Interannual variations of monthly and seasonal normalized difference vegetation index (NDVI) in China from 1982 to 1999

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[1] In this paper, we analyzed interannual variations of normalized difference vegetation index (NDVI) and their relationships with climatic variables (temperature and precipitation) and human activity in China between 1982 and 1999. Monthly and seasonal NDVI increased significantly at both the country and biome scales over the study period. NDVI shows the largest increase (14.4% during the 18 years and a trend of 0.0018 yr^{-1}) over 85.9% of the total study area in spring and the smallest increase (5.2% with a trend of 0.0012 yr^{-1}) over 72.2% of the area in summer. The NDVI trends show a marked heterogeneity corresponding to regional and seasonal variations in climates. There is about a 3-month lag for the period between the maximum trend in temperature (February) and that in NDVI (April or May) at the country and biome scales. Human activity (urbanization and agricultural practices) also played an important role in influencing the NDVI trends over some regions. Rapid urbanization resulted in a sharp decrease in NDVI in the Yangtze River and Pearl River deltas, while irrigation and fertilization may have contributed to the increased NDVI in the North China plain. *INDEX TERMS:* 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 1620 Global Change: Climate dynamics (3309); 1640 Global Change: Remote sensing; *KEYWORDS:* trends in NDVI, NDVI-climate relationship, human activity, China

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1. Introduction

[2] Climate-related interannual variations of terrestrial vegetation activity have been investigated by various approaches, including studies of plant phenology [*Bradley et al.*, 1999; *Menzel and Fabian*, 1999], carbon process models [*Melillo et al.*, 1993; *Dai and Fung*, 1993; *Schimel et al.*, 2000], and analyses of satellite-derived normalized difference vegetation index (NDVI) data [*Myneni et al.*, 1997, 1998, 2001; *Los et al.*, 2001; *Kawabata et al.*, 2001; *Tucker et al.*, 2001; *Zhou et al.*, 2001; *Hicke et al.*, 2002a, 2002b; *Slayback et al.*, 2003]. These studies have suggested that growing season duration has lengthened and photosynthetic activity has increased in the northern middle and high latitudes over the past few decades.

[3] Satellite observations provide a useful and powerful database for evaluating the dynamics of terrestrial biosphere because of its global coverage and short revisit interval [*Cramer et al.*, 1999]. The availability of the long-term NDVI data derived from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) has motivated many scientists to study interannual variations of vegetation activities. *Myneni et al.* [1997] found that the growing season of terrestrial vegetation in northern high latitudes has advanced. This finding is consistent with observations of atmospheric CO_2 concentration [*Keeling et al.*, 1996] and was further confirmed [*Los et al.*, 2001; *Tucker et al.*, 2001; *Zhou et al.*, 2001, 2003; *Hicke et al.*, 2002a, 2002b; *Lucht et al.*, 2002; *Slayback et al.*, 2003].

[4] Variations in vegetation activity have been linked with changes in climates [*Los et al.*, 2001; *Tucker et al.*, 2001; *Zhou et al.*, 2001, 2003; *Lucht et al.*, 2002]. Investigating interannual variations of NDVI and their relationships with climate is critical for understanding the mechanisms of climate-derived variations in vegetation activity, carbon and hydrological cycles, and dynamics of vegetation structures [*Schloss et al.*, 1999; *Los et al.*, 2001]. However, most of these studies were based on coarse resolution climate data, and few detailed studies using regional ground observations have been done.

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[5] China, especially the eastern part, is dominated by a typical monsoon climate, with cold and dry winters and hot and humid summers. This, and China's geographic size, causes the country to have a large climate range, from the tropical to subarctic/alpine and from rain forest to desert, together with diverse and species-rich vegetation types. In the present study, we used the NDVI data from 1982 to 1999, together with information on climate, vegetation, and human activity, to explore interannual variations of monthly and seasonal NDVI and their relationships with climate and land use change. Climate variables in this paper include monthly and seasonal precipitation and air temperature. Seasonal NDVI trends were analyzed in three seasons (spring, summer and autumn) to avoid spurious NDVI trends due to winter snow, while monthly NDVI trends were applied to all 12 months throughout all year.

2. Data and Methods

2.1. NDVI Data

[6] The NDVI data used in this study were from the Global Inventory Monitoring and Modeling Studies (GIMMS) group derived from the NOAA/AVHRR Land data set, at a spatial resolution of 8×8 km^2 and 15-day interval, 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 El Chichon and Mount Pinatubo eruptions in April 1984 and June 1991 and overcome most problems noted in previous generations of NDVI data sets [*Los*, 1998; *Myneni et al.*, 2001; *Tucker et al.*, 2001; *Zhou et al.*, 2001].

[7] Interannual signals of plant canopy reflectance are subtle and therefore subject to nonvegetation effects. Many factors, unrelated to ecosystem structure or function such as navigation uncertainties, calibration uncertainties, atmospheric effects, variations in the viewing and illumination geometry, and variations in the soil background, introduce extraneous variability in NDVI, both in space and time, and can be easily misidentified as real NDVI variability [*Gutman*, 1999]. In the AVHRR time series, the major problems are with the continuous changes in sensor sensitivity (calibration problem) 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]. Successful removal of nonvegetation effects, at global and continental scales, remains a challenge.

[8] Some of these nonvegetation effects can be minimized, to a large extent, by processing and analyzing only the maximum NDVI value within each 15-day period [*Holben*, 1986]. The quality of this data set has been assessed by *Tucker et al.* [2001] and *Zhou et al.* [2001, 2003]. They found that this data set could be used to identify the long-term trends in vegetation activity. Recent comparisons among four AVHRR NDVI data sets indicate that variations due to satellite drifts and changeover in the GIMMS data are small in latitudes above 40°N. [*Slayback et al.*, 2003].

[9] To further reduce residual atmospheric and bidirectional effect, we produced a monthly NDVI data set, using the maximum NDVI value in each month [*Holben*, 1986]. However, some variations due to satellite drift/changeover, incomplete corrections for calibration loss and atmospheric effects (clouds, aerosols, etc) may still remain in the GIMMS NDVI data. Here we assume that such variations are smaller than those due to environmental drivers.

[10] These monthly NDVIs were then aggregated to grid cells of $0.1° \times 0.1°$ from the original 8-km resolution data. In this study, the total study area was 803×10^4 km^2, 85.5% of China's land area (940×10^4 km^2). Grid cells with <0.1 of annual average NDVI during 18 years were excluded to reduce the influence of soil (over deserts and sparsely vegetated grids) and snow on the NDVI trend.

2.2. Climate Data

[11] Monthly mean 2 m air temperature and precipitation data at $0.1° \times 0.1°$ resolution were compiled from the 1949–1999 temperature/precipitation database of China. These data were generated from 680 climatic stations across the country [*Fang et al.*, 2001]. Figure 1 shows the locations of these stations, together with the geographical and elevational background of China. Some errors may result from the interpolation in the Tibetan Plateau because of limited meteorological stations available. The annual mean air temperature varies from ca. -6°C in the northeast region and the central Tibetan Plateau to ca. 30°C in south China, Hainan Island, and Taiwan (Figure 2). Precipitation varies greatly from <50 mm in the Taklimakan Desert (the driest desert in China) to about 3000 mm in south China. In the eastern half of China, temperature decreases from south to north and rainfall is relatively abundant (over 500 mm per year), while in the western half temperature is generally below 10°C and very dry because of the influence of the Tibetan Plateau (Figure 2).

2.3. Vegetation Type

[12] Vegetation data were obtained from a digitized actual vegetation map of China derived from ground observations (Figure 3a) [*Institute of Geography, Chinese Academy of Sciences*, 1986]. China's vegetation was grouped into the following 10 types: evergreen broadleaf forests, deciduous broad-leaf forests, broadleaf and needleleaf forests, evergreen needleleaf forests, deciduous needleleaf forests, broadleaf shrubs, temperate grasslands, alpine meadows and tundra, deserts, and cultivation. The data were aggregated to grid cells at $0.1° \times 0.1°$ resolution, as done for the NDVI and climate data sets. To compare the vegetation classification with the distribution of NDVI values, a map of annual mean NDVI for the 18 years was shown in Figure 3b.

