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Climate Change Contribution to Forest Growth in Eastern China over Past Two Decades

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ABSTRACT

China has experienced substantial climate change during past decades. To understand the response of forests to this change, we investigated the trends in forest growth and the control mechanism behind the observed variations in the North-South Transect of Eastern China (NSTEC). Interpretations were made based on the Normalized Difference Vegetation Index (NDVI) and temperature and precipitation data from 1982 to 2006. Our results indicated that the growing season NDVI trend showed a significant linear relationship with the mean growing season temperature and precipitation trend exhibiting inconsistent or even opposite performances from the north to south of the NSTEC. Prevalent forest greening was observed in the cold and dry regions where the climate becomes warmer and drier, while forest browning appeared to dominate in the warm and humid areas where climate turns warmer and wetter. These phenomena indicated the positive effect of growing season climates on forest growth may stall under warmer and wetter conditions in the much warmer and wetter regions. Our findings showed a difference in growth trend between needle leaf forests and broadleaf forests. In the cold and dry regions, the NDVI of most needle leaf forests showed an increasing trend, but nearly half of the broadleaf forests exhibited a negative NDVI slope while the other broadleaf forests exhibited a positive NDVI slope.

Key words: GIMMS NDVI, Climate changing, NSTEC (North-South Transect of Eastern China), Forest, Vegetation greening, Vegetation browning

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1. INTRODUCTION

Forests compose a major part of terrestrial ecosystems, occupying about 30% of the world's land area (Dixon et al. 1994). Forests play an important role in the global carbon cycle due to their huge C pool and high productivity (Barford et al. 2001; Fang et al. 2001). It is estimated that over 80% of global aboveground carbon (C) is stored in forest vegetation (Dixon et al. 1994). The annual C flux between forests and the atmosphere through photosynthesis and respiration is up to 90% of the total annual flux of terrestrial ecosystems (Winjum et al. 1993), which is one of the key processes that need to be assessed in the context of the Kyoto Protocol (Yu et al. 2008). Moreover, forests carry important roles in the planetary energetic and hydrologic cycle, closely related to regional climate (Bonan 2008), as well as global value for the services they provide to society (Berck and Bentley 1997).

Climate change is pronounced in Eurasia, especially in China during the last century (IPCC 2001a, b). Besides the prominent annual trends in climate change, remarkable variations in seasonal trends and spatial patterns were also detected in China (Ding et al. 2007; Piao et al. 2010). The distinct spatial patterns of climatic variables may result in different vegetation activity spacial patterns (Zhou et al. 2003; Angert et al. 2005; Piao et al. 2011). The climate-induced changes in vegetation growth over Eurasia have been

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investigated using various approaches (Piao et al. 2005; Piao et al. 2009). Compared to previous direct field measurements and model-based estimation, satellite data, such as Normalized Difference Vegetation Index (NDVI) derived from infrared channel and near-infrared channel remote sensing data can exhibit temporal and spatial information on the integrated responses of plant growth to both natural and anthropogenic influences (Tan et al. 2007). Previous researches demonstrated that NDVI is an indicator of vegetation activity and is proven to be positively correlated with productivity (Tucker et al. 2005, Bunn and Goetz 2006). Over the past decade due to consistent global vegetation coverage with a relatively broad spatial coverage and high temporal resolution, remotely sensed vegetation indices have been widely used to explore changes in vegetation activity at national and continental scales (Dong et al. 2003).

Previous studies used satellite-derived NDVI datasets to identify that vegetation growth was strongly disturbed by climate change (Goetz et al. 2005; Piao et al. 2010). The linkage between climate change and vegetation growth in China has not been adequately quantified (Peng et al. 2011). Vegetation growth significantly increased in most areas of China during last three decades, probably resulting from increased temperature (Piao et al. 2003, 2011). In Inner Mongolia and northwest China a significant reversion in the growing season NDVI trend occurred in the 1990s and early 2000s due to drought stress strengthened by warming and less precipitation (Angert et al. 2005; Lotsch et al. 2005; Park and Sohn 2010). The increased temperature boosted vegetation growth through an increase in the growing season length and enhanced photosynthesis (Slayback et al. 2003; Piao et al. 2006a). However, the vegetation growth response to climate change varies across different seasons and ecosystems (Piao et al. 2003). The mechanisms of these phenomena present substantial uncertainties. Hence, more detailed studies at regional scale are essential and urgently needed to better understand the terrestrial ecosystem response to recent climate system changes. The ability to predict future interactions between vegetation and changing climate and developing effective strategies to deal with climate change are critical.

In China the plentiful terrestrial ecosystems and environmental gradients provide a unique scientific platform for detecting the responses of forests to changing climate (Zhang et al. 2006a). The North-South Transect of Eastern China (NSTEC), the 15th standard transect of the Global Change and Terrestrial Ecosystems (GCTE) project of the International Geosphere-Biosphere Program (IGBP), is selected as study area in our present work. The terrestrial transects approach for global change research was developed by IGBP as a way to address large spatial phenomena with both regional and global implications (Koch et al. 1995). The IGBP Terrestrial Transects were established in critical regions of the world to cover most environmental conditions and biomes/ecotones with special attention to highly sensitive regions with strong feedbacks to global change. We followed the terrestrial transects approach in this study aimed to investigate the trends in forest growth across NSTEC and the control mechanism of behind the observed variations in Eastern China.

2. STUDY AREA

The study area is along the NSTEC, which is one of the IGBP mid-latitude transects, located between 118°E/54°N to128°E/40°N and 108°E/40°N - 118°E/17.5°N from Hainan Island to the northern border of China. The NSTEC covers about 1/3 of the territory of China, one of the most important ecological, political, economic and cultural regions of China (Fig. 1). The eastern Asian monsoon influence causes the climate in East Asia to differ greatly from that in Europe and North America, with apparent latitudinal temperature and precipitation gradients along the NSTEC (Yu et al. 2006). A vegetation sequence is distributed from north to south along the NSTEC (Zhang et al. 2006b) that includes a cold temperate coniferous forest, temperate mixed forests, warm temperate deciduous broadleaf forests, subtropical evergreen coniferous forests, evergreen broadleaf forests and tropical rainforests (Sheng et al. 2011). This regional area is also an ideal and natural proving ground for studying the temperature increase effect on the climate and ecosystem. Comparison of the annual variations in NDVI for different forests can help understand the ecosystem carbon sequestration environmental controls in Eastern China and elucidate the response and adaptation of these forests to climate change.

