

This discussion paper is/has been under review for the journal Hydrology and Earth System Sciences (HESS). Please refer to the corresponding final paper in HESS if available.

Climate change, growing season water deficit and vegetation activity along the north-south transect of Eastern China from 1982 through 2006

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Received: 7 May 2012 – Accepted: 15 May 2012 – Published: 29 May 2012

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Published by Copernicus Publications on behalf of the European Geosciences Union.

HESSD

9, 6649–6688, 2012

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5 Considerable work has been done to examine the relationship between environmental constraints and vegetation activities represented by the remote sensing-based Normalized Difference Vegetation Index (NDVI). However, the relationships along either environmental or vegetation type gradients are rarely examined. The aim of this paper was to identify the vegetation types that are potentially susceptible to climate change through examining the interaction between vegetation activity and water deficit. We selected 12 major vegetation types along the north-south transect of Eastern China (NSTEC), examined their time trends from 1982 to 2006 with respect to climate change, 10 vegetation activity and water deficit.

The results showed that all vegetation types experienced warming during the study period, and the majority of them experienced precipitation decline. Warming and growing season water deficit exert counteracting controls on vegetation activity. Our study found insignificant greening trends in the northernmost cold temperate coniferous forest (CTCF), three temperate herbaceous types including the meadow steppe (TMS), grass steppe (TGS) and grassland (TG), where the growing season warming exerted more than offset effect on vegetation activity (phenology) than growing season water deficit. For the three temperate forest including the coniferous (TCF), mixed (TMF) and deciduous-broadleaved (TDBF), growing season water deficit was the main constraint on vegetation activity. Differently, the growing season browning in subtropical or tropical forests of coniferous (STCF), deciduous-broadleaved (SDBF) and evergreen-broadleaved (SEBF) and subtropical grasslands (STG) were likely attributed to decline in sunshine duration due to increased summer cloudiness. Poor water status in TDS, TG, TMS and severe drought in TGS have been identified by using growing season water deficit index (GWDI), suggested these ecosystems were subjected to severe progressing drought that may create greening trend reversal in future. The emerging water deficit in CTCF, TCF and SDBF suggested their rising susceptibility to future climate change.

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1 Introduction

Vegetation change (in form or functioning) as a result of climate change has been a long-time concern to the scientific community. It is recognized that regional variations in temperature and precipitation affect vegetation distribution and productivity, thus impacting regional carbon and hydrological cycles (IPCC, 2007). Warming is expected to promote increases in evapotranspiration (ET) or precipitation (P) and consequently may lead to intensification of the global water cycle (Held and Sodden, 2000; Huntington, 2006). However, the frequent regional droughts became the main constraint of plant growth and net primary production in the last decade (Zhao and Running, 2010). Thus, there is a critical need to assess the susceptibility of individual terrestrial ecosystems to large scale drying trend (Tan, 2007; Donohue et al., 2009; Scheiter and Higgins, 2009), particularly change in hydrologic condition (Gerten et al., 2004) or moisture availability (Milly, 2005).

Temperature (T) and precipitation (P) are main forcing environmental factors governing vegetation change (Zhang et al., 2001; Sun et al., 2011), whereas their respective sensitivities and interactive influences in different ecosystems are far from clear. Increasing air temperature may prolong the length of growing season (Piao et al., 2006a; Dragoni et al., 2011; Yu et al., 2010), but it may not be beneficial to vegetation because it alters the ecosystem water balance. Precipitation is known to be a dominant factor controlling vegetation productivity, but its effect differs according to ecosystem moisture availability (Martiny, et al., 2006). Therefore, the ecosystem water balance may hold clues about interactions between climate change and vegetation activities. Vegetation change in coverage or composition and their effects on local or regional water balance have been extensively studied at different spatial scales (Niehoff et al., 2002; Huntecha and Bárdossy, 2004; Sun et al., 2005, 2006; Zhang and Schilling, 2006; McVicar et al., 2007; Wei and Zhang, 2010), particularly with dramatic forest disturbance such as intensive logging (Zhang et al., 1999; Andréassian, 2004; Brown et al., 2005) or forest

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fires (Lavabre et al., 1993). These significant forest disturbances dramatically change the vegetation coverage and consequently alteration of hydrological processes.

