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Variation in a satellite-based vegetation index in relation to climate in China

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Abstract. Climate-related increases in terrestrial vegetation activity in the northern regions of the Northern Hemisphere have been identified by recent satellite based studies. However, evidence for this increase from ground observations is very limited. In the current study, we used a time series data set for the Normalized Difference Vegetation Index (NDVI) for the growing season (April to October) from 1982 to 1999, along with historical climate data, to analyse year to year variations in vegetation activity and to explore the relationship between the growing season NDVI and climatic variables in China. Vegetation activity, as measured by NDVI, increased in 81% of the study area, with significant gains in 27% of the region. The magnitude of the mean growing season NDVI for the 1980s and the 1990s was not significantly different. The increase in NDVI corresponded to an increase in temperature on the national scale, while regional variations in NDVI appeared to be related to precipitation. The NDVI trend showed a large spatial heterogeneity, possibly associated with changes in regional climate, land use and vegetation type. Our study suggests that agricultural practices caused an increase in NDVI in some regions, and rapid urbanization on the east coast resulted in a sharp decrease in NDVI since the 1980s.

Keywords: Growing season; Land use; NDVI; Remote sensing.

Abbreviations: AVHRR = Advanced Very High Resolution Radiometer; GIMMS = Global Inventory Monitoring and Modelling Studies; MVC = Maximum NDVI Value Composite; NDVI = Normalized Difference Vegetation Index; NOAA = National Oceanic and Atmospheric Administration.

Introduction

Recent studies based on atmospheric CO_2 and O_2 data (e.g. Ciais et al. 1995; Keeling et al. 1996; Bousquet et al. 2000), forest inventory and land use data (Houghton et al. 1999; Fang et al. 2001a; Pacala et al. 2001) and carbon process models (Mellilo et al. 1993; Schimel et al. 2000; Fang et al. 2003) have revealed that terrestrial photosynthetic activity in the middle and high latitudes in the Northern Hemisphere has increased significantly. This increase has been confirmed by satellite-based studies, which used the multi-year normalized difference vegetation index (NDVI) derived from the satellite sensor, the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) (Myneni et al. 1997; Potter et al. 1999; Los et al. 2001; Tucker et al. 2001; Zhou et al. 2001; Hicke et al. 2002; Slayback et al. 2003). Although the application of NDVI data in the analysis of inter-annual variability in vegetation activity has been questioned by some researchers (e.g. Brest et al. 1997), studies suggest that the data set is valid for this application because inter-annual trends reflected in vegetation activity are significantly larger than those resulting from other possible sources (e.g. Kaufmann et al. 2000; Zhou et al. 2001; Piao et al. 2003). Furthermore, the NDVI data set is especially useful for identifying dynamics of the terrestrial biosphere because of its global coverage and short revisit interval (Fung et al. 1987; Tucker et al. 1994).

Although primary production is increasing overall in the northern regions, trends vary geographically (Myneni et al. 1997; Zhou et al. 2001; Fang et al. 2003). Changes in climate, land use/land cover and vegetation structure (biome type) are proposed as the main drivers for such geographical heterogeneity (Schimel et al. 2001).

However, few studies have explicitly examined the inter-annual trends in vegetation processes and their geographical heterogeneity at a regional level using well recorded historical ground observations.

We conducted such a study addressing China's terrestrial ecosystems. China's climate ranges from tropical to arctic (alpine) and from rainy to extremely dry, resulting in diverse vegetation types including forests, grasslands, savannas and deserts. Since the early 1980s, urbanization and land use changes in China have been accelerated due to rapid economic developments, resulting in significant alterations in both quantity and quality of vegetation. Detailed historical climate records are available for China, permitting assessment of relationships between variations in NDVI indicated vegetation activity and climate across diverse geographical conditions. The objectives of this study were: (1) to explore inter-annual variations in vegetation activity (as measured by NDVI) throughout China, (2) to analyse relationships between trends in NDVI and climatic factors and (3) to assess variation in NDVI changes among vegetation types.