3. DATA AND METHODS

3.1 NDVI

NDVI data at a spatial resolution of 0.083° and 15 day interval were acquired from the Global Inventory Monitoring and Modeling Studies (GIMMS) group derived from the NOAA/AVHRR Land data set for the period January 1982 to December 2006 to explore vegetation activity. The GIMMS NDVI datasets were corrected to minimize volcanic eruption, solar angle and sensor error and shift effects and has been proven to be one of the best products for evaluating the long-term trends in vegetation dynamics at regional and global scales (Slayback et al. 2003; Beck et al. 2011). To further reduce the residual atmospheric and bidirectional effect we used the Maximum Value Composite (MVC) to produce a monthly NDVI data set (Holben 1986). Pixels with average annual NDVI less than 0.1 during the 25 year period were considered as non-vegetated areas and thus removed to eliminate the impact of bare and sparsely vegetated regions in this study (Piao et al. 2006b).

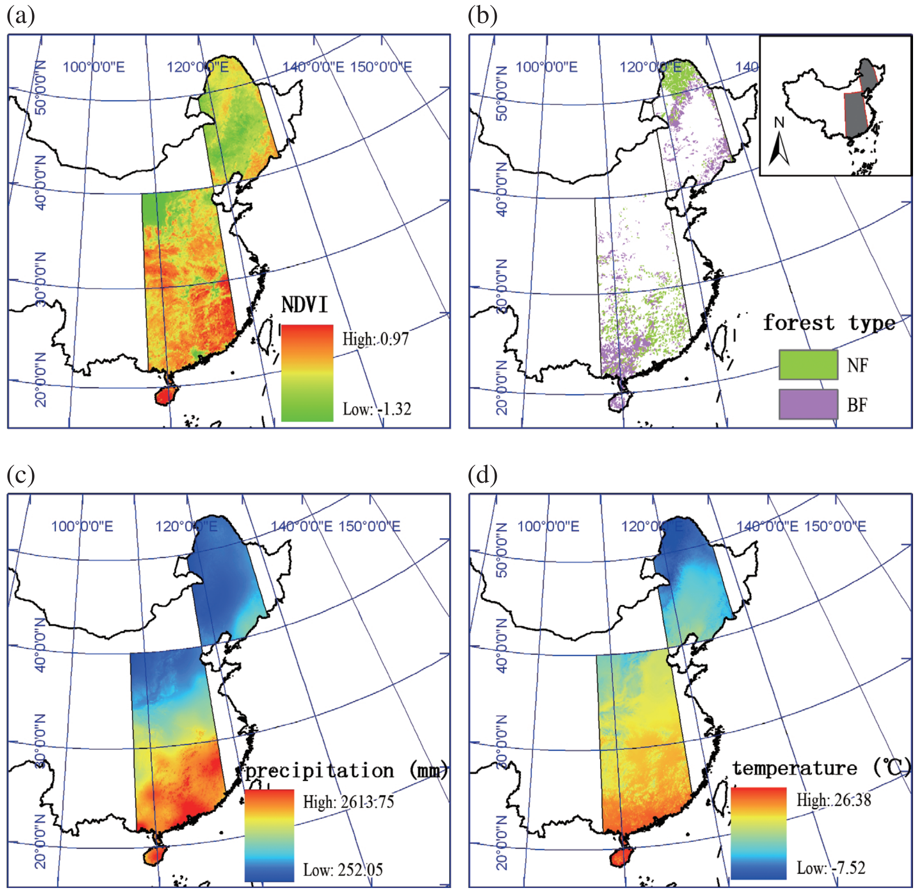

Fig. 1. The North-South Transect of Eastern China: (a) multi-year mean NDVI, (b) spatial distribution of needleleaf forests (NF) and broadleaf forests (BF), (c) multi-year mean precipitation and (d) multi-year mean temperature.

Our analysis was confined to the growing season, defined as from April to October to be consistent within the whole country (Piao et al. 2011). It should be noted that the actual growing season may be different from that defined in this study. For instance, the growing season for subtropical southern China is usually longer than our definition. The spatial pattern of average NDVI from April to October during 1982 - 2006 on the NSTEC is shown in Fig. 1a. In light of the conclusions of Piao et al. (2011), we calculated the annual trends in NDVI and climatic factors over the entire period based on a linear regression model more appropriate for most parts of China (Peng et al. 2011). To investigate the potential climatic drivers of NDVI trends, we further calculated Pearson correlation coefficients between the NDVI and climatic factors.

3.2 Forest Types

The distribution of forest types information was obtained from a digitized vegetation map of China with a scale of 1:1000000 (Editorial Committee of Chinese Academy of Chinese Vegetation Maps 2001). Based on this map, 5 forest types were recognized, i.e., evergreen broadleaf forests, deciduous broadleaf forests, broadleaf and needleleaf mixed forests, evergreen needleleaf forests and deciduous needleleaf forests. To easily document different forests growth responses to climate change the forests were further grouped into two types: broadleaf forests (BF) and needleleaf forests (NF) (Piao et al. 2006b). Figure 1b shows the spatial distribution of the two forest types in NSTEC with a spatial resolution of 0.083°.