With a growing need to assess forest change and hydrological responses under a changing climate, a quantitative indicator such as remotely detectable vegetation index (VI) can be used to quantify changes in vegetation form and functioning. The most commonly used VI is the normalized difference vegetation index (NDVI), which is associated to leaf chlorophyll content and green leaf density (Tucker and Sellers, 1986), and it has been widely used as an indicator for large-scale vegetation activities, including aboveground primary production (Tan, 2007) or vegetation phenology (Piao et al., 2006a; Dragoni et al., 2011; Yu et al., 2010). The seasonal dynamic of plant foliation acclimates to the seasonal hydrologic cycles, which is exactly in accord to the revisit periods of diverse satellite sensors that provide NDVI datasets with different spatial resolutions. Through vegetation activity, NDVI is capable of tracking water balance status in large catchments (Sun et al., 2008). Specifically, linking vegetation NDVI to catchment water balance components (i.e. ET) is an important measure in evaluating hydrological effect of land cover changes, particularly for those areas where vegetation is under gradual changes. The NDVI data acquired from short revisit-period remote sensing imagery such as NOAA/AVHRR, SPOT/VEGETATION, and MODIS, can be used to examine vegetation phenological trends at large spatial scales with high temporal resolution (White et al., 1997, 2005) over a long time period. NOAA AVHRR/NDVI dataset has been available since 1980s, and has long been used to quantify ecological response to climate change at regional, continental, and global scales over the past decades (e.g., Reed et al., 1994; McVicar and Jupp, 1998; Huemmrich et al., 1999; Tucker et al., 2001; White et al., 2005).

The long-term, fine temporal and spatial resolutions dataset of remote sensed NDVI promotes research into addressing the relationships between vegetation functioning and climate change, indicated by climate or climate-based indices, such as aridity index (Arora, 2002; Suzuki et al., 2006), scaled drought condition index (SDCI) (Rhee and Carbone, 2010) and temperature/vegetation condition index (TVDI) (Patel et al.,

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2009; Chen et al., 2011). The majority of available literature only focused on the relationships between VI and precipitation (Méndez-Barroso et al., 2009) or temperature (Prasad et al., 2006, 2007). These studies, conducted to investigate the ecosystem susceptibility, only take single climate constraints into account. As a result, the time trends in vegetation change may be confused with interannual variability (Bradley and Mustard, 2008). Actually, the time trends of ecosystem water balance status and its interaction with vegetation activity may hold clues about differential ecosystem response to environment forcing, thus being indicative of ecosystem stability. For example, P and ET water balance terms determine ecosystem water yield, and have been widely used to determine land management alternatives in response to extreme climatic events or land use changes around the world (Brown et al., 2008; Liu et al., 2009; Liu and Yang, 2010; Sun et al., 2011). Considering the fact that drought or water deficit becomes the main constraint of plant growth (Zhao and Running, 2010). Water balance is essential to evaluate ecosystem susceptibility by associating with vegetation activities and functioning. Recently, application of remote sensing on ET estimation in large-scale has been well tested (Suzuki et al., 2007; Mu et al., 2007; Zhang et al., 2009), which may greatly facilitate the large-scale quick evaluation of ecosystem water-balance status as well as its spatial correlation with vegetation change.

The goal of this study was to identify the vegetation types that are potentially susceptible to climate change as indicated by interaction between vegetation activity and water balance. For this, we selected 12 vegetation types along the north-south transect of Eastern China (NSTEC), analyzed the spatial patterns and temporal trends in climate factors, NDVI and water balance from 1982 to 2006. Sensitivity analysis of NDVI in response to temperature and precipitation change was also conducted. In addition, we formulated a novel index of annual water deficit to evaluate the water balance status for different vegetation types. The index was associated with vegetation activity (NDVI), and was used to assess the potential susceptibility of different vegetation types.

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2 Methods and datasets

2.1 North-south transect of Eastern China and vegetation distribution

The north-south transect of Eastern China (NSTEC) was formally established in year 2000 as an IGBP (International Geosphere and Biosphere Program) terrestrial transect of the world. The ten-degrees wide and 3700 km-long transect stretches from the warm and humid tropical south to the cold semi-humid north. This transect is characterized by a strong north-south temperature gradient and an east-west precipitation gradient. Mean annual precipitation (MAP) of the NSTEC varied from 500 mm to 1800 mm and mean annual temperature (MAT) was from about 1 °C to 22 °C. The great spatial variations of solar energy and water availability are the dominant causes of ecosystems distribution along the NSTEC. We selected twelve major natural vegetation types distributing along the transect from the north to the south (Table 1).

2.2 Datasets and spatial interpolation

The digitized 1:1 000 000 vegetation map of the NSTEC was originated from an open electronic source of a published vegetation atlas by the Institute of Botany, Chinese Academy of Science in 2007. This atlas includes 55 vegetation types, 960 types of formations, and more than 2000 dominant plant species on a national scale. Twelve typical natural ecosystems within the NSTEC have been selected based on the above vegetation map. These 12 ecosystems were clipped and merged into a set of scattered polygons. In order to minimize the “edge effect” (i.e., if the area outside the ecosystem boundary is a disturbed or unnatural system, the natural ecosystem can be seriously affected for some distances from the edge), two steps of GIS spatial process were conducted based on ARCGIS (Version 9.2, ESRI) spatial analysis tools: (1) discarding polygons less than 64 km² in size, and (2) applying buffering to identify the inside region for a fixed distance (4 km) away from the polygons’ boundary. The new vegetation map was therefore created, which is much smaller in size after the above two

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steps. The above procedures were used to ensure the selected vegetation types are accurate with clear boundaries, and would significantly reduce the NDVI noise in subsequent overlay analysis. Only natural vegetation types were selected in this study, and all human influenced areas including urban area and farmland were excluded.