3. Results and Discussion

3.1. Trends of Seasonal NDVI and Climate

[13] In this section we discuss the NDVI trends and their relationships with climatic variables by three seasons: spring (March to May), summer (June to August), and autumn (September to November). Linear time trends were estimated by ordinary least squares for NDVI and climate variables. In this paper, trends in both NDVI and climate variables were not removed for correlation analysis. We realize that positive trends in both NDVI and climate may result in higher correlations, 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

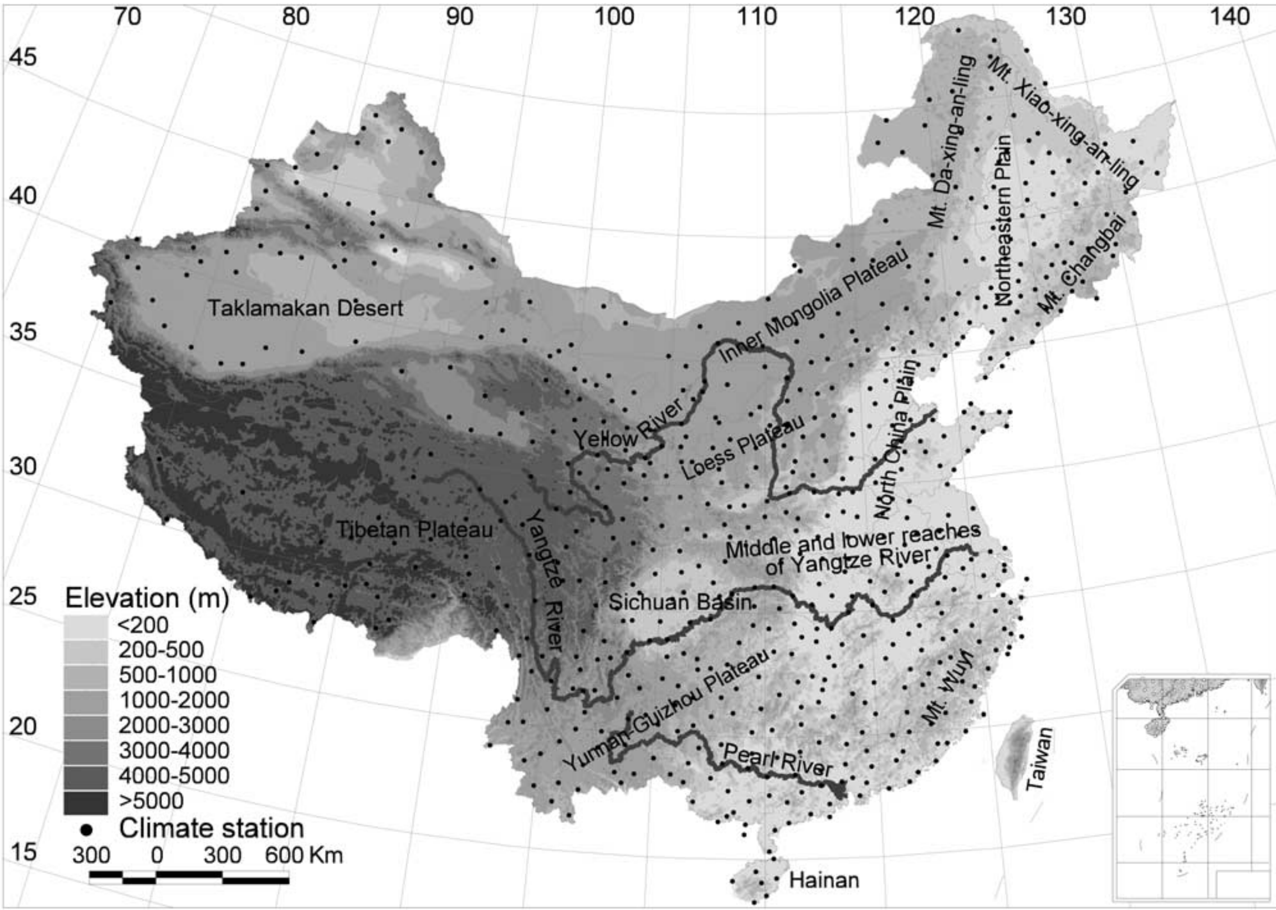

Figure 1. Major geographical regions in China, together with location of climatic stations used. A total of 680 stations are almost uniformly distributed across China. Boundaries of 31 provinces (cities or autonomous regions) are shown. Geographical regions are based on *Editorial Committee for Physical Geography of China* [1985].

contains a stochastic trend [*Kaufmann et al.*, 2000]. Furthermore, statistically meaningful relations were found after detrending or differencing the NDVI and climate data [*Zhou et al.*, 2001].

3.1.1. Trends at the Country Scale

[14] The NDVI trends for all three seasons increased significantly (Figure 4a). The largest NDVI increase ($r^2 = 0.40$, $p = 0.005$) was in spring, with a magnitude of 14.4% over the 18 years and a trend of 0.0018 yr^{-1} (the 18-year averaged NDVI was 0.231). The increase for summer and autumn was 5.2% and 5.4% with a trend of 0.0012 yr^{-1} and 0.0009 yr^{-1}, respectively.

[15] Increased NDVI was parallel with increased temperature (Figure 4b). There is a significant positive correlation between seasonal mean NDVI and temperature for all seasons, with a correlation coefficient of 0.70, 0.59, and 0.47 for spring, summer, and autumn, respectively. Temperature exhibits corresponding increases, with trends of 0.062 °C yr^{-1} ($r^2 = 0.47$, $p = 0.002$), 0.042 °C yr^{-1} ($r^2 = 0.37$, $p = 0.007$), and 0.047 °C yr^{-1} ($r^2 = 0.19$, $p = 0.07$) for these three seasons. Precipitation has a significant increasing trend in summer ($r^2 = 0.27$, $p = 0.03$), but a significant decreasing trend in autumn ($r^2 = 0.33$, $p = 0.01$) (Figure 4c). No apparent trend is seen in spring ($r^2 = 0.00$, $p = 0.79$).

[16] Table 1 summarizes the changes in seasonal NDVI over the 18 years and the correlations between NDVI and climatic factors for each season. Because the positive trends in both NDVI and temperature may cause a higher correlation between these two variables, we used the method proposed by *Zhou et al.* [2001] to calculate the relationship ($R_{T\text{-}NDVI}^*$) between NDVI and the detrended temperature. As expected, the $R_{T\text{-}NDVI}^*$ values were smaller than that before detrending; however, they showed a statistically meaningful correlation.