3.3 Climates

The monthly climate data used in this study includes surface temperature and precipitation data at a spatial resolution of 0.1° for the years 1982 - 2006, generated using a kriging interpolation algorithm from daily temperature and precipitation records from 728 meteorological stations across China (National Meteorological Information Center of China Meteorological Administration, www.nmic.gov.cn, Ding et al. 2007). Using a bilinear interpolation resampling method we resampled the monthly surface air temperature and precipitation to a spatial resolution of 0.083° to be consistent with the NDVI dataset. Along the NSTEC the spatial patterns of average growing season temperature and precipitation from

1982 to 2006 are shown in Figs. 1c and d (Peng et al. 2011). To avoid repeating and disturbing readers in understanding present paper, we used the words of "NDVI (temperature, precipitation)" to indicate "average monthly NDVI (temperature, precipitation) for the growing season" respectively, and used "multi-year mean NDVI (temperature, precipitation)" to indicate "mean of growing season NDVI (temperature, precipitation) from 1982 to 2006" in the following text.

4. RESULTS AND DISCUSSION

4.1 Latitudinal Variations in Growing Season Climates and NDVI

Figure 2 shows the multi-year mean temperature, precipitation and NDVI with latitude in the two forests along the NSTEC from 1982 to 2006. The needleleaf forests (NF) distributed from 22 to 54°N in the NSTEC, located mainly in the southern (23 - 33°N) and northern (47 - 54°N) part of the transect. The multi-year mean temperature of NF coverage area ranged 5 - 26°C from north to south (Fig. 2a), and it exhibited a strictly linear relationship with latitude ($R^2 = 0.926$, $P = 0$) that the temperature decreased gradually with increasing latitude. For NF, the relationship between multi-year mean precipitation and latitude (Fig. 2c) also presented a significant negative linear relationship ($R^2 = 0.887$, $P = 0$). The multi-year mean precipitation in the south (ca. 1600 mm)

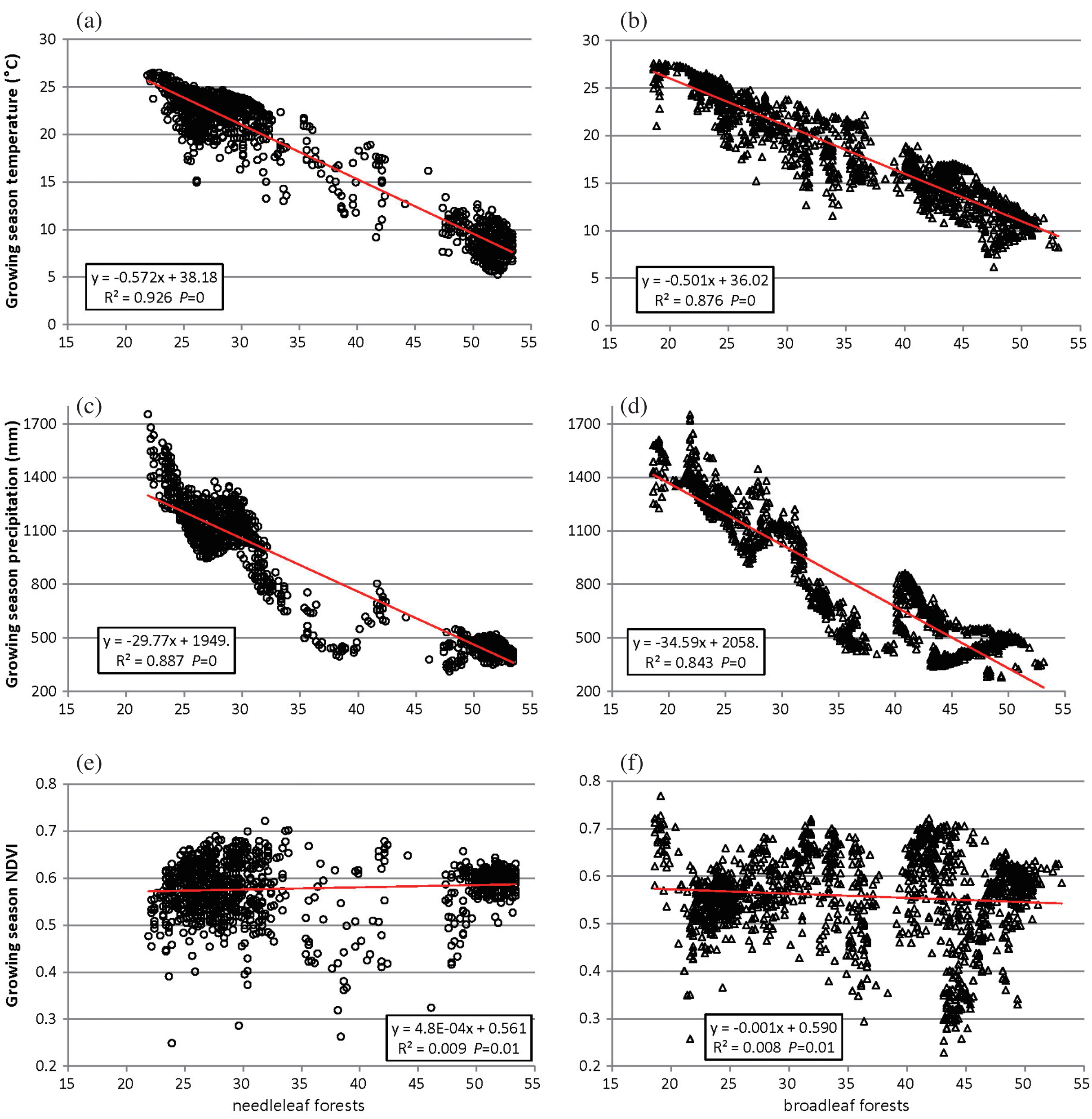

Fig. 2. The mean growing season temperature, precipitation and NDVI in the two forests along the NSTEC from 1982 to 2006.

was obviously higher than that in the north (ca. 350 mm) overall. Due to the influence of the eastern Asian monsoon, the precipitation at 42°N around (ca. 600 - 800 mm) was more than that at lower (35 - 40°N, ca. 400 - 500 mm) or higher (> 45°N, 300 - 600 mm) latitudes. In general, the range of multi-year mean NDVI of NF was heterogeneous along the transect, which was mainly 0.45 - 0.7 in the south while 0.55 - 0.65 in the north. While a statistically significant linear relationship ($R^2 = 0.009$, $P = 0.01$) was observed between the NDVI and latitude in NF along the NSTEC (Fig. 2e). The NDVI-latitude correlation was too weak to exhibit the latitudinal variation of NDVI significant.