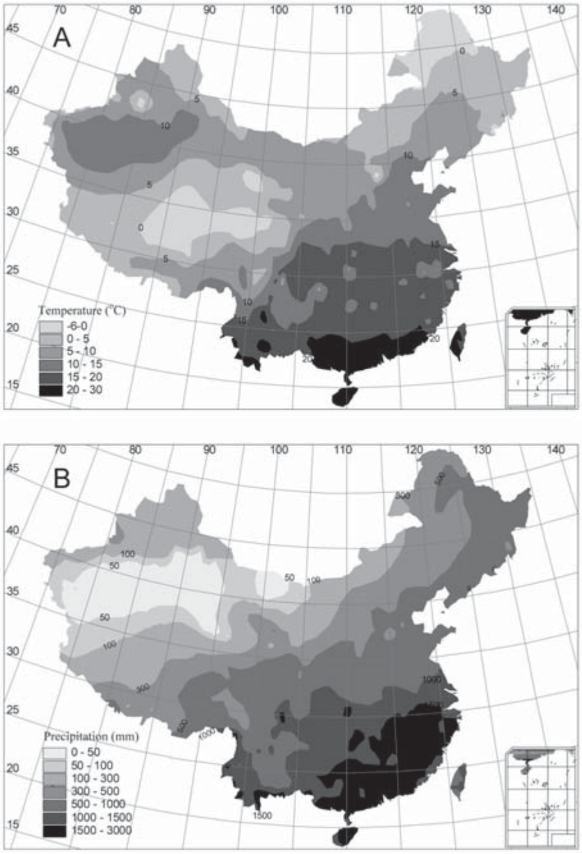

Fig. 1. Climate of China. **(A)** Mean annual temperature and **(B)** Mean annual precipitation over the study period, 1982 to 1999.

Data and Methods

NDVI data set

We used NDVI data from the Global Inventory Monitoring and Modeling Studies (GIMMS) group, derived from the NOAA/AVHRR land data set, at a spatial resolution of 8 km × 8 km and taken at 15-day intervals, for the period January 1982 to December 1999 (Tucker et al. 2001; Zhou et al. 2001). This third generation data set has been corrected to remove the effects of stratospheric aerosol loadings from the El Chichon and Mount Pinatubo eruptions in April 1984 and June 1991 and to overcome most problems noted in previous generations of NDVI data sets (Kaufmann et al. 2000; Myneni et al. 2001). Detailed calibrations on this NDVI data set can be found in Los (1998) and Tucker et al. (2001). Slayback et al. (2003) used four different processed and corrected AVHRR NDVI data sets to evaluate the effects of NDVI trends unrelated to vegetation activity, and found that the GIMMS data set can be used to identify long-term trends in vegetation activity.

Because maximum NDVI value composite (MVC) (a maximum daily NDVI value in each 15 days) minimizes atmospheric effects, scan angle effects, cloud contamination and solar zenith angle effects (Holben 1986), we used the largest 15 day MVC for a month to produce the monthly NDVI data set. The monthly NDVI values for each year were then aggregated to grid cells of 0.1° × 0.1° from the original 8-km resolution data.

To reduce the impact of bare and sparsely vegetated grids on the NDVI trend, grid cells with smaller than 0.1 of annual mean NDVI over the 18 yr were excluded from the analysis, as in Zhou et al. (2001). For this reason, the total study area in this study was 803.10^4 km^2, 85.5% of China's land area (940.10^4 km^2). To avoid spurious NDVI trends due to winter snow, we use NDVI of the growing season (defined as April to October) to analyse vegetation activity.

Climate data set

We compiled monthly mean temperature and precipitation data at 0.1° × 0.1° from the temperature/precipitation database for China for the period 1949-1999, which was generated from 680 climate stations distributed across China (Fang et al. 2001b). Annual mean temperature over the study period (1982-1999) ranges from ca. – 6 °C in the northeast region and the central Tibetan Plateau to ca. 30 ºC in southern China, Hainan Island and Taiwan (Fig. 1A). Annual precipitation varies from < 50 mm in the Takelamagan Desert to ca. 3000 mm in southern China (Fig. 1B). In the eastern half of the country, temperature decreases from south to north and rainfall is relatively abundant (> 500 mm.yr^{-1}), while in the western half temperature is generally < 10 °C due to the high altitude of the Tibetan Plateau, most parts of the region are very dry.