[17] Consistent with previous studies, the largest increase in NDVI occurred in the early growing season because of a large temperature rise and advanced growing season [*Myneni et al.*, 1997, 1998; *Los et al.*, 2001; *Zhou et al.*, 2001; *Tucker et al.*, 2001; *Hicke et al.*, 2002b; *Slayback et al.*, 2003]. Concurrent increases in temperature and precipitation in summer may improve light use efficiency and moisture availability for plants and thus lead to an increase in plant growth. This may be critical or at least partially account for the large NDVI increase in China's terrestrial vegetation. Although total annual precipitation has not increased over the past two decades, significantly increased summer rainfall could improve moisture availability for vegetation growth (Figure 4c). Autumn precipitation shows a marked decrease but may not exert a large effect on plant growth in autumn,

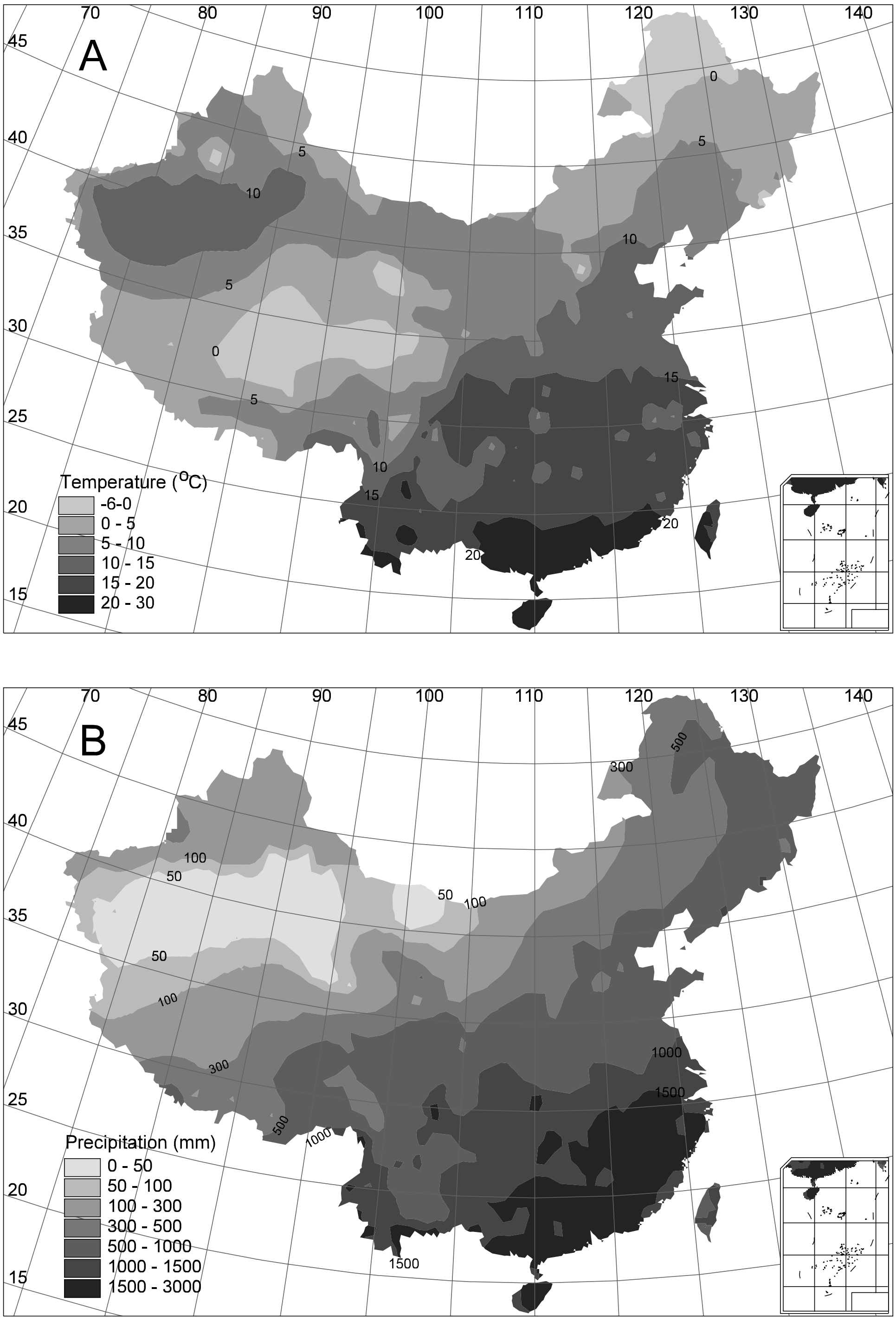

Figure 2. Spatial patterns of 18-year averaged (a) annual temperature and (b) precipitation over the study period from 1982 to 1999.

because increased summer rainfall could be stored in soils and remain available in autumn for vegetation.

[18] Despite the pronounced NDVI increases in all three seasons, several large fluctuations appeared in the NDVI trends. For example, seasonal NDVI was large in 1990 but small in 1992 for all three seasons (Figure 4a), maybe associated with seasonal climate patterns and moisture availability. In 1990, both temperature and precipitation were high (Figures 4b and 4c), and this may lead to an increase in NDVI, while in 1992 the worldwide cooling due to the Pinatubo eruption and low precipitation in summer and autumn may cause a decline of NDVI [*Hansen et al.*, 1996; *Zhou et al.*, 2001] for these two seasons; alternatively, not all of the aerosol effects are removed from the data.

[19] A relatively large NDVI trend (Figure 4a) was also found in the middle of growing season (summer) with a rate of 0.0012 yr^{-1}, following that in spring (0.0018 yr^{-1}). This suggests that summer vegetation activity is important to an

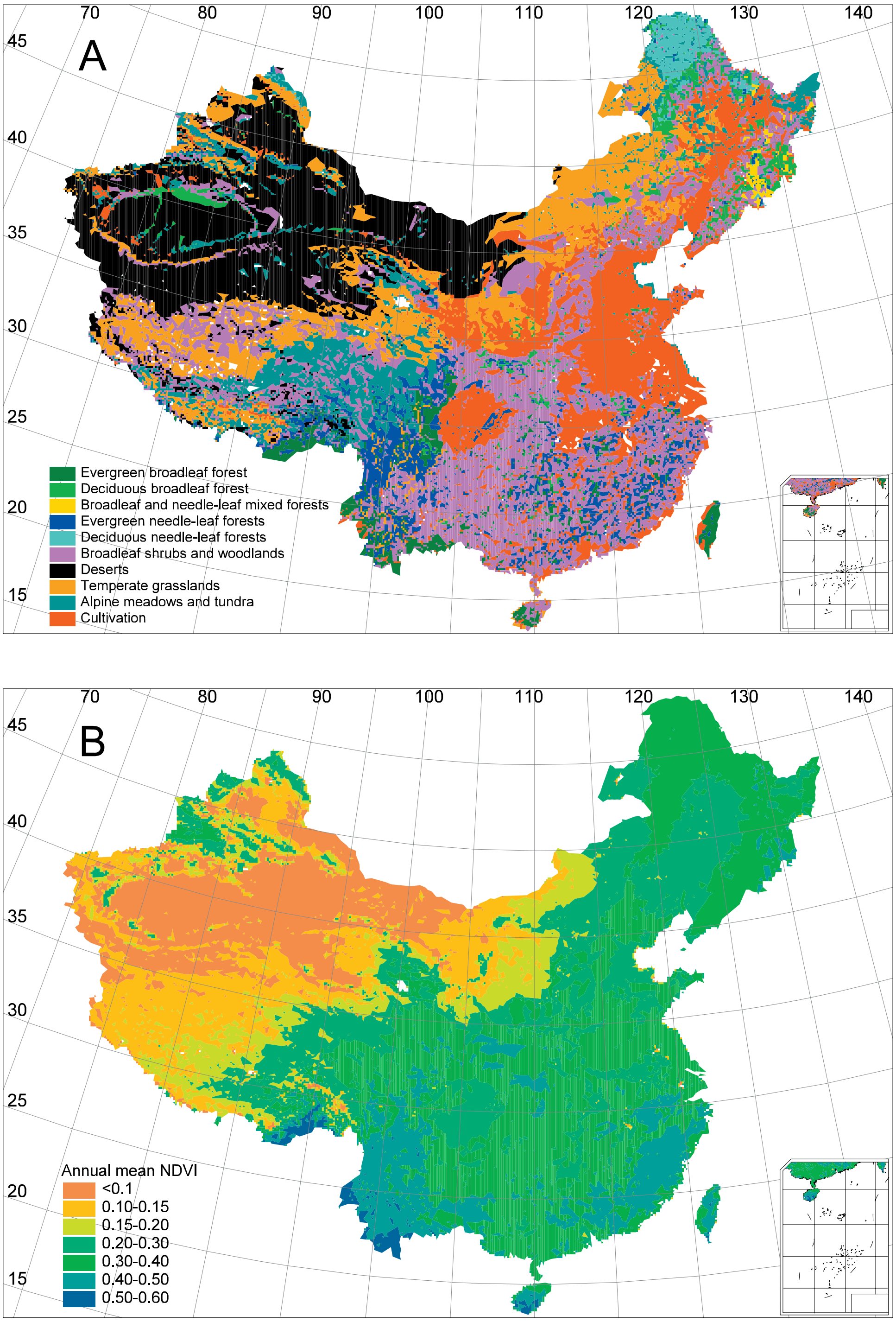

Figure 3. (a) Vegetation map of China derived from ground observations (based on *Institute of Geography, Chinese Academy of Sciences* [1986]), and (b) map of annual mean NDVI calculated from the 18-year GIMMS NDVI data set from 1982 to 1999. For details, see text.

increase in annual plant growth that could be attributed to global warming [*Melillo et al.*, 1993], increasing CO_2 concentration [*Keeling et al.*, 1996], and nitrogen deposition [*McGuire et al.*, 1995].