The broadleaf forest (BF) location was a little farther south than that for the NF, relatively evenly distributed between 17.5 and 54°N. The multi-year mean temperature in BF coverage area varied from 7 to 27°C (Fig. 2b), and the range and latitudinal pattern of mean precipitation was nearly consistent with that of NF across the NSTEC (Fig. 2d). Similar to NF, the multi-year mean climates in BF coverage area showed significant linear reduced gradients with increasing latitude (temperature-latitude: $R^2 = 0.876$, $P = 0$; precipitation-latitude: $R^2 = 0.843$, $P = 0$) . The range of multi-year mean NDVI in BF was mainly 0.4 - 0.7 in the south while 0.3 - 0.7 in the north of the NSTEC (Fig. 2f). The NDVI exhibited a statistically significant linear relationship with latitude ($R^2 = 0.008$, $P = 0.01$), but showed almost no latitudinal variation as that of NF.

4.2 Correlation Between Growing Season Climates and NDVI

To analyze the relationship between the NDVI and climatic variables along climate gradients, we calculated the Pearson correlation coefficient between NDVI and temperature, and that between NDVI and precipitation for each grid cell respectively. Figure 3 shows the change in correlation between NDVI and temperature with multi-year mean temperature in NF (Fig. 3a) and BF (Fig. 3c), and correlation between NDVI and precipitation with multi-year mean precipitation in NF (Fig. 3b) and BF (Fig. 3d) from 1982 to 2006. Along the NSTEC, the overall Pearson correlation coefficient between temperature and NDVI fell in the range of -0.5 to 0.5 in NF. The temperature-NDVI correlation exhibited a significant linear relationship with multi-year mean temperature ($R^2 = 0.226$, $P = 0$), that the Pearson correlation coefficient between temperature and NDVI decreased with increase in temperature (Fig. 3a). A positive correlation exists between temperature and NDVI exhibited in areas with low temperature, while a negative correlation was found in regions with high temperature probably because increased

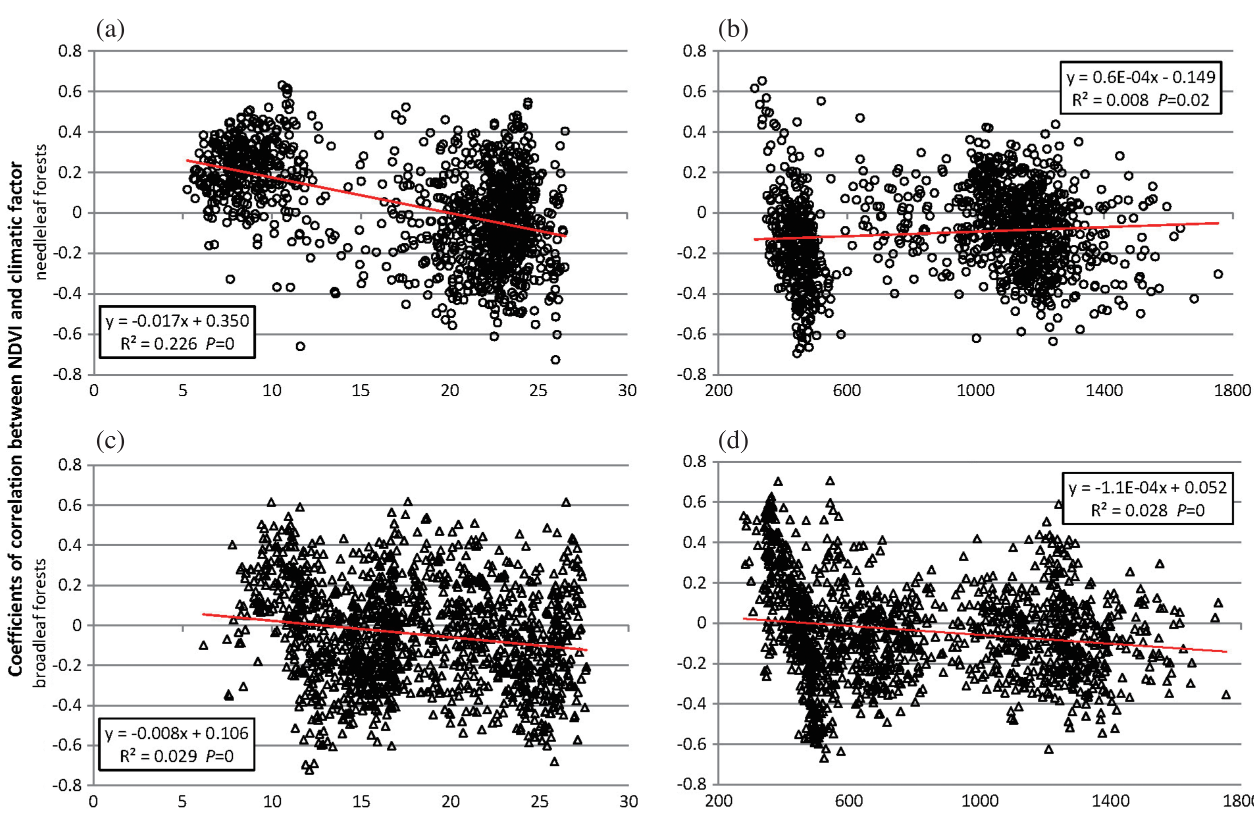

Fig. 3. Change in correlations between growing season temperature/precipitation and NDVI with mean growing season temperature/precipitation in the two forests on the NSTEC.

temperature accelerates water evaporation and reduces water use efficiency, restricting vegetation growth (Jobbágy et al. 2002). This indicates that the sensitivity of needleleaf forests to temperature may decrease in the warming areas with low growing season temperature, which is consistent with the previous study on the temperate grasslands response to climate change in China (Piao et al. 2006b). For BF, the Pearson correlation coefficient of temperature-NDVI ranged from -0.6 to 0.5, decreasing with increasing multi-year mean temperature in a statistically significant linear relationship ($R^2 = 0.029$, $P = 0$) as NF (Fig. 3c). However, the correlation between temperature-NDVI and multi-year mean temperature was much weaker than that of NF, indicating the sensitivity of broadleaf forest growth to temperature was quite inconsistent in the NSTEC.

