Precipitation patterns alter growth of temperate vegetation

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[1] In this paper, we use growing season Normalized Difference Vegetation Index (NDVI) as an indicator of plant growth to quantify the relationships between vegetation production and intra-annual precipitation patterns for three major temperate biomes in China: grassland, deciduous broadleaf forest, and deciduous coniferous forest. With increased precipitation, NDVI of grassland and deciduous broadleaf forest increased, but that of deciduous coniferous forest decreased. More frequent precipitation significantly increased growth of grassland and deciduous broadleaf forest, but did not alter that of deciduous coniferous forest at low precipitation levels and constrained its growth at high precipitation levels. The relationships between NDVI and average precipitation per event were opposite to those between NDVI and precipitation frequency. Such nonlinear feedback suggests that the responses of vegetation production to changes in precipitation patterns differ by both biome type and precipitation amount. **Citation:** Fang, J., S. Piao, L. Zhou, J. He, F. Wei, R. B. Myneni, C. J. Tucker, and K. Tan (2005), Precipitation patterns alter growth of temperate vegetation, *Geophys. Res. Lett.*, *32*, L21411, doi:10.1029/2005GL024231.

1. Introduction

[2] In the past several decades, both experimental and observational studies have shown that mean precipitation and extreme precipitation events of the Northern Hemisphere have undergone substantial changes [*Easterling et al.*, 2000; *Bell et al.*, 2004]. These changes can exert profound impacts on ecosystems [*Walther et al.*, 2002; *Stenseth et al.*, 2002; *Parmesan and Yohe*, 2003]; however, very few studies have reported the influence of precipitation variability on ecosystems [*Knapp et al.*, 2002; *Weltzin et al.*, 2003]. In this paper, we use growing season Normalized Difference Vegetation Index (NDVI) as an indicator of vegetation net primary productivity (NPP), in combination with ground-based observations, to examine the relationships between vegetation growth and precipitation patterns for temperate biomes in China.

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2. Data and Methods

2.1. Study Area

[3] We focused our study on three major natural temperate biomes in China distributed between 36 and 53° N: temperate grasslands, temperate broadleaf forests, and cold-temperate deciduous coniferous forests (Figure 1). We chose these biomes because they are located in the northern mid-latitudes where satellite-measured NDVI trends are least contaminated by substantial solar zenith angle effects [*Slayback et al.*, 2003], and continuously distributed in relatively low altitudes, and grow in little-disturbed environmental conditions.

2.2. Digitization of Vegetation Maps

[4] We digitized a 1/1 000 000 vegetation map of China [*Editorial Committee for Vegetation Map of China*, 2001] to obtain information on distribution of the three biomes. Vegetation maps covering the whole study area were scanned, and transferred to vector maps by using Arcinfo 7.2 GIS software, and converted to geographical projection grid maps at 0.1 × 0.1 degree resolution which corresponded to that of the NDVI dataset. Only continuous areas of these biomes were analyzed; patches far from the concentrated areas of these biomes and fragmented pixels were excluded from analysis.

2.3. NDVI Dataset

[5] Due to the robust relationship between NDVI and vegetation production, NDVI has commonly been used as a proxy of NPP [e.g., *Paruelo et al.*, 1997; *Jobbagy et al.*, 2002]. The NDVI dataset used was produced by the Global Inventory Monitoring and Modeling Studies (GIMMS) group, and was derived from the NOAA/AVHRR Land data set, at a spatial resolution of 8×8 km^2 and at 15-day intervals, for the period 1982 to 1999 [*Zhou et al.*, 2001; *Piao et al.*, 2003]. A monthly NDVI dataset was composited from the bimonthly values by choosing the maximum NDVI and then aggregated into grid cells of $0.1° \times 0.1°$. To further reduce the impact of bare and sparsely vegetated grids on the NDVI trend, grid cells with <0.1 of annual mean NDVI were excluded from our analysis. In order to eliminate spurious NDVI trends due to winter snow, we used NDVI during the growing season (April to October) to analyze vegetation production. The NDVI data for the years 1991 and 1992 were excluded to avoid the effect of the Pinatubo eruption [*Slayback et al.*, 2003]. The sum of the growing season NDVI values (referred to as growing season NDVI hereafter) was used for our data analysis.