3.1.2. Spatial Patterns of Trends

[20] Although the increasing trend of seasonal NDVI is apparent for three seasons at the national scale, we find a high degree of spatial heterogeneity that varies seasonally (Figures 5a, 6a, and 7a). In spring (Figure 5a), NDVI tends to increase in most areas, especially in the North China Plain and hilly and plain areas of Central China, but decreases sharply in the Yangtze River and Pearl River deltas, where a rapid urbanization has taken place over the past 20 years. Summer NDVI show a fragmented pattern, increasing in most areas of the Northeast China Plain, the

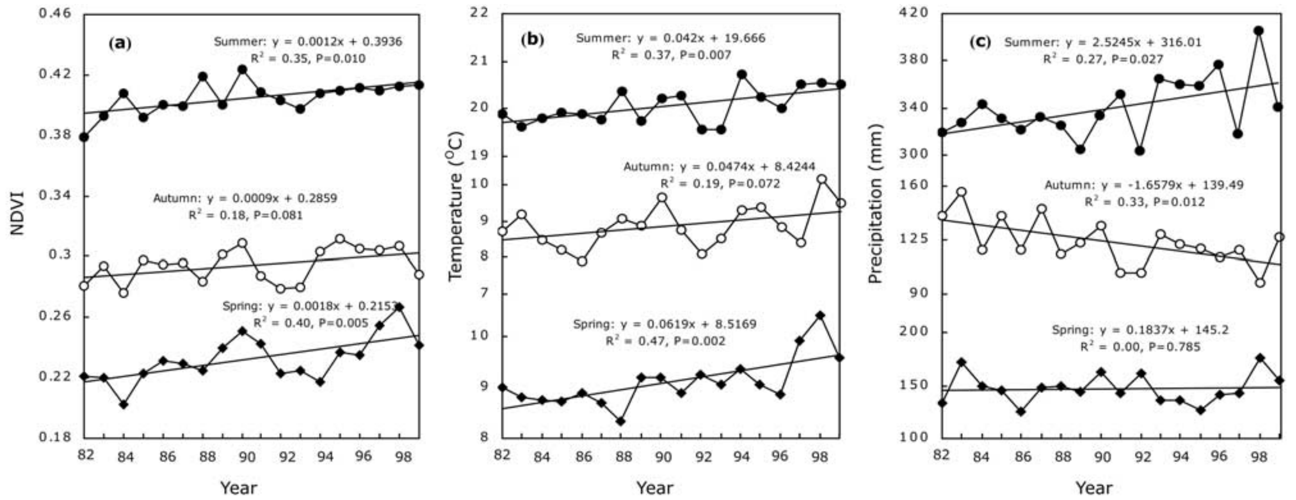

Figure 4. Interannual variations in (a) seasonal mean NDVI, (b) seasonal mean temperature, and (c) seasonal precipitation over the period 1982–1999 in China.

North China Plain, the Sichuan Basin and the Hainan Island, and decreasing in the Loess Plateau and southern parts of Yangtze River. The area characterized by a decline in NDVI has expanded markedly in the deltas of the Yangtze and Pearl Rivers (Figure 6a). The area with increasing NDVI trends declines considerably in autumn across the country (Figure 7a). Concomitantly, a decrease in NDVI was observed in a large area of Northeast China, the lower reaches of the Yellow River, the Yunnan-Guizhou Plateau-Sichuan Basin, and the central Tibetan Plateau.

[21] To analyze effects of regional climates on seasonal NDVI trends, correlations between NDVI and climate (temperature and precipitation) were showed for these three seasons (Figures 5, 6, and 7). In spring, NDVI was positively correlated with temperature in most areas (Figure 5b), suggesting that the possible effects of temperature on increased spring NDVI for most parts of China. A negative correlation between NDVI and temperature in the North China Plain could be explained, at least in part, as a result of agricultural practices, because NDVI increased significantly even though temperature showed insignificant change. There was a weak positive correlation between NDVI and precipitation over most areas in spring, but a negative correlation appeared in Mt. Xiao-xing-an-ling in northeast China where winter and spring were cold and snowy, and in southeast China where spring is particularly rainy (Figure 5c). A negative correlation was also seen in Tibet, where increased precipitation might lead to an increase in snow and ice cover. In addition to their direct effects on NDVI, increased snowfall and rainfall could also shorten the growing season and reduce incoming solar radiation, thus decrease NDVI in cold and rainy regions.

[22] In summer, a negative correlation between NDVI and temperature was found in most areas of north Yangtze River (e.g., the Loess Plateau), where significantly increased temperature and decreased precipitation could reduce moisture availability for plants (Figures 6b and 6c). In southwest areas of China, where summer rainfall was abundant, the correlation was also negative probably because of precipitation-related temperature reduction. Increased precipitation was accompanied by an increase in clouds and thus a reduction in incoming solar radiation. On the other hand, in the Yangtze River Valley, where increased summer rainfall results in flooding [*Xu and Zhao*, 1999], NDVI variations were parallel with changes in temperature (Figure 6b), not those in precipitation (Figure 6c), probably because increased summer rainfall and flooding resulted in a reduction of plant growth.

[23] In autumn, a weak positive correlation between temperature and NDVI occurred in most areas of China (Figure 7b). In contrast, a negative correlation between precipitation and NDVI was observed in most of the country (Figure 7c).

[24] Figure 8 summarizes changes of NDVI on the area base for different seasons. Over the past 18 years, the area with the largest NDVI increase occurred in spring, while the least increase was in autumn (Figure 8a). For example, the area with the NDVI increase of 10–30% and >30% over the 18 years was 45.6% and 10.2% of the total study area, while in autumn this value was only 27.0% and 2.5%, respectively (Figure 8a). Statistically, 85.9% of the total study area has increased over the 18 years in spring, of which 25.9% had a significant increase at the 5% level, while in summer and autumn 72.2% (16.8% at the 5% level) and 73.0% (12.0% at the 5% level) of the total area had increased, respectively (Figure 8b).