The Pearson correlation coefficient between precipitation and NDVI fell mainly in the range -0.6 to 0.5 in NF and -0.6 to 0.6 in BF respectively in the transect. Unlike the grassland biome precipitation threshold (Tucker et al. 1991), a statistically significant linear relationship between precipitation-NDVI correlation coefficient and multi-year mean precipitation was observed in both NF and BF (Figs. 3b and d). However, the each correlation was substantially weak, implying that vegetation growth was less sensitive to precipitation in forests in eastern China. Our results are in overall agreement with the previous study (Peng et al. 2011) that NDVI is significantly positively correlated with temperature but not precipitation during the forest growing season at regional scale in China. Although our results supported their conclusions in part, we found that the correlations between NDVI and climates were inconsistent in either different forest ecosystems or different climatic conditions at a finer scale along the NSTEC.

4.3 Correlation Between Growing Season Climates and NDVI Trend

To explore the relationship between vegetation growth trend and climates we calculated the single linear regression trend in NDVI changes and multi-year mean temperature and precipitation for each grid cell in two forests along the NSTEC. Figure 4 exhibits the relationship between NDVI trend and multi-year mean climates in NF and BF from 1982 to 2006. For NF, the NDVI linear trend from 1982 to 2006 mainly fell in the range -0.003 to 0.003 yr^{-1} along the NSTEC. A significant linear relationship ($R^2 = 0.238$, $P = 0$) between multi-year mean temperature and NDVI trend during the study period was observed in this region and the NDVI trend decreased with increasing temperature by 0.0001°C^{-1} (Fig. 4a). The NDVI trend pattern showed spatial heterogeneity along the transect which reflected the latitudinal variation. Overall, the NF exhibited a greening

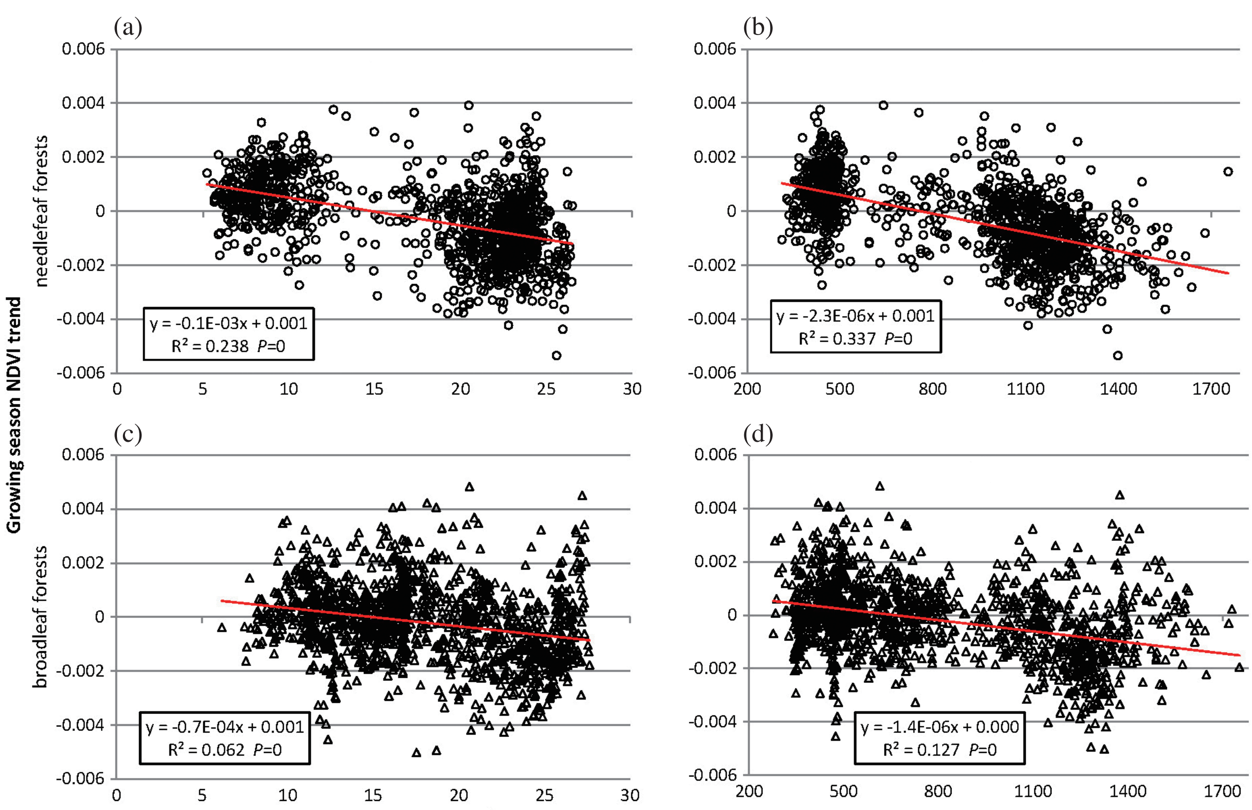

Fig. 4. The relationship between growing season climates and NDVI trend in the two forests on the NSTEC.

trend in the low-temperature (multi-year mean temperature < 15°C) regions while browning appeared in the high-temperature (multi-year mean temperature > 20°C) areas. This indicated that under global warming conditions, the positive temperature effect on the growth of needleleaf forests decreased as the temperature increased resulting in accelerated water evaporation and declining photosynthetic efficiency, especially in warmer regions.