2.4. Precipitation Data and Precipitation Class

[6] The climate data set used was the daily precipitation database obtained from 665 spatially well-distributed climate stations of the China Meteorological Administration.

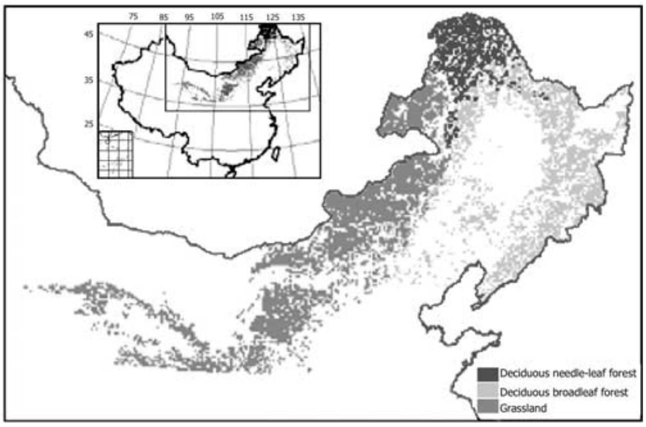

Figure 1. Distribution of three biomes examined in this study: temperate grasslands, temperate deciduous broadleaf forests, and cold-temperate deciduous coniferous forests.

The variables used included annual precipitation amount, annual precipitation frequency (PFR), or precipitation events, and mean precipitation amount per event (MPAE). The PFR was defined as the number of events in which precipitation exceeded 0.1 mm from the preceding November to the current October of each year. Annual precipitation was counted from the preceding November to the current October to take into account for the lag in vegetation response to precipitation because a time lag exists between vegetation growth and precipitation at the global scale [*Los et al.*, 2001] and at the biome scale [*Piao et al.*, 2003]. Precipitation events occurring continuously over several days were counted as a single event. Daily precipitation data at a resolution of 0.1 $\times$ 0.1 degrees over the study period were obtained using Kriging interpolation, corresponding to the resolution of the NDVI dataset.

[7] To investigate the relationship between PFR and NDVI at the same precipitation amount, for each biome type, we grouped its pixels for each year into different annual precipitation classes at a 50 mm interval (e.g. 400∼450 mm, 450∼500 mm, and so on) to obtain a precipitation gradient. At each precipitation class, the PFR for every pixel was counted and the corresponding growing season NDVI was calculated. The partial correlation analysis was used to determine whether the growing season NDVI, for each precipitation class, is primarily determined by PFR or by total annual precipitation. The results suggested that for most of the precipitation classes (21 of 24 classes), growing season NDVI is strongly and significantly correlated with PFR (statistic level < 0.001), but not strongly correlated to annual precipitation (only 5 classes exhibited a significant correlation, at a 0.05 significance level) (Tables S1, S2 and S3 in the supplementary materials[1]), suggesting a major effect of PFR on the NDVI for a given precipitation class.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024231.

[8] In addition, we calculated MPAE by dividing the annual precipitation by PFR for each pixel to quantify the relationship between the MPAE and NDVI at each precipitation class. To ensure the reliability of our statistical analysis, we only used precipitation classes with a sample size of >40 pixels for the analysis.