[25] Evidently, the spatial and seasonal heterogeneity of NDVI trends may mainly result from differences in regional

Table 1. Mean Value, Trend, and Relative Increase of Seasonal NDVI, and Correlation Coefficients Between Seasonal Mean NDVI and Mean Temperature ($R_{T\text{-}NDVI}$) and Seasonal Precipitation ($R_{P\text{-}NDVI}$), and Between Seasonal NDVI and the Detrended Temperature ($R_{T\text{-}NDVI}$*)

	Seasonal NDVI					
Season	Mean ± SD	Trend, per Year	Relative Increase, %	$R_{T\text{-}NDVI}$	$R_{P\text{-}NDVI}$	$R_{T\text{-}NDVI}$*
Spring	0.23 ± 0.02	0.0018	14.4	0.70	0.27	0.47
Summer	0.40 ± 0.01	0.0012	5.2	0.59	0.32	0.36
Autumn	0.29 ± 0.01	0.0009	5.4	0.47	−0.02	0.35

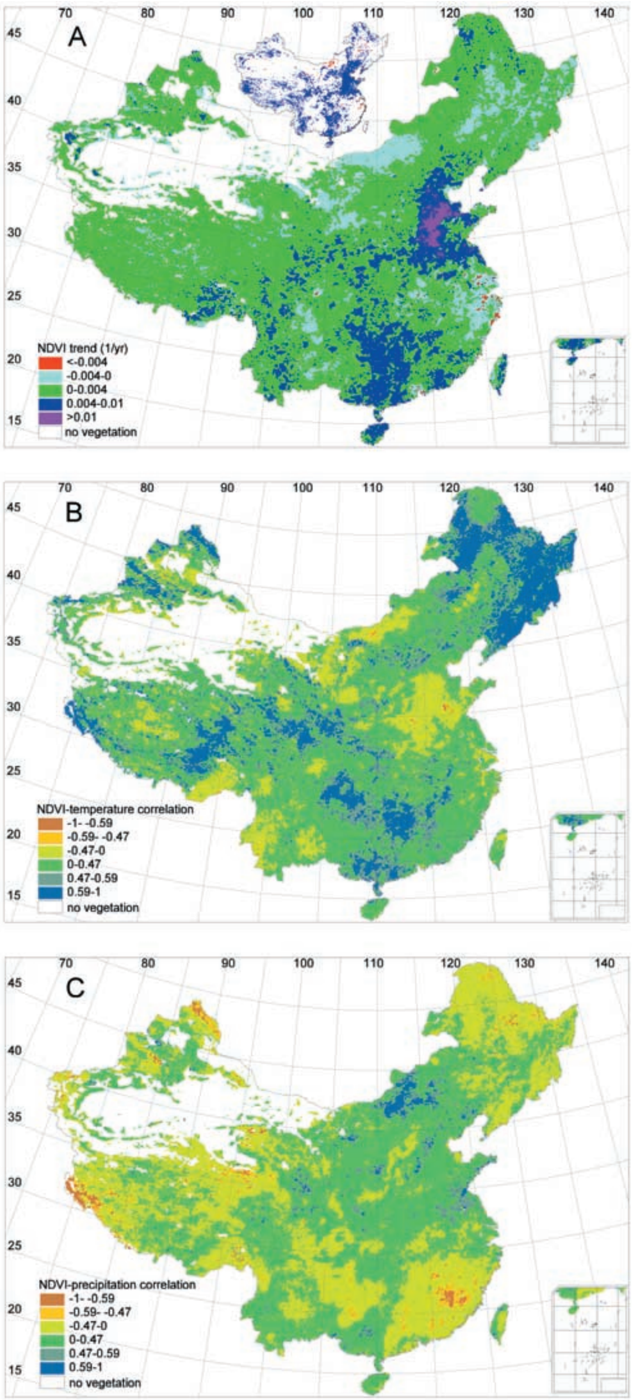

Figure 5. Spatial patterns of (a) mean NDVI trends, and correlation between (b) NDVI and temperature and (c) NDVI and precipitation for each grid cell for spring (March to May) in China. The above insert map in Figure 5a shows significant increase (blue) or decrease (red) in NDVI over the 18 years. The values of 0.47 and 0.59 for coefficients of correlation in the legends of Figures 5b and 5c correspond statistically to 5% and 1% significance levels, respectively.

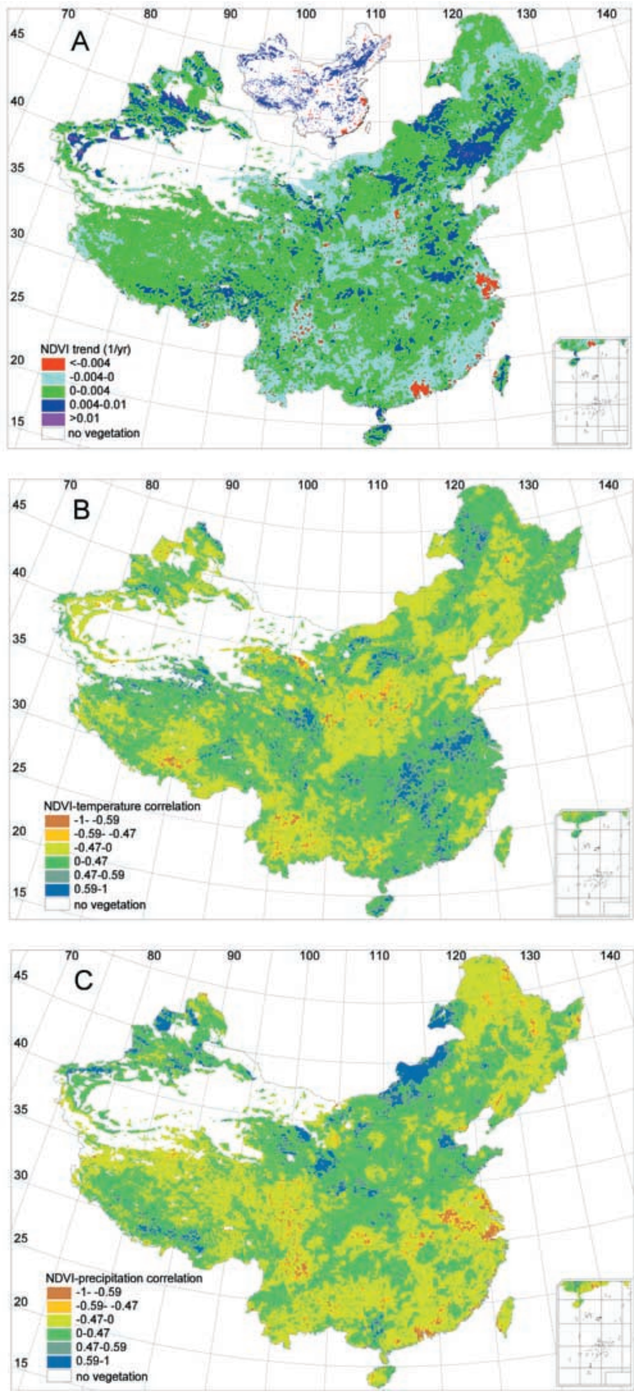

Figure 6. Spatial patterns of (a) mean NDVI trends, and correlation between (b) NDVI and temperature and (c) NDVI and precipitation for each grid cell for summer (June to August) in China. The above insert map in Figure 6a shows significant increase (blue) or decrease (red) in NDVI over the 18 years. The values of 0.47 and 0.59 for coefficients of correlation in the legends of Figures 6b and 6c correspond statistically to 5% and 1% significance levels, respectively.

climates and vegetation structures. In spring, temperature increased significantly all over the country and thus caused an increase in NDVI in most parts of China (Figure 5). In summer, reduced precipitation and increased temperatures enhanced drought and likely led to a decrease in NDVI in a large area north of the Yangtze River, especially in the Loess Plateau (Figure 6). In autumn, decreased precipitation and increased temperatures could lead to a decrease in