Vegetation type

Based on the digitized vegetation map of China (Anon. 1996), vegetation was assigned to ten types: evergreen broad-leaved forests, deciduous broad-leaved forests, mixed broad-leaved and needle-leaved forests, evergreen needle-leaved forests, deciduous needle-leaved forests, broad-leaved shrubs, temperate grasslands, alpine meadows and tundra, deserts and cultivation. Each 0.1° × 0.1° grid cell was assigned to the most extensive vegetation type within the cell (Fig. 2) to correspond to NDVI and climate data. Grid cells with the annual mean NDVI value < 0.1 were excluded from the analysis, as described above.

Results and Discussion

Inter-annual variations in mean growing season NDVI

The mean values for the largest 15-day NDVI MVCs for each month in the growing season were calculated for each year and used as annual mean growing season NDVI. As shown in Fig. 3a, the growing season NDVI increased significantly ($r^2 = 0.59$; $p < 0.001$) over the study period from 0.328 (3-yr mean for 1982-1984) in the early 1980s to 0.356 (1997-1999 mean) in the late 1990s, with an annual increase rate of 0.44%. This suggestion of increasing vegetation activity is consistent with findings from other studies in northern regions (Myneni et al. 1997; Tucker et al. 2001; Zhou et al. 2001). The increasing trend of the growing season NDVI corresponded closely with that of temperature. Annual mean temperature has increased by ca. 0.84 °C over the past 18 yr, with an increase of 0.046 °C.yr^{-1} ($r^2 = 0.43$; $p = 0.003$) (Fig. 3b). In comparison, overall change in precipitation was relatively small ($r^2 = 0.02$; $p = 0.55$), although large fluctuations were observed (Fig. 3c).

