982 to 1999. Total food yields were converted to carbon by multiplying by a conversion factor of 0.45. Food crops included paddy, wheat, potato, corn, broomcorn, millet, soybean, and others (ECCAY 2000).*

The increased NPP may be primarily the result of increased vegetation activity (amplitude of growth cycle) during the middle of the growing season (summer) and advanced growing season (spring) (Keeling *et al.* 1996; Myneni *et al.* 1997; Los *et al.* 2001; Zhou *et al.* 2001). In order to compare the contribution of plant growth in different seasons with the increase in annual NPP, the rate of change of mean NPP in spring (March–May) and summer (June–August) over the past 18 years was derived from the difference between 3-year spring (or summer) mean NPP for 1997–1999 and that for 1982–1984, divided by the 18-year spring (or summer) mean NPP for 1982–1999. As a result, much of the trend in NPP appeared to reflect a change towards an earlier growing season. During the past 18 years, the greatest increase in NPP occurred in spring, and increased by 7.9% per year. Results from China (Piao *et al.* 2003) and Eurasia (Zhou *et al.* 2001) also support this finding. Vegetation activity during summer also increased, but to a lesser extent. The mean summer NPP increased by only 1.6%.

Although NPP showed a marked increase in China, the trends indicated a large geographical heterogeneity, corresponding to land cover and its changes and to regional climates (Figure 3). To investigate the geographical differences, the linear function of NPP over time (from 1982 to 1999) was calculated using a regression for each pixel. The slope of the linear function was used as the indicator of an average year-to-year trend in NPP for each pixel – a positive slope indicated an overall increase and vice versa. Results showed that NPP