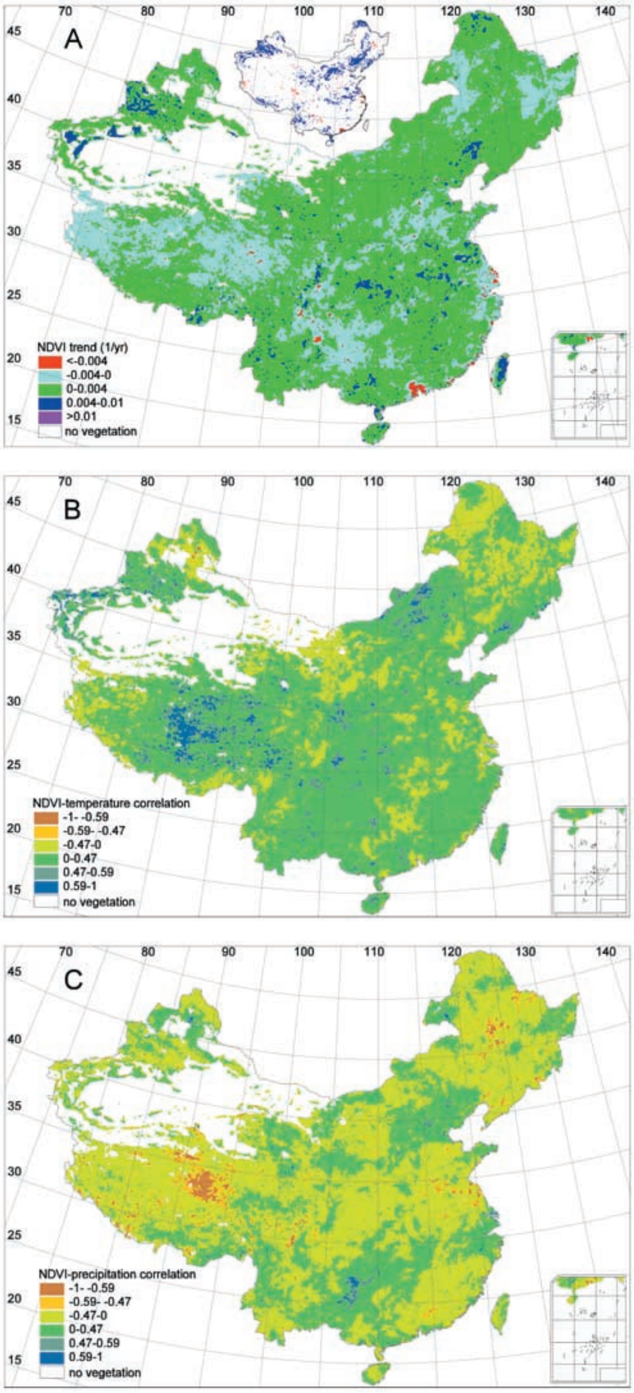

Figure 7. Spatial patterns of (a) mean NDVI trends, and correlation between (b) NDVI and temperature and (c) NDVI and precipitation for each grid cell for autumn (September to November) in China. The above insert map in Figure 7a shows significant increase (blue) or decrease (red) in NDVI over the 18 years. The values of 0.47 and 0.59 for coefficients of correlation in the legends of Figures 7b and 7c correspond statistically to 5% and 1% significance levels, respectively.

NDVI in most of eastern and central China (Figure 7). Accordingly, the spatial pattern and magnitude of seasonal NDVI trends in China appears to be linked with changes in temperature and precipitation. Using the same NDVI data set, *Hicke et al.* [2002b] analyzed trends of net primary production (NPP) and their relation with climate in North America from 1982 to 1998. They found that changes in climate influenced NPP in the Central Plains and eastern Canada where summer NPP increased, but did not influence NPP in southeastern US where NPP increased in the absence of climate variations. This suggests not only in China, but also in North America, the interannual change in vegetation activity varies spatially and seasonally.

[26] Land use change, an important determinant for carbon exchange between air and land [*Sampson et al.*, 1993; *Loveland and Belward*, 1997; *Kicklighter et al.*, 1999;

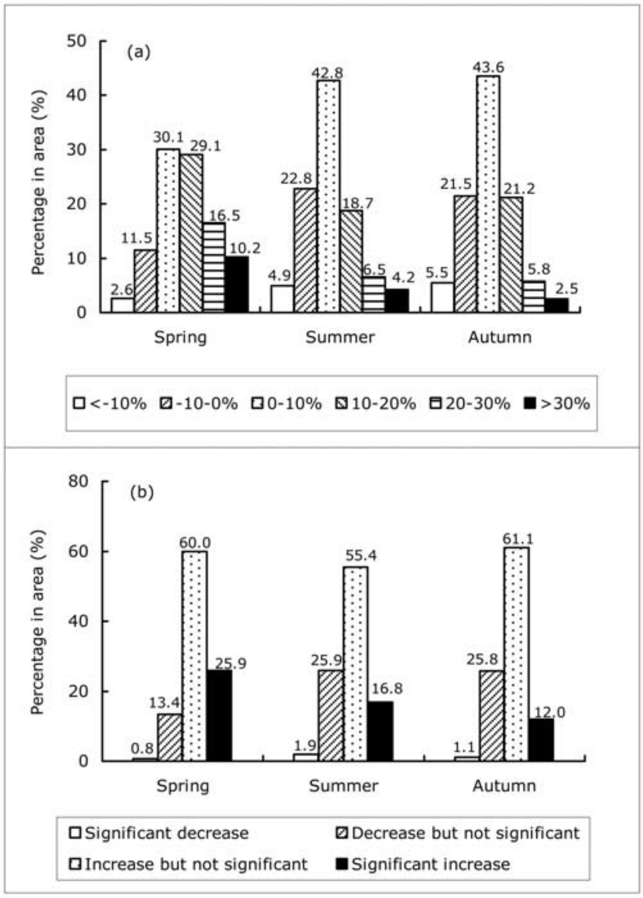

Figure 8. NDVI increase/decrease on the area base for different seasons in China. (a) Percentage of NDVI increase/decrease in the magnitude (change by less than −10%, −10–0%, 0–10%, and so on, over the 18 years) in area. Over the past 18 years the area with the largest NDVI increase occurred in spring, while the least increase in autumn (Figure 8a). For example, the area with a NDVI increase of 20–30% and of >30% in spring was 16.5% and 10.2% of the total study area, while in autumn this value was 5.8% and 2.5%, respectively (Figure 8a). (b) Percentage of NDVI increase/decrease at the statistical significance levels in area. Statistically, 85.9% of the total study area has increased over the 18 years in spring, 25.9% of which had a significant increase at the 5% level, while in summer and autumn 72.2% (16.8% at the 5% significance level) and 73.0% (12.0% at the 5% significance level) of the total study area had increased, respectively (Figure 8b).

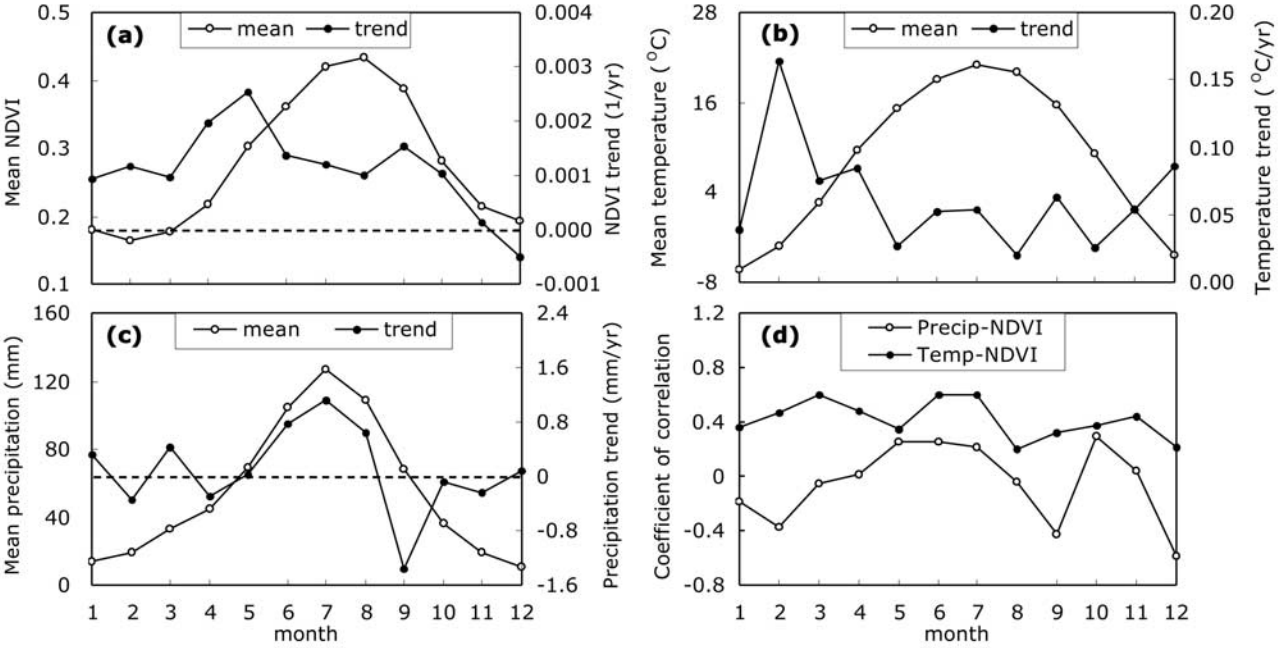

Figure 9. Seasonal changes in monthly NDVI and climatic variables over the 18 years from 1982 to 1999 in China. (a) 18-year averaged monthly NDVI and its trend. (b) 18-year averaged monthly mean temperature and its trends. (c) 18-year averaged monthly precipitation and its trend. (d) Correlations between monthly NDVI and temperature and between monthly NDVI and precipitation.