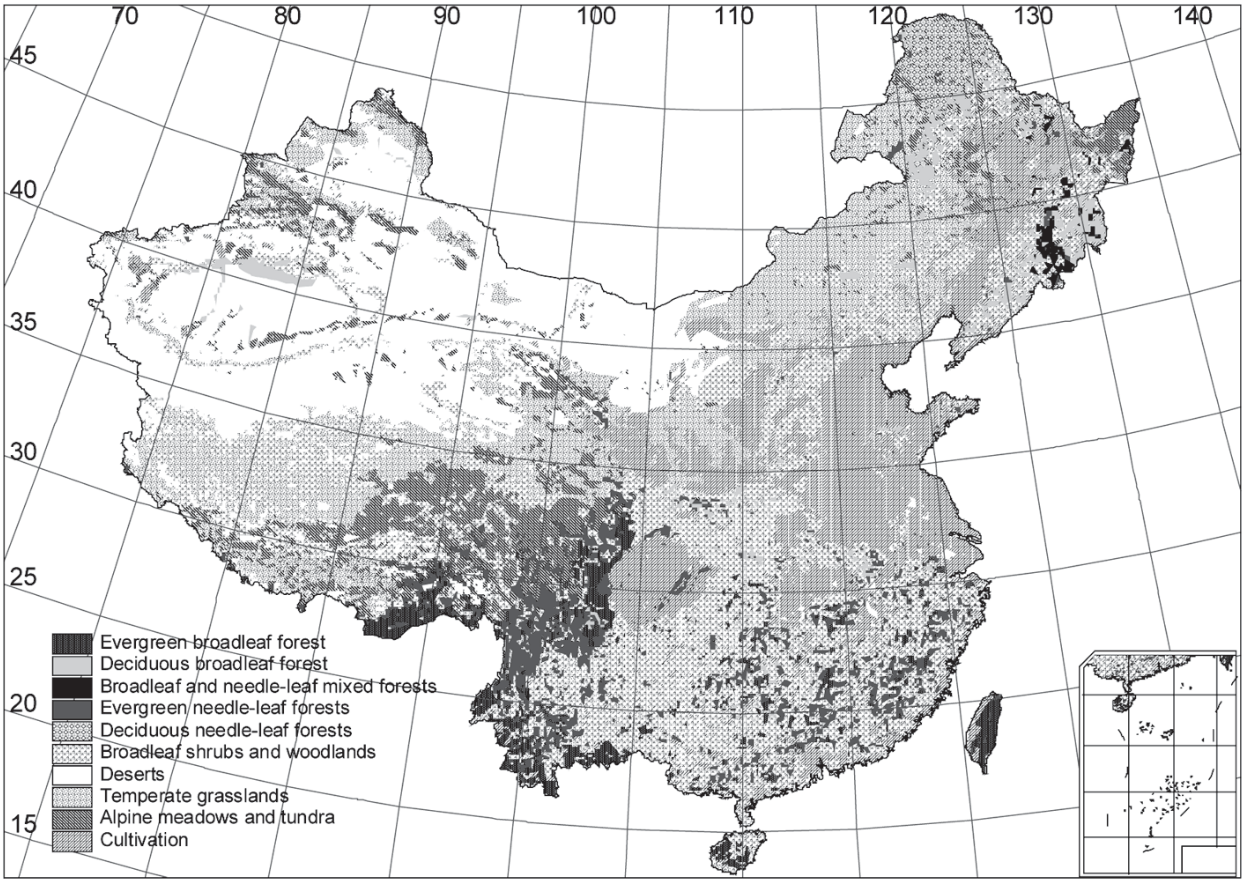

Fig. 2. Vegetation map of China (Anon. 1996). Vegetation is grouped into ten types (see legend).

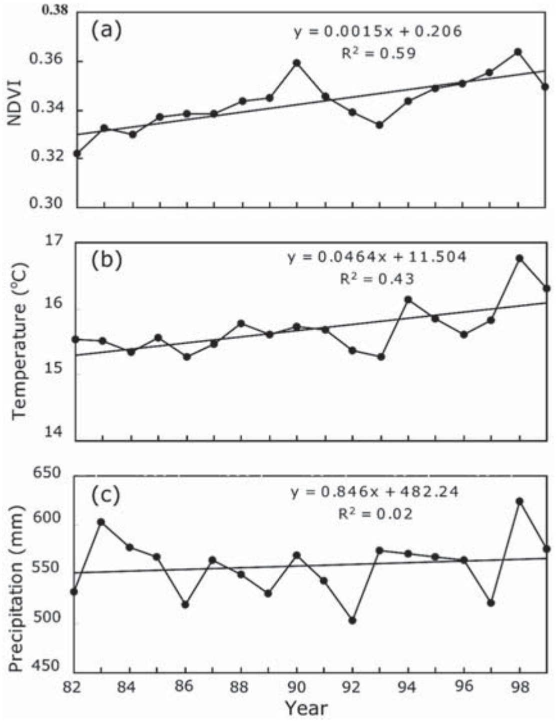

Fig. 3. Inter-annual variations in NDVI and climate over the period 1982-1999. **(a)** annual mean NDVI for growing season, **(b)** annual mean temperature and **(c)** annual precipitation.

Along with the general increase over the period of study, there were several fluctuations in the NDVI trend. NDVI was high in 1990 and 1998, and low in 1992-1994 (Fig. 3a). These variations were associated with climate variation: high NDVIs occurred when precipitation in the current or previous year was higher and temperature was higher than average (Fig. 3b, c). Low NDVI values in 1992-1994 were associated with the coldest, driest year (1992) over the 1990s. Low NDVI was also observed in other northern regions for this period, and probably resulted from the cooling effect of the Pinatubo eruption (Hansen et al. 1996).