The relationship between the NDVI linear trend and multi-year mean precipitation (Fig. 4b) also exhibited a significant negative linear relationship ($R^2 = 0.337$, $P = 0$). The NDVI trends in NF reduced by ca. 2.3E-04 with an increase in precipitation of per 100 mm. In the less humid regions (multi-year mean precipitation < 800 mm), over 85% of the pixels show an increasing trend in NDVI, suggesting a widespread NF greening of mid-latitudes where precipitation is not a limitation for forest growth (Zhang et al. 2012). However, NF browning appeared to dominate in the humid areas (multi-year mean precipitation > 800 mm), with ca. 83% of the pixels exhibiting a decreasing trend in NDVI. This indicated that the positive effect of precipitation on needleleaf forest growth decreased as precipitation rose. Because greater increased precipitation fails to raise NDVI due to the water-use capacity limits of forests, and probably led to lower temperature and sunshine levels which restrict vegetation growth (Xu 2005; Zhang et al. 2012).

The NDVI linear trend for BF, which mainly fell in the range -0.003 to 0.003 yr^{-1} as NF, also exhibited a statistically significant negative linear relationship with the multi-year mean temperature ($R^2 = 0.062$, $P = 0$) (Fig. 4c). However, the correlation between the NDVI trend and temperature was quite poor, indicating NDVI BF trend insensitivity to multi-year mean temperature. Overall, vegetation browning was observed in the high-temperature (multi-year mean temperature > 20°C) areas, suggesting a high temperature negative effect on broadleaf forests growth.

Similar negative correlation between the multi-year mean precipitation and NDVI trend appeared in BF (Fig. 4d), suggesting that overall growing season forest growth in humid transect areas was probably stalled by the precipitation. Although a statistically significant negative linear relationship ($R^2 = 0.127$, $P = 0$) between them was observed in BF, the correlation was weaker than that of NF, and the vegetation browning exhibited a more obvious spatial heterogeneity. Our results, at least in part, are in agreement with Peng et al. (2011) that the linear regression model predicts a significant increase in NDVI of all ecosystems except desert during last three decades. However, NDVI showed an opposite tendency south of the NSTEC, suggesting the vegetation growth responses to climate change are spatially heterogeneous across different ecosystems.

4.4 Correlation Between Growing Season Climates Trend and NDVI Trend

To further analyze the vegetation growth response to climate change in the forests of eastern China, we calculated the annual linear regression trend in NDVI and climates changes for each grid cell from 1982 to 2006. Figure 5 shows the relationship between the NDVI and temperature trends in NF and BF along the NSTEC. The axes mean the NDVI and temperature trends and the marker colors denote

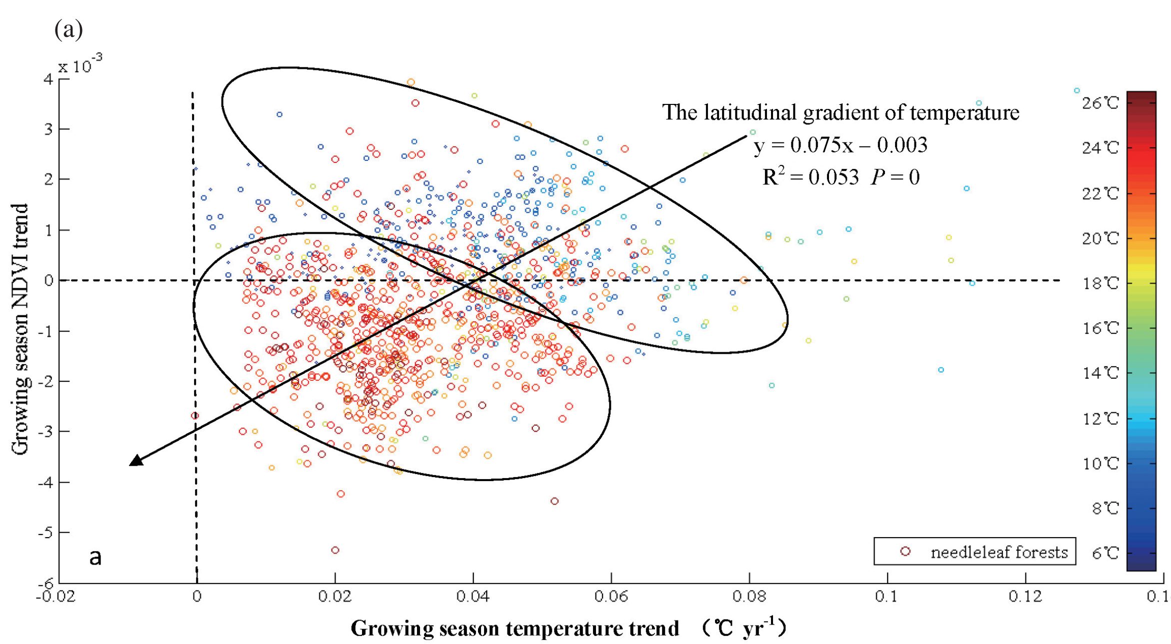

Fig. 5. The relationship between growing season NDVI trend and growing season temperature trend in the two forests on the NSTEC (The color of point stands for the multi-year average growing season temperature).