Schimel et al., 2000], could also play a key role in the spatiotemporal changes in NDVI in the economic core zones of coastal China (Figures 5, 6, and 7). In the Yangtze River and Pearl River deltas, NDVI declined sharply throughout all seasons because of rapid urban expansion. In contrast, in the North China Plain, increased NDVI was partly a result of improved agricultural practices: irrigation and fertilizer use have increased in the past several decades [*Editorial Committee for China's Agricultural Yearbook*, 2000]. According to the China's Agricultural Yearbook 2000, food yields of major crops per area in this region had increased by 40% from 1982 to 1999, although we could not identify in this paper how much of such increase was resulted from the agricultural practices. The large NDVI trends for the cultivated crops, shown in section 3.2.2, also suggest the importance of human activity for the observed NDVI trend and its spatial patterns.

3.2. Trends of Monthly NDVI and Climate

3.2.1. Monthly Trends at the Country Scale

[27] The magnitude of monthly NDVI and its change over time are important indicators of the contribution of vegetation activity in different months to annual plant growth total. In China, monthly NDVI reached maximum values in August and was rather small from December through March (Figure 9a). The monthly NDVI trends showed positive values for all months, indicating that NDVI increased throughout the year over the 18-year study period (Figure 9a). The largest two trends were in May and April, three to four months ahead of the largest monthly NDVI. That is, plant growth peaks in the middle of growing season (summer), while the largest NDVI increase occurred in the early growing season (spring).

[28] NDVI trends and their patterns were likely coupled with those of climatic variables (Figures 9b and 9c). Changes in monthly mean temperature and its trend were consistent with those of NDVI: high values in summer and low ones in winter. However, the highest mean temperature was in July instead of August, the month with the largest mean NDVI (Figure 9b). Assuming 5°C as the threshold of the growing season [*Prentice et al.*, 1992], the duration of growing season would be about seven months long at the national scale, beginning from about mid-March and ending around mid-October. The corresponding NDVI value was about 0.20 at the beginning of growing season and 0.25 at the end of the growing season. The different NDVI values at the beginning and end of the growing season should be important for the satellite-based study of plant phenology.

[29] The temperature trends were positive for all months, indicating that mean temperature has increased in every month over the study period (Figure 9b). The largest temperature rise was in February with an annual rate of 0.16°C, which means that temperature in this month has increased by 3.2°C over the past two decades; the second largest were in December and April, both with a annual rate of 0.09°C. Temperature increase was also large in March with a rate of 0.07 °C yr^{-1}. Clearly, the appearance of the largest NDVI trend lagged behind that of the largest temperature trend by three months at the national scale.

[30] Monthly precipitation showed a similar pattern to that of temperature and NDVI: large values in summer and small in winter (Figure 9c). However, the precipitation trend indicated a large fluctuation: summer saw significant increases while September suffered a steep decrease. Concurrent increased summer rainfall and temperature could enhance plant growth, as we discussed in section 3.1.1.

[31] Correlations between monthly climatic variables and NDVI are showed in Figure 9d. A positive correlation between temperature and NDVI was seen for all months. NDVI significantly correlated with temperature (5% level) in February to July, but not in August and September (Figure 9d). The relationship between precipitation and NDVI was more complicated than that between NDVI and temperature at the national scale: positive correlations appeared for May, June, July, and October, and other months were weak negative or insignificant (Figure 9d).

3.2.2. Monthly Trends by Vegetation Type

[32] Similar to monthly NDVI and its trend over the past 18 years at the country scale (Figure 9a), monthly NDVI and its trends showed the largest value in summer and spring for most vegetation types (Figure 10). In general, the monthly NDVI was largest in July or August, and was rather small values in winter and spring for all the vegetation types, except evergreen broadleaf forests whose monthly NDVI was relatively large from summer through winter, and the lowest in spring (Figure 10a). The monthly NDVI trends showed that NDVI has increased in the growing season for all vegetation types. The largest increase was in the early growing season (April or May) for most vegetation types except broadleaf and needleleaf mixed forests (Figure 10c) and temperate grasslands (Figure 10h), which had similar magnitudes of the NDVI trend throughout the growing season. The largest NDVI trend in the early growing season reflects an effect of the advanced growing season. It is noteworthy that the NDVI trend in August was small for most vegetation types except deserts (Figure 10g) and temperate grasslands (Figure 10h), consistent with the trend of the country as a whole (Figure 9a).

[33] The seasonal changes in the trends of monthly temperature and precipitation by vegetation type were shown in Figure 10. Among the highlights of the temperature trend:

[34] 1. Monthly mean temperatures have increased over the past 18 years for most vegetation types, except deciduous needleleaf forest (Figure 10e) in northeast China where a negative temperature trend was observed in March, November, and December.

[35] 2. The temperature rise was not significant during summer season for all vegetation types, especially for evergreen broadleaf forests, deciduous broad-leaf forests, evergreen needleleaf forests, and deciduous needleleaf forests.

[36] 3. In general, the temperature increase was larger in vegetation types in northern areas than in southern areas. For instance, the largest temperature annual rise (February) was 0.3°C for broadleaf and needleleaf mixed forests (Figure 10c), 0.24–0.26°C for deciduous broad-leaf forests (Figure 10b) and deciduous needleleaf forests (Figure 10e), and 0.08°C (April) for evergreen broadleaf forests in south China (Figure 10a).

[37] 4. Seasonal patterns of precipitation trends by vegetation type were almost consistent with those for the whole country: increases in summer and decreases in September for most vegetation types, except broadleaf and needleleaf mixed forests (Figure 10c) and deciduous needleleaf forests (Figure 10e) where precipitation decreased in summer.

3.2.3. Lagged Effect of Climate

[38] In China, NDVI showed a consistent seasonal pattern with those of temperature and precipitation: large values in summer and small in winter (Figure 9a). However, the peak NDVI was seen in August, not in July with the largest temperature and precipitation (Figures 9b and 9c). This was somewhat different from results in other northern regions reported by *Schloss et al.* [1999] and *Kicklighter et al.* [1999], who suggested that the highest vegetation activity was in June or July, the months with the highest temperature and precipitation in the northern regions. The possible reasons for such difference is unknown, possibly due to different approaches, namely using the carbon process models by *Kicklighter et al.* [1999] and the satellite-derived analysis by the present study.

[39] A discrepancy between maxima in NDVI and climatic variables may suggest a lagged response of NDVI to changes in climate. This lagged response was clearly shown in the relationship between trends in monthly NDVI and temperature at the country scale (Figure 9). The analysis of correlation between NDVI and temperature by vegetation type also confirmed such a lag: the largest temperature increase occurred in February, about 3 months in advance of the largest NDVI increase for all vegetation types except evergreen broadleaf forests (Figure 10). To illustrate this further, Figure 11 plots the correlations of February mean temperature to monthly NDVI values from March through July at the national scale. A strong correlation was found between the mean temperature and NDVI value for April (r^2 = 0.33, p = 0.01) and May (r^2 = 0.34, p = 0.01), confirming the time-lag and the importance of February mean temperature to the NDVI change. *Braswell et al.* [1997] found that a lag of about 2 years was between NDVI and temperature at the global scale. *Los et al.* [2001] explained this by the climatic oscillations, which had a similar periodicity (ca. 2 years) during the 1980s, and suggested shorter lags at regional scales. The time lag of 3 months between NDVI and temperature identified at national and biome scales in China may suggest that the result from the present study has provided regional information on the response of vegetation activity to temperature.