Several studies have suggested that increased growing season NDVI can result from both lengthened growing season and accelerated vegetation activity (amplitude of growth cycle) (e.g. Myneni et al. 1997; Los et al. 2001). To assess the contribution of particular months to the increase in growing season NDVI, 3-yr means of monthly NDVI were compared for the early 1980s (1982-1984) and the late 1990s (1997-1999) (Fig. 4A). The largest NDVI increases were in the early growing season (April and May) and in early autumn (September) (Fig. 4B). This suggests that a longer growing season, especially in spring, is a primary contributor to increased NDVI, although NDVI increases in all months also suggest increased overall vegetation activity (Fig. 4B).

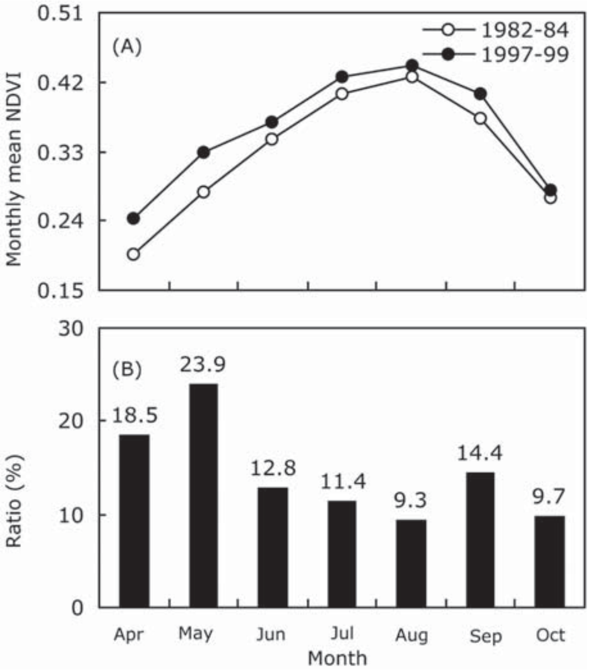

Fig. 4. Comparison of seasonal changes in monthly mean NDVI for growing season between the early 1980s and late 1990s in China. **(A)** Changes in 3 yr monthly mean NDVI for growing season 1982-1984 and 1997-1999 and **(B)** Ratio of monthly mean NDVI increase to total growing season NDVI increase.

Spatial patterns in NDVI trends in relation to regional climate

For each pixel, the linear trend of annual mean NDVI over the study period was estimated using ordinary least-squares regression (Fig. 5A). The NDVI trend was spatially heterogeneous, corresponding well to regional climate and land use/land cover patterns. Large NDVI increases appeared mainly in eastern agricultural regions (especially in the plains of northern China), southern and eastern Tibet and Tianshan Mts. in the region of Xinjiang (Fig. 5B). In contrast, a significant decrease in the NDVI occurred primarily in areas experiencing rapid urbanization (Yangtze River and Pearl River deltas around Shanghai and Shenzhen).

To investigate statistical significance of NDVI trends coefficients of correlation for growing season NDVI vs year were calculated for each grid cell and classified into four types, significantly negative ($R < -0.468$; $n = 18$; df = 16; 5% significance level), negative ($R = -0.468 - 0$), positive ($R = 0 - 0.468$) and significantly positive ($R > 0.468$; 5% significance level). The results showed that over the study period the NDVI value in 81% of the total study area had increased and 27% had a significant increase. Only 1.4% of the study area had a significant decrease (Fig. 5B).