3. Results

[9] Figure 2 illustrates relationships between annual precipitation and growing season NDVI for three biomes. The NDVI increased with annual precipitation for grasslands (r^2 = 0.43, p < 0.001) and temperate deciduous forests (r^2 = 0.20, p < 0.001), but decreased for the deciduous coniferous forests (r^2 = 0.29, p < 0.001). The same relationships can be documented for these biomes using all the pixels rather than using the classified pixels based on the precipitation classes (Figure S1 in the supplementary materials). It has been commonly observed that increasing precipitation enhances plant growth for temperate grasslands [*Huxman et al.*, 2004], but few studies have reported that plant growth tended to decrease with an increase of precipitation in a relatively cold region. This suggests that the NPP of different biomes responds differently to precipitation changes.

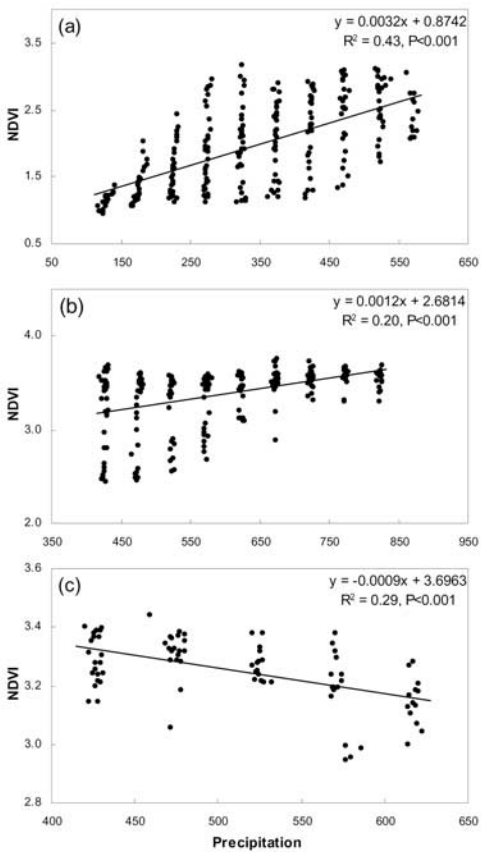

Figure 2. Relationships between annual precipitation and growing season NDVI for (a) temperate grasslands, (b) temperate deciduous broadleaf forests, and (c) cold-temperate deciduous coniferous forests.