4. Concluding Remarks

[40] The multiyear NDVI data set and a corresponding climate data set from 1982 to 1999 were used to analyze monthly and seasonal NDVI trends and their relationships with climate and human activity. The results indicate that both monthly and seasonal NDVI increased at the national and biome scales. These trends showed a large spatial and temporal heterogeneity, corresponding mainly to regional and seasonal changes in climate, suggesting that climate change is playing an important role for the patterns of NDVI trends.

[41] 1. At the national scale, seasonal mean NDVI and temperature showed a significant increase for spring, summer and autumn. Several large fluctuations in the NDVI trends were likely due to fluctuations in precipitation. These results suggested that both temperature and precipitation are critical to interannual variability of NDVI.

[42] 2. The NDVI trends showed a large spatial heterogeneity, roughly corresponding to regional climate and its seasonal changes. In general, increased temperature and precipitation could lead to an increase in NDVI in most areas, but increased temperatures could also cause seasonal

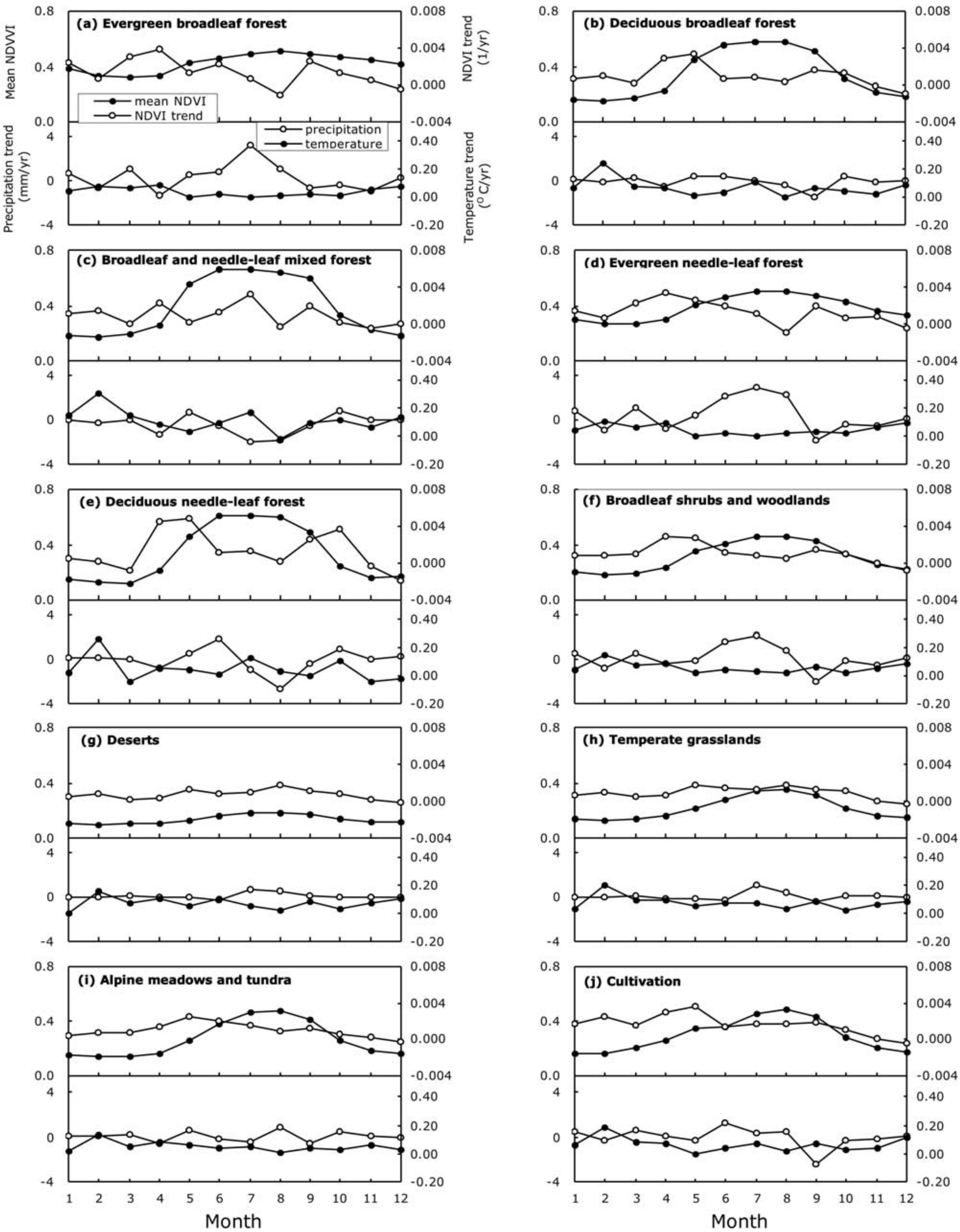

Figure 10. Seasonal changes in averaged monthly NDVI, NDVI trend, monthly mean temperature trend, and monthly precipitation trend over the period of 1982–1999 by vegetation type in China. (a) Evergreen broadleaf forests. (b) Deciduous broadleaf forests. (c) Broadleaf and needleleaf mixed forests. (d) Evergreen needleleaf forests. (e) Deciduous needleleaf forests. (f) Broadleaf shrubs and woodlands. (g) Deserts. (h) Temperate grasslands. (i) Alpine meadows and tundra. (j) Cultivation.

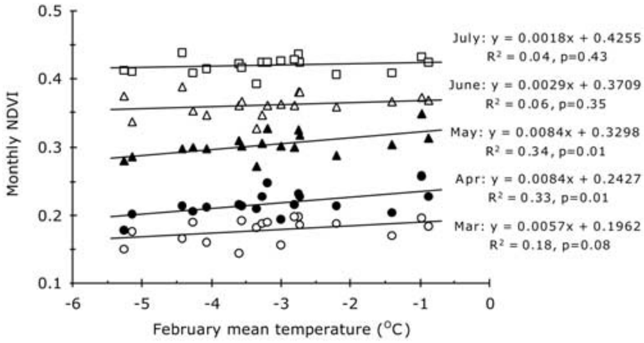

Figure 11. Correlations between February mean temperature and monthly NDVI of March to July at the country scale. A strong correlation showed between the mean temperature and the NDVI value for April ($r^2 = 0.33$, $p = 0.01$) and May ($r^2 = 0.34$, $p = 0.01$) suggests the importance of February mean temperature to the NDVI increase for these 2 months.

drought in arid regions (such as in summer in the Loess Plateau), and increased precipitation could lead to a decrease in plant photosynthesis due to decreased solar radiation in rainy regions (such as in summer in the Yangtze River valley and spring in south China) and owing to decreased temperature and solar radiation in cold regions (Tibet and northeast China). The rate and extent of NDVI increase varied seasonally. The largest increase appeared in spring by 14.4% in magnitude during the 18 years over 85.9% of the total study area (with a significant increase of 25.9% in area at 5% significance level). The increase in summer and autumn was by 5.2% and 5.4% over 72.2% (with a significant increase of 16.8%) and 73.0% (with a significant increase of 12.0%) of the study area, respectively (Figure 8).

[43] 3. Human activities (urbanization and agricultural practices) have exerted a large effect on the spatiotemporal patterns of NDVI trends in some regions. Rapid urbanization has caused a sharp decrease in NDVI in the Yangtze River and Pearl River deltas, while irrigation and fertilizer use have probably increased plant growth in North China Plain.

[44] 4. At the national and biome scales, a time lag of about three months (February and May) was found between vegetation activity and temperature change.

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