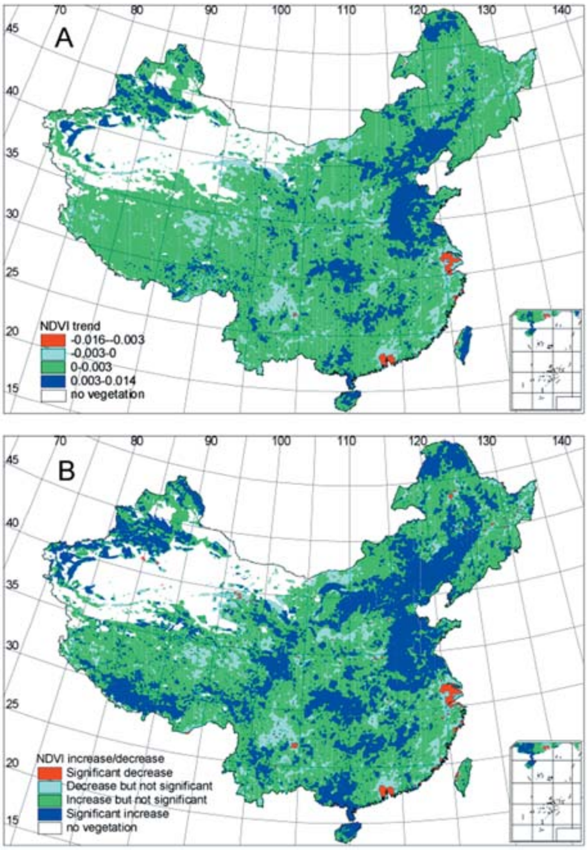

Fig. 5. Spatial patterns of NDVI trends over the period 1982-1999. **(A)** magnitude and **(B)** statistical test at 5% significance level.

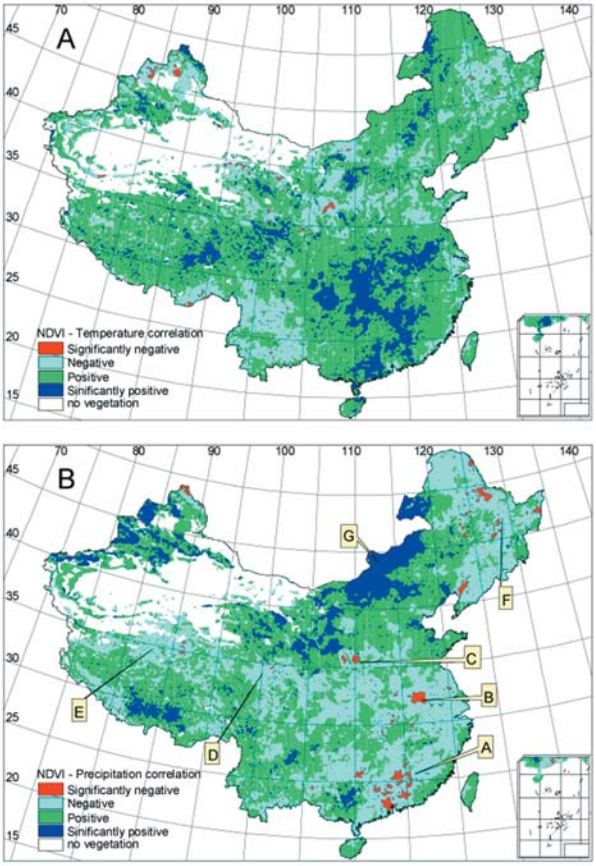

Fig. 6. Spatial patterns of correlation between annual mean NDVI for growing season and **(A)** temperature and **(B)** annual precipitation at 5% significance level: significantly negative ($R < -0.468$, $n = 18$, df = 16), negative ($R = -0.468 \sim 0$), positive ($R = 0 \sim 0.468$) and significantly positive ($R > 0.468$). **(A)** Mt. Wuyi area; **(B)** Middle and lower reaches of Yangtze River, **(C)** East Daba Mountain-East Qinling Mountain; **(D)** Upper reach of Yellow River-Songpan (northwest Sichuan) wetland area; **(E)** Mts. Tanggula, Konglun and Kandis; **(F)** Eastern Mts. Da-xing-an-ling, Xiao-xing-an-ling and Changbei; **(G)** grasslands in northern China.

The spatial pattern in the NDVI trends (Fig. 5A) corresponded to climate changes over most of China. Fig. 6 shows the spatial patterns of correlation between growing season NDVI and climates (temperature and precipitation). Similar to Fig. 5B, the coefficients of correlation were classified into four types, significantly negative, negative, positive and significantly positive. NDVI was positively correlated with temperature in most areas of China, especially in the middle and lower reaches of the River Yangtze , south China and parts of the Tibetan Plateau with a rainy or cold climate. Negative correlations between temperature and NDVI occurred primarily in arid northern areas (such as Inner Mongolia grasslands) and eastern parts of Yunnan-Guizhou Plateau, suggesting that increased temperature may have resulted in decreased NDVI in these regions (Fig. 6A).