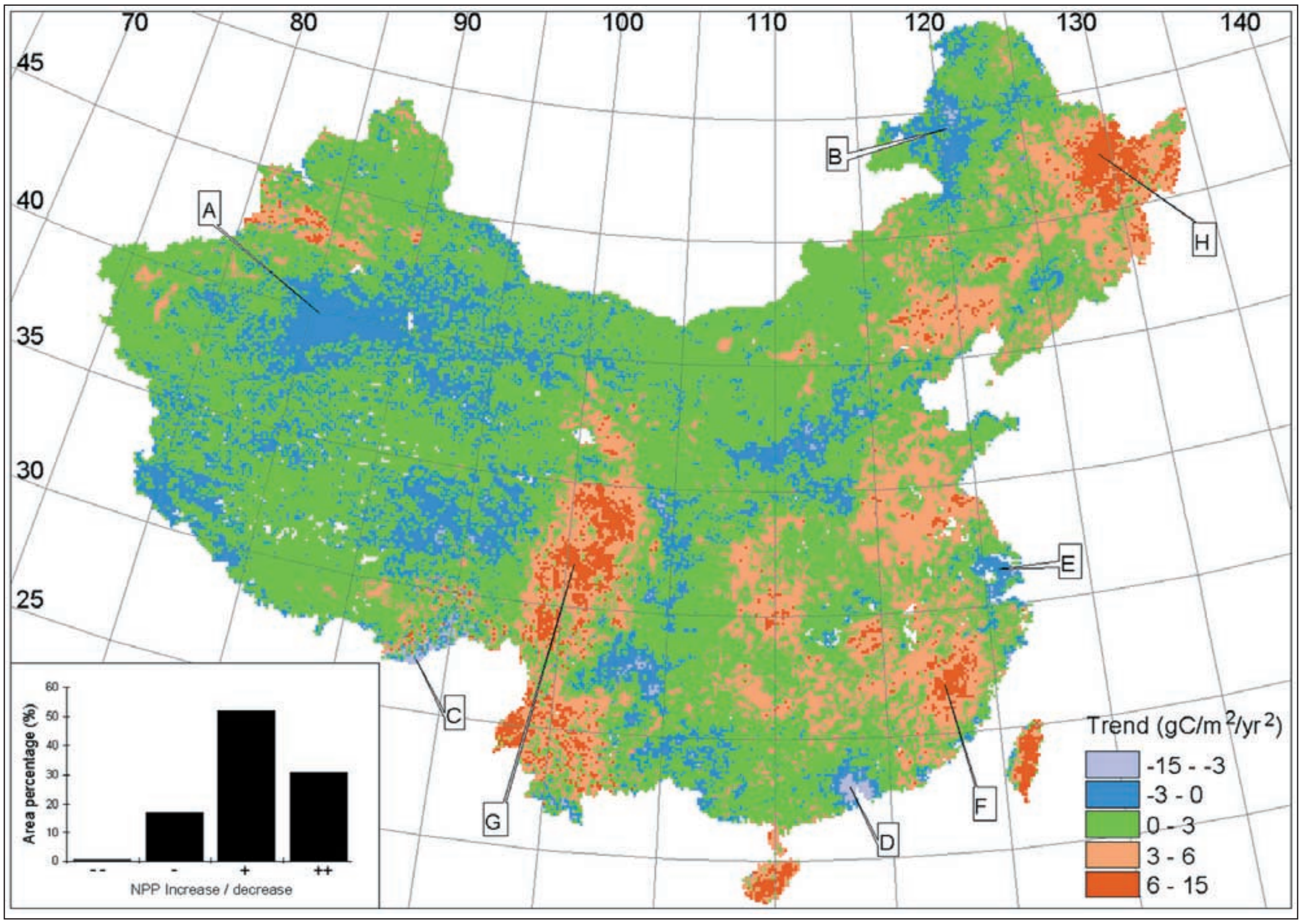

Figure 3. *Geographical distribution of the NPP trends from 1982 to 1999. NPP has increased in most areas of eastern China, but decreased in most arid western regions (Talimu and Chaidamu Basin, A), some grassland areas in northeast China (western parts of Mt Da-xing-an-ling, B), and the lowlands of southeast Tibet (C), where solar radiation has markedly decreased due partly to increased precipitation. In the Pearl River delta (D) and the Yangtze River delta (E), NPP decreased sharply due to rapid urbanization. A marked increase in NPP occurred mainly in the regions dominated by monsoon climate systems, the Southeast Monsoon (Hainan and Taiwan Islands, F) and Southwest Monsoon (southwest Yunnan and south Sichuan provinces, G), suggesting that rainfall contributes greatly to the increase in NPP. In the eastern wetlands of northeast China (H), NPP also shows a substantial increase, as a result of increased temperature. The inset graph denotes the area frequency distribution of NPP changes in four classes: decreasing significantly (--, at 5% significance level), decreasing (-), increasing (+), and increasing significantly (++, at 5% significance level).*

increased over most of eastern China and decreased over those areas along the coastal zone that underwent rapid urbanization (Figure 3). Overall, NPP increased in 51.6% of the country, and increased significantly in 30.8% (at the 5% significance level), giving a total increase of 82.4%; NPP decreased in 17.0%, and decreased significantly in only 0.63% (at the 5% significance level), giving a total decrease of 17.6% (Figure 3 inset).

The fact that a large area of China showed a significant increase in vegetation growth was mirrored in other Eurasian regions, according to NDVI-based studies (eg Myneni *et al.* 1997, 2001; Tucker *et al.* 2001; Zhou *et al.* 2001; Slayback *et al.* 2003). For example, Zhou *et al.* (2001) reported that about 61% of the total vegetated lands in Eurasia between 40° N and 70° N has shown a persistent increase in NDVI over the past two decades.

Conclusions

The use of satellite observations coupled with widespread Chinese ground-based observations revealed that China's terrestrial NPP increased by 18.7%, at a mean annual rate of 1.04%, from 1982 to 1999. An increase of this magnitude, duration, and geographic extent highlights an unexpected aspect of biosphere dynamics. The extent of the increase is much greater than would be expected to result from the fertilization effect of elevated CO_2 (Thompson *et al.* 1996), and also greater than expected from climate, based on broad geographic patterns (Lieth 1975).

Our approach does not, however, establish the causes of the NPP increase. Since no single factor could produce so significant a trend, it is probable that the observed NPP increase is due to the combined effects of changes in climate, resources (such as CO_2), and land management (Schimel *et al.* 2001). Further studies are needed to separate the contributions of different factors.

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References

Cao MK, Prince SD, Li KR, *et al.* 2003. Response of terrestrial carbon uptake to climate interannual variability in China. *Global Change Biol* **9**: 536–46.

ECCAY (Editorial Committee for China's Agricultural Yearbook). 2000. *China's agricultural yearbook 1982 to 1999*. Beijing: Agriculture Press.

Cramer W, Bondeau A, Woodward FI, *et al.* 2001. Global response of terrestrial ecosystem structure and function to CO_2 and climate change: results from six dynamic global vegetation models. *Global Change Biol* **7**: 357–73.