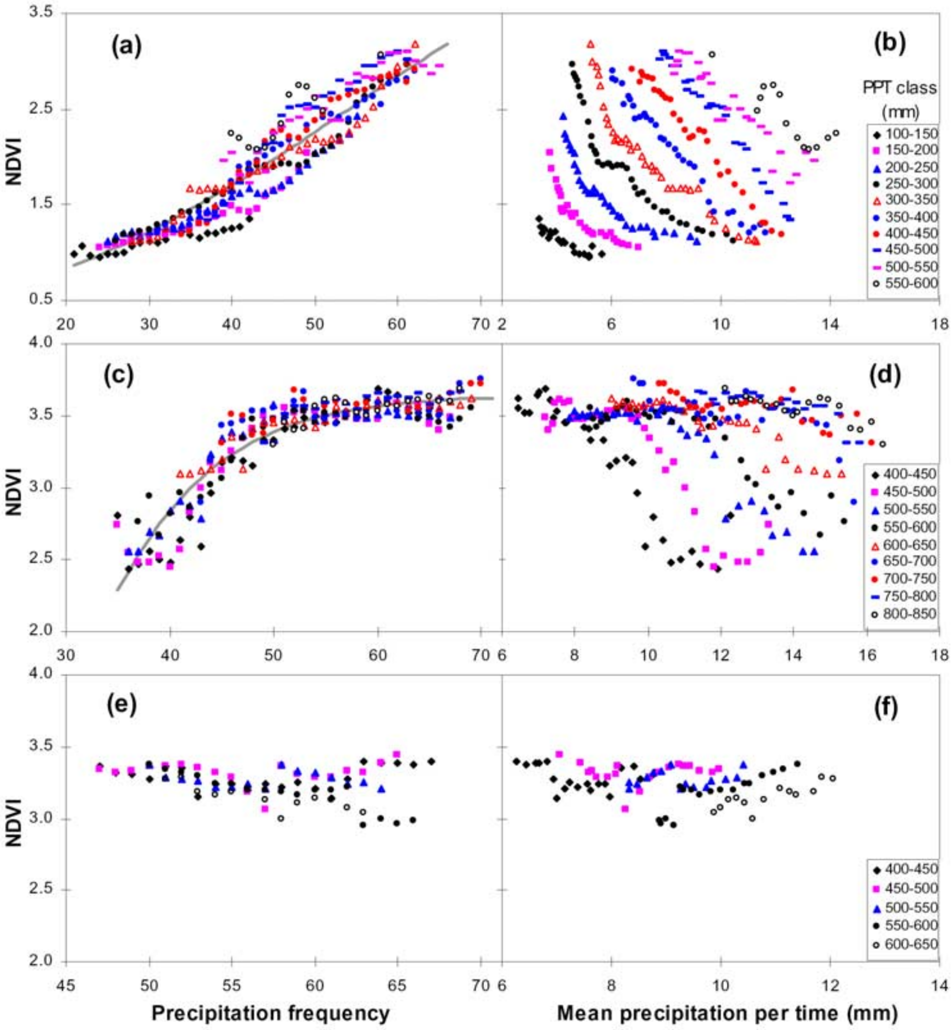

Figure 3. Changes in growing season NDVI with precipitation frequency (number of precipitation events per year) and mean precipitation amount per event for each precipitation class for temperate grasslands (a and b), temperate deciduous broadleaf forests (c and d), and cold-temperate deciduous coniferous forests (e and f). Solid curves in (a) and (c) represent the overall trend (irrespective of precipitation class) of the relationship between growing season NDVI and precipitation frequency for grassland and deciduous broadleaf forest (for details, see text).

[10] Figure 3 depicts that at the same precipitation level (precipitation class), growing season NDVI for different biomes and for the same biome but at different precipitation classes showed different responses to changes in PFR and MPAE. For grasslands, growing season NDVI showed an exponential increase with PFR (R^2 = 0.87∼0.98, p < 0.001; see Table S4 in supplementary materials), suggesting that more precipitation events with the same precipitation amount promote vegetation growth. At the same PFR, NDVI increased with mean precipitation amount (PPT) (Figure 3a), expressed as $a = 4.61 \times 10^{-5}\ PPT + 0.0124$ (a is a power index of exponential function; r^2 = 0.90, p < 0.001). To detect the general relationship between vegetation growth and precipitation events, a logistic equation [$NDVI = 1/(0.2 + 2.548 \times 0.954^{PFR})$, r^2 = 0.90] was used to predict the overall trend of NDVI vs. PFR, using all the data across the PPT levels (Figure 3a). In contrast, the NDVI declined exponentially with increases in MPAE at the same precipitation class (Figure 3b). These results suggested that more frequent but less intense and evenly distributed precipitation patterns promote plant growth for temperate grasslands.

[11] Temperate deciduous broadleaf forests exhibited different responses (Figure 3c). With an increase in PFR, the NDVI first increased significantly, but then became unresponsive after reaching a threshold of events (45–55 times), in accordance with a trajectory of the Gompertz growth function (r^2 = 0.73∼0.92, p < 0.001; see Table S5 in supplementary materials). Like temperate grasslands, NDVI of this biome tended to increase with an increase in total precipitation at the same PER, expressed as $b = 7.89 \times 10^{-4}\ PPT - 0.2815$ (r^2 = 0.59, p = 0.026) (b is the parameter showing the upper limit of NDVI in the Gompertz function). Conversely, NDVI decreased as MPAE increased (Figure 3d).

[12] Similar to Figure 3a, the Gompertz function was used to describe overall pattern of NDVI vs. PFR, using all the data, irrespective of PPT levels (Figure 3c, $NDVI = 3.644e^{-e^{3.536-0.123PFR}}$, $r^2 = 0.86$).