It must be recognized, however, that positive trends in both NDVI and temperature may result in higher correlations between these two variables, and the results based on detrended data may be more reliable. However, detrending is acceptable only if the time series contains a deterministic trend, otherwise it may introduce errors if the time series contains a stochastic trend (Kaufmann et al. 2000).

On the other hand, significant negative correlations of NDVI with precipitation were found in wet, mountain regions, perhaps because increasing precipitation led to extended snow cover in cold areas (Fig. 6B, areas D and E) or increased cloud cover (areas A, C and F). Agricultural activities may have contributed to negative correlations in area B, where NDVI increased while precipitation declined. In grassland areas (area G), increasing precipitation was positively correlated with NDVI, presumably a consequence of moisture limiting vegetation activity.

Comparison between NDVI trends in the 1980s and 1990s

Several studies have suggested that the northern land carbon sink in the 1990s was significantly larger than that in the 1980s (Schimel et al. 2001). This should be reflected in vegetation activity expressed as NDVI. The mean growing season NDVI was 0.338 per grid cell in the 1980s and 0.347 in the 1990s; the latter was larger by only 2.8%, suggesting that the difference is not significant ($F = 2.28 < F_{\alpha = 0.05} = 4.49$).

However, NDVI spatial trends were very different between the 1980s and 1990s. Nearly all of the regional increases in Fig. 5 were significant at the decade scale only for the 1980s; only in extreme northeastern China were significant increases observed over the 1990s. In the central Tibetan Plateau, moderate increases in the 1980s were balanced by decreases in the 1990s. Effects of urbanization (decreasing NDVI) were much more pronounced in the 1990s. Overall, the area with the NDVI increase was 83.5% of the total study area in the 1980s (17.8% with a significant increase) and 69.5% (11.5% with a significant increase) in the 1990s. The area with a significant decrease in NDVI was 0.2% in the 1980s while it was 1.9% in the 1990s. Although the area with increased NDVI was smaller in the 1990s than in the 1980s, total mean NDVI showed a slight increase in the 1990s, probably because of the NDVI increase in southern China where the initial NDVI values were large.

NDVI trends by vegetation type

NDVI increased for all ten vegetation types over the 18 yr of the study. The magnitude of the increase varied with vegetation type (Table 1). The deciduous needle-leaved forests and cultivated areas increased the most, increases ca. 0.0020-0.0026.yr^{-1}, while other vegetation types had a similar trend range of 0.0010-0.0015.yr^{-1} (Table 1). However, when increases were compared, the largest increases were evident in desert, deciduous needle-leaved forests, cultivated vegetation, and temperate grassland while broad- and needle-leaved mixed forest had the lowest relative increase. The evidence for such increases can also be found from ground observations. For example, the large NDVI increase for cultivated areas was supported by persistently increased food production in China (Anon. 2001). Based on Agricultural Statistics of China (2001), food yield per ha in China increased by 35.2% over the past two decades. A forest inventory study also showed a significant increase in forest vegetation biomass resulting from afforestation and reforestation, especially in east, south and central China where total mean biomass of planted forests per ha increased twice as much over the past two decades (Fang et al. 2001a).