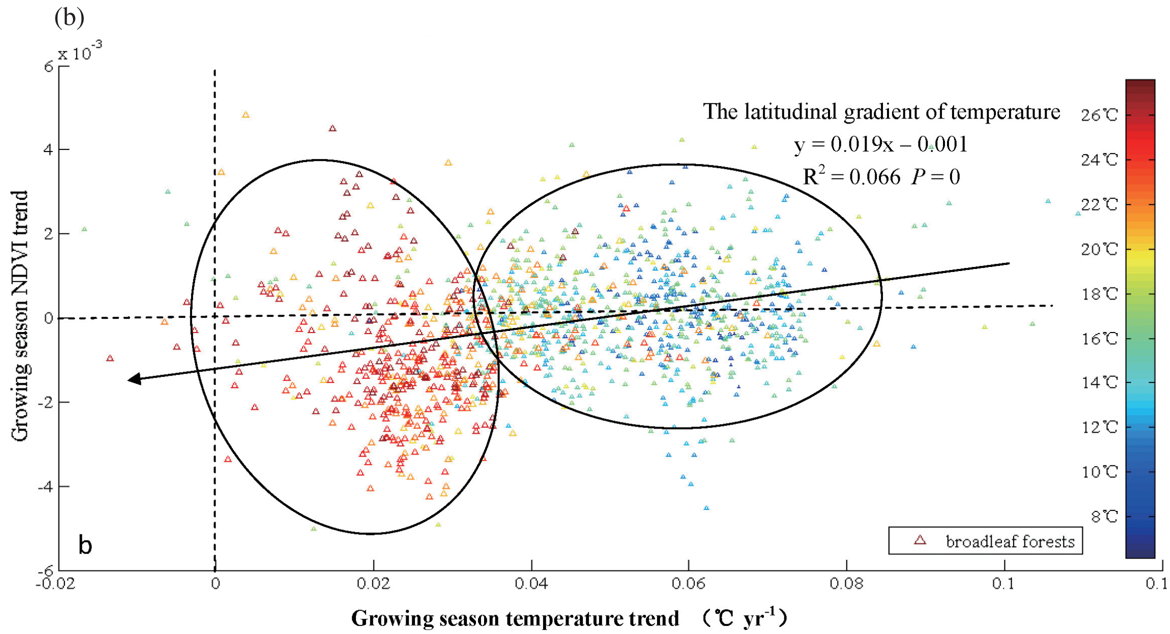

Fig. 5. (Continued)

the annual average temperature. In most NF coverage areas along the NSTEC, the temperature exhibited an increasing trend in the range 0 to 0.1 during the study period (Fig. 5a). However, the NDVI response to changing temperature exhibited significant spatial heterogeneity along the transect. A statistically significant positive linear relationship ($R^2 = 0.053$, $P = 0$) was observed between the temperature and NDVI trends along the multi-year mean temperature gradient with latitude. The NDVI increased with increasing temperature in areas with low annual average temperature, while it decreased in the warming areas with high annual average temperature during the study period, probably because of recent hotter and drier summer climate across the Northern Hemisphere (Lotsch et al. 2005; Park and Sohn 2010). For BF, both the temperature trend (in the range -0.02 to 0.09) and the positive linear relationship between temperature trend and NDVI trend ($R^2 = 0.066$, $P = 0$) were overall similar to that of needleleaf forests (Fig. 5b). The broadleaf forests browning observed to dominate in warming areas with high multi-year mean temperature, but the number of broadleaf forests with positive NDVI slope was similar to that with negative NDVI slopes in areas with low annual average temperature.

Similar trends between NDVI and temperature appear in east and northeast Siberia (Peng et al. 2011). This suggested that in widespread forests, especially needleleaf forests, greening appeared dominant at the mid-high latitudes and the greening trend may continue following warming, while the positive effect of temperature on the growth of forests may stall under global warming conditions in much warmer regions as concluded above. The decline in NDVI means weakening carbon sequestration to some extent, which may lead to a positive feedback between the carbon cycle and climate warming, increasing atmospheric CO_2 and amplifying warming (Friedlingstein et al. 2006). There is significant land-use change due to the conversion of forest ecosystems into agricultural lands and urban areas in the northern low- and mid-latitudes (largely developed countries) over the past century (Hurrt et al. 2006). These land-use changes can be a possible reason for the negative NDVI trend in regions with high-temperature.

Figure 6 shows the relationship between the NDVI and precipitation trends in two types of forests during the study period along the transect. The x-axis denotes the NDVI trend and the y-axis means precipitation trend. The marker colors represent the annual average precipitation in NF and BF. Along the NSTEC, the most precipitation trend fell in the range -0.05 to 0.06 in NF during the study period (Fig. 6a). Overall, the precipitation increased in the areas with high annual average season precipitation while decreased in the areas with low annual average precipitation. A significant negative linear relationship ($R^2 = 0.193$, $P = 0$) was observed between the precipitation trend and NDVI trend along the multi-year mean precipitation gradient with latitude. The NDVI increased with reduced precipitation in areas with low annual average precipitation, and decreased with enhanced precipitation in areas with high annual average precipitation during the study period. A prevalent vegetation greening was observed in the drying environment in NF while vegetation browning appeared to dominate in the wetter areas, suggesting that the positive effect of precipitation on NF growth decreased as precipitation rose. This is