[13] Cold-temperate deciduous coniferous forests exhibited more complicated relationships (Figure 3e). At low precipitation levels (400∼550 mm), growing season NDVI was likely to be independent of precipitation frequency, ranging from 3.1 to 3.4 (r^2 = 0.000∼0.051, p = 0.376∼0.934). However, at higher precipitation levels (550–650 mm), more frequent precipitation led to an apparent decrease in NDVI (r^2 = 0.82, p = 0.001 for 550∼600 mm, and r^2 = 0.65, p = 0.001 for 600∼650 mm; see Table S6 in supplementary materials). Moreover, at the same PFR, NDVIs for pixels with high precipitation amounts tended to be smaller than those with low precipitation amounts, opposite to the trends of the other two biomes. Correspondingly, as the MPAE increased, the NDVI did not change at low precipitation levels, but increased at high precipitation levels (Figure 3f). This suggests that for regions or years with more precipitation, unlike grasslands, high precipitation frequency does not benefit vegetation growth for this biome.

[14] Observed data of annual precipitation, PFR and NDVI at weather stations for each biome have confirmed such results obtained from the interpolated daily precipitation data. The growing season NDVI was significantly positively correlated with the observed annual precipitation and annual precipitation frequency for both grassland (r = 0.17, p = 0.001 and r = 0.39, $p < 0.001$) and deciduous broadleaf forest (r = 0.21, p = 0.001 and r = 0.30, $p < 0.001$).

4. Discussion

[15] Several experimental studies have shown that increased precipitation promotes plant growth of temperate biomes [*Lane et al.*, 1998; *Knapp et al.*, 2002]. This is consistent with our results obtained from temperate grasslands and deciduous broadleaf forests of China (Figures 2a and 2b), but inconsistent with those from cold deciduous coniferous forests, where vegetation production decreases with increasing precipitation. Possibly, the latter results from the decreases in temperature and sunshine due to increased precipitation. Such a result has been reported in relatively wet highlands [*Los et al.*, 2001] and humid subtropical China [*Piao et al.*, 2003], suggesting various responses of different biomes to changes in precipitation amount.

[16] Different biomes respond to the changes in precipitation patterns in more complicated fashions. Experimental studies have indicated that for the mesic grasslands of North America, reduced rainfall frequency without a modification of total rainfall amount clearly decreased soil water content, and thus led to a decrease in vegetation productivity [*Knapp et al.*, 2002; *Fay et al.*, 2003]. Our results for grasslands support this finding. However, the relationships between vegetation growth and both precipitation amount and precipitation frequency differ among biomes. For deciduous broadleaf forests, vegetation growth increased first with precipitation frequency, but exhibited an equivocal response after precipitation frequency increased to a certain level. In other words, in the regions with high frequent precipitation, the influence of precipitation became less significant. For deciduous coniferous forests under relatively low precipitation conditions, neither an increase in precipitation frequency nor a change in average precipitation amount per event leads to a notable change in vegetation growth. Conversely, vegetation growth in rainy areas was constrained by more frequent, fewer precipitation events. Accordingly, the responses of vegetation production to changes in precipitation pattern differ by both vegetation type and precipitation amount. Such nonlinear responses of ecosystems to precipitation have previously been investigated only in a few animal communities [*Stenseth et al.*, 2002], but little evidence has been reported from plant communities.

5. Conclusions

[17] Using remote sensing dataset and ground-based observations, we have analyzed the relationship between precipitation patterns and vegetation growth for three temperate biomes in China. Changes in precipitation patterns seem to influence plant growth in non-linear fashions at the biome level, depending on both precipitation amount and biome type. This finding not only provides insight for experimental studies on terrestrial ecosystems, but also suggests the necessity of taking precipitation patterns into account in predictive climatic and ecological models. However, due to data limitation our research could not examine how precipitation in different seasons influences vegetation growth, which should be a key facet in the study on future climate change and ecosystem responses.

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