The growing season NDVI trend showed a positive correlation with temperature for most vegetation types ($R = 0.35 - 0.79$; $p < 0.156$) except for evergreen broad-leaved forests ($R = 0.14$) (Table 1). However, correlations between NDVI and precipitation were significant only for temperate grasslands and deserts (both positive) (Table 1). This significant positive correlation suggests that increased precipitation can significantly increase vegetation growth in the arid areas in China. Interestingly, a weak negative correlation was found between NDVI and precipitation for broad- and needle-leaved mixed forest ($R = -0.31$) and deciduous needle-leaved forests (*Larix* spp.) ($R = -0.26$). These two vegetation types occur mainly in northeast China where winters are cold and dry and growing season duration is only 5-6 months. Apparently, they are not sensitive to precipitation variations. In particular, the broad- and needle-leaved mixed forest appears on Mts. Changbei, Xiao-xing-an-ling and Wuandashan in northeastern China, where the summer is extremely humid (Fang & Yoda 1990). In these areas, increased precipitation could reduce incoming solar radiation, and shorten the dura-

Table 1. Mean growing season NDVI and its NDVI trend, and coefficients of correlation between NDVI and temperature ($R_{\text{T-NDVI}}$) and between NDVI and precipitation ($R_{\text{P-NDVI}}$) for each vegetation type in China. Relative trend (%) = slope/mean NDVI × 100.

Vegetation type	Annual NDVI Mean	Annual NDVI SD	Trend (/yr)	Relative trend (%)	$R_{\text{T-NDVI}}$	$R_{\text{P-NDVI}}$
Evergreen broad-leaved forests	0.456	0.021	0.0014	0.314	0.14	0.27
Deciduous broad-leaved forests	0.458	0.014	0.0015	0.329	0.50	-0.04
Broad-leaved and needle-leaved forests	0.528	0.017	0.0012	0.222	0.35	-0.31
Evergreen needle-leaved forests	0.437	0.016	0.0015	0.337	0.36	0.18
Deciduous needle-leaved forests	0.460	0.024	0.0026	0.559	0.40	-0.26
Broad-leaved shrubs and woodlands	0.382	0.012	0.0015	0.379	0.61	0.11
Deserts	0.151	0.008	0.0010	0.670	0.56	0.50
Temperate grasslands	0.267	0.010	0.0013	0.504	0.70	0.55
Alpine meadows and tundra	0.345	0.010	0.0014	0.416	0.79	0.23
Cultivated areas	0.374	0.014	0.0020	0.530	0.47	0.02

tion of the growing season, which could result in a decrease in NDVI. This suggests that the vegetation type should be taken into consideration when using satellite data to analyse relationships between variations in vegetation activity and climate on a large scale (Bondeau et al. 1999).

Correlations suggesting a positive response of NDVI indicated vegetation activity to warming (Table 1) are consistent with results from other studies in northern latitudes (Myneni et al. 1997, 2001; Tucker et al. 2001; Zhou et al. 2001; Fang et al. 2003). In wet and cold regions, this correlation can be explained physiologically because increased temperature could increase plant photosynthesis. However, in arid regions such as grasslands, where increased temperature would decrease moisture availability for plant growth, mechanisms leading to a positive correlation between NDVI and temperature are less clear. Simultaneous increases in temperature and precipitation in the growing season in China might be an important cause for this pattern (Piao et al. 2003). This suggests that seasonal information must be taken into consideration and interpreted cautiously when analysing the linkage between NDVI and climate.

Conclusions

Over the past 18 yr terrestrial vegetation activity, quantified by satellite derived NDVI, has increased in most parts of China (81% of the area). The NDVI increase was closely related to increases in temperature on the national scale, while regional variations in NDVI trend were related to variation in precipitation.

NDVI trends were spatially heterogeneous, corresponding to regional climatic properties, land use change and vegetation types in China. In humid and cold regions, temperature was the major correlate with NDVI variations, while precipitation was the major factor in arid regions. Human activities also influenced the NDVI trends. Agricultural intensification and reforestation probably increased vegetation activity, while urbanization resulted in a decrease in NDVI. Interpretations of relationships between NDVI indicated vegetation activity and climate must take into account both the effects of human activities and interaction among climatic variables. Thus, it is important to reference related ground observations when using NDVI data to analyse vegetation activity at a regional scale.

Our approach does not, however, use more concrete and detailed data about land use change to assess the immediate causes of the observed NDVI trend, and accordingly the suggestions of relationships between NDVI change and human activities are somewhat speculative. This remains a great challenge for further studies on the relationship between NDVI and land use change.

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