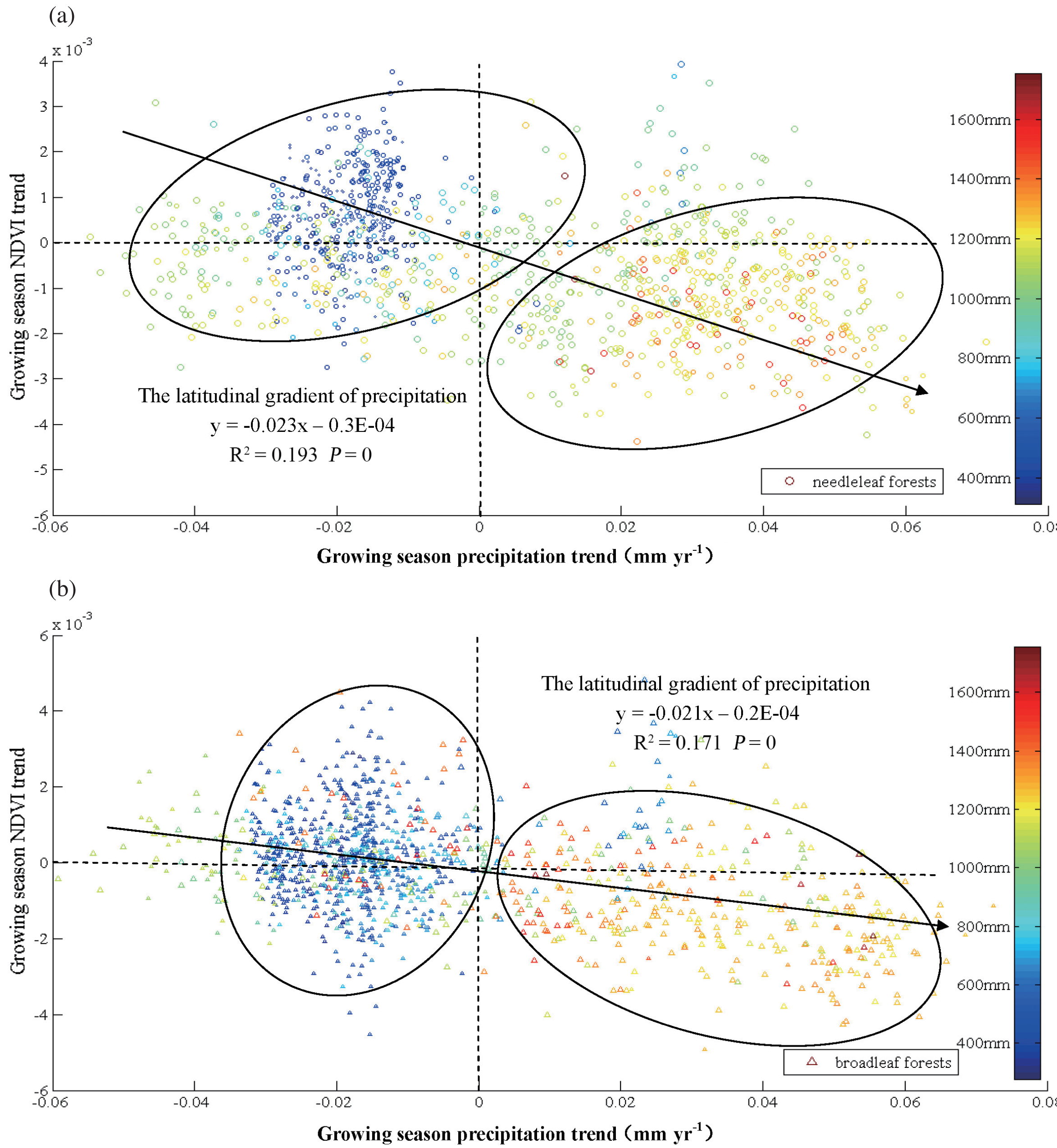

Fig. 6. The relationship between growing season NDVI trend and growing season precipitation trend in the two forests on the NSTEC (The color of point stands for the multi-year average growing season precipitation).

because the solar radiation is the limitation for vegetation growth rather than precipitation in the moist southern China area (Xu 2005; Zhang et al. 2012). The increased precipitation would result in lower photosynthetic available radiation (PAR), thereby restricting vegetation growth.

The precipitation trend for BF in the range -0.05 to 0.07 was overall similar to that of NF along the NSTEC (Fig. 6b). The relationship between precipitation and NDVI trends also exhibited a statistically significant linear relationship (R^2 = 0.171, P = 0), that the NDVI trend decreased with increase in precipitation. The BF browning was dominant in the wetter areas with high annual average precipitation as NF. However, the opposite NDVI response occurred to decreasing precipitation in the drying areas with low annual average precipitation, indicating insensitivity to reduced precipitation by BF.

5. CONCLUSIONS

Due to the projection that China would experience a significant increase in temperature and summer precipitation over the next century, it is necessary to understand the vegetation response to climate change in the past two decades so that future interactions between terrestrial ecosystems and the climate system can be predicted and effective countermeasures adopted to solve these problems. Based on the terrestrial transect and remote sensing vegetation index approaches, this study showed the variations in forests growth with climates, revealing the relationship between forest growth trends and climate change along the climatic gradients in eastern China. We found a correlation between forest NDVI and temperature decrease with increase in multi-year mean temperature overall. The correlation between forest NDVI and precipitation insignificantly varied with multi-year mean precipitation. The NDVI linear trend exhibited a significant linear relationship with multi-year mean climate and climate trend with spatial heterogeneity along the NSTEC from 1982 to 2006. For the multi-year mean climate, forests exhibited a greening trend in the cold and dry regions and browning in the warm and humid areas. In the region that turned warmer and drier, the NDVI of forest exhibited an increasing trend. However, in the region that turned warmer and wetter, the NDVI of forest presented a dominant decline. We found a difference in growth trend between needleleaf forests and broadleaf forests. In the warm and humid areas, the growth trends of both forest types exhibited consistent variation. In the cold and dry region, NDVI of needleleaf forests mainly increased during the study period. Nearly half of broadleaf forests presented an increase NDVI trend while the other broadleaf forests declined in NDVI.

While some improvements in NDVI-based analysis of variations in vegetation growth have been achieved in our present study, there are a few problems that are still unclear and should be addressed due to the nonlinear response of vegetation growth to climate change and uncertainties of the response detection based on satellite-based remote sensing (Zhou et al. 2001; Zhang et al. 2010). The integration of long-term ground-based and satellite-based vegetation growth observations and climate change is urgently needed to further extend our present study. Further studies considering numerous other factors which may partly account for the observed NDVI variations, such as increased atmospheric CO_2 fertilization effect, nitrogen deposition and land use/cover change would be extremely valuable in predicting future vegetation greening or browning. Our present work supported and complemented previous studies on the response of forests to climate change and the control mechanism behind these observed variations in eastern China.

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