Fang JY, Piao SL, Tang ZY, *et al.* 2001a. Relationship between interannual variability in net primary production and precipitation. *Science* **293**: 1723a.

Fang JY, Chen AP, Peng CH, and Zhao SQ. 2001b. Changes in forest biomass carbon storage in China between 1949 and 1998. *Science* **292**: 2320–22.

Fang JY, Liu GH, and Xu SL. 1996. Biomass and net production of forest vegetation in China. *Acta Ecol Sinica* **16**: 497–508.

Field CB, Randerson JT, and Malmstrom CM. 1995. Global net primary production: combining ecology and remote sensing. *Remote Sens Environ* **51**: 74–88.

Hicke JA, Asner GP, Randerson JT, *et al.* 2002. Satellite-derived increases in net primary productivity across North America, 1982–1998. *Geophys Res Lett* **29**: 10.1029/2001GL013578.

Holben BN. 1986. Characteristics of maximum value composite images from temporal AVHRR data, *Int J Remote Sens* **7**: 1417–34.

IGCAS (Institute of Geography, Chinese Academy of Sciences). 1996. Digitized vegetation map of China. Beijing: National Laboratory for GIS and Remote Sensing.

ISSCAS (Institute of Soil Science, Chinese Academy of Sciences). 1986. The soil atlas of China. Beijing: Cartographic Publishing House.

Kaufmann RK, Zhou LM, Knyazikhin Y, *et al.* 2000. Effect of orbital drift and sensor changes on the time series of AVHRR vegetation index data. *IEEE T Geosci Remote* **38**: 2584–97.

Keeling CD, Chin JFS, and Whorf TP. 1996. Increased activity of northern vegetation inferred from atmospheric CO_2 measurements. *Nature* **382**: 146–49.

Lieth H. 1975. Modeling the primary productivity of the world. In: Lieth H and Whittaker R (Eds). Primary productivity of the biosphere. New York: Springer-Verlag. p 237–63.

Los SO. 1998. Estimation of the ratio of sensor degradation between NOAA AVHRR channel 1 and 2 from monthly NDVI composites. *IEEE T Geosci Remote* **36**: 202–13.

Los SO, Collatz GJ, Bounoua L, *et al.* 2001. Global interannual variations in sea surface temperature and land surface vegetation, air temperature, and precipitation. *J Climate* **14**: 1535–49.

Lucht W, Prentice LC, Myneni RB, *et al.* 2002. Climatic control of the high-latitude vegetation greening trend and Pinatubo effect. *Science* **296**: 1687–89.

Myneni RB, Dong J, Tucker CJ, *et al.* 2001. A large carbon sink in the woody biomass of Northern forests. *P Natl Acad Sci USA* **98**: 14784–89.

Myneni RB, Keeling CD, Tucker CJ, *et al.* 1997. Increased plant growth in the northern high latitudes from 1981–1991. *Nature* **386**: 698–702.

Ni J. 2000. Net primary production, carbon storage and climate change in Chinese biomes. *Nord J Bot* **20**: 415–26.

Piao SL, Fang JY, Zhou LM, *et al.* 2003. Interannual variations of monthly and seasonal NDVI in China from 1982 to 1999. *J Geophys Res–Atmos* 108, doi: 10. 029/2002JD002848.

Potter CS, Randerson JT, Field CB, *et al.* 1993. Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochem Cy* **7**: 811–41.

Schimel DS, House JI, Hibbard KA, *et al.* 2001. Recent patterns and mechanism of carbon exchange by terrestrial ecosystems. *Nature* **414**: 169–72.

Schimel D and Sulzman E. 1995. Variability in the earth climate system – decadal and longer timescales. *Rev Geophys* **33** (2 Suppl): 873–82.

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

Thompson MV, Randerson JT, Malmström CM, and Field CB. 1996. Change in net primary production and heterotrophic respiration: how much is necessary to sustain the terrestrial carbon sink? *Global Biogeochem Cy* **10**: 711–26.

Tucker CJ, Slaback DA, Pinzon JE, *et al.* 2001. Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999. *Int J Biometeor* **45**: 184–190.

Zhou LM, Tucker CJ, Kaufmann RK, *et al.* 2001. Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999. *J. Geophys Res –Atmos* **106** (D17): 20069–83.

Zhou YL. 1997. Geography of the vegetation in Northeast China. Beijing: Science Press.