Climate dataset was provided by China Meteorological Administration (CMA) based on a total of 741 standard stations across China. The ANUSPLIN package (Ver. 4.1; Australian National University, Center for Resources and Environmental Studies, Canberra, Australia), which supports transparent analysis and interpolation of noisy multi-variate data using thin plate smoothing splines (Hutchinson and Gessler, 1994), was employed to interpolate climate surfaces of the national scale. The ANUSPLIN has been widely applied on spatial interpolation of hydro-meteorological variables and has enhanced utility over other spatial interpolation approaches such as kriging (McVicar et al., 2007). In this study, a tri-variate partial thin plate spline incorporating a bi-variate thin plate spline as a function of longitude, latitude and constant linear dependences on elevation were used in simulating surfaces of monthly precipitation and temperature (Sun et al., 2008).

Biweekly NDVI data were derived from the AVHRR sensor aboard NOAA polar orbiting satellites (specifically NOAA 7, 9, 11, 14, and 16), which was calculated from AVHRR visible and infrared bands as:

$$\text{NDVI} = (R_{\text{nir}} - R_r) / (R_{\text{nir}} + R_r)$$

where, R_r is the spectral reflectance in red region (550–700 nm) and R_{nir} is the spectral reflectance in near infrared region (730–1000 nm). NDVI data used in this study were derived from the open source of GIMMS (Global Inventory Modeling and Mapping System) at NASA's Goddard Space Flight Center as described by Tucker et al. (2005). The calibration based on invariant desert targets has been applied to the original data to minimize the effects of sensor degradation. The NDVI monthly data at 8 km spatial resolution was generated from previously processed biweekly NDVI composites using the maximum value compositing procedure to minimize the effects of cloud contamination

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(e.g., McVicar and Bierwirth, 2001). A kriging interpolation removed noise and attenuated the effect of cloudy and missing pixels for spatially-averaged NDVI of 12 natural ecosystems in NSTEC (Table 1).

The time-integrated NDVI (TI-NDVI) can be a metric of vegetation activity (Jia et al., 2006). However, the non growing season snow cover will contaminate information on the vigorousness of vegetation growth in growing season. Zhao et al. (2001) found out that in China, the relationship between annual total NDVI and precipitation and temperature is insupportable in ecological theory but it is supportable only when the growing season data are used (i.e., April to October). Therefore in this study, we use the cumulative value of NDVI during growing season (from May to October). The duration of growing season was decided accordingly to our previous phenological analysis (Yu et al., 2010) for all vegetation types along the transect (Table 1). The growing seasons' NDVI were accumulated when above 0.29, which is very near to 0.3 as suggested by Zhou et al. (2001) in Eurasia. We set the threshold 0.29, because it is the low point of evergreen types and near to the onset point of green up of deciduous types in their phenological curves. More over, it enabled further removing of snow or other non-vegetation disturbances. This index is distinctive in reflecting the vegetation activity by highlighting the active water consumption seasons.

$$\text{TI-NDVI}_g = \sum_{i=5}^{10} \text{NDVI}_i \quad (1)$$

where TI-NDVI_g is the time integrated NDVI for growing season, i is month of the year, NDVI value is the spatial average of specific vegetation type. Correspondingly, the Accumulated Growing Degree Days (AGDD) is defined by:

$$\text{AGDD} = \sum_{t=i}^j \text{GDD} \quad (\text{if } \text{GDD}_t > 0^\circ\text{C}) \quad (2)$$

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where t is the day of the year (DOY), i and j are the beginning and end DOYs respectively for the growing season. The Growing Degree Days (GDD) is the summation when surface temperature above 0°C over the growing season.

2.3 PET and ET algorithm

5 Several methods can be used to calculate or simulate surface evapotranspiration (ET). However, water balance remains one of the most difficult components to quantify at specific large scales (Mu et al., 2007). The Hamon's method has been widely used in humid Eastern US, and could provide reasonable estimation of potential evapotranspiration (PET) for forested conditions (Sun et al., 2008). The method uses temperature
10 as a major driving force, but also includes other variables such as daytime length (h) and saturated vapor pressure (e_s).

$$\text{PET} = 1.1651 \cdot h \cdot d \cdot k \quad (3)$$

$$d = 216.7 \cdot e_s / (T + 273.3) \quad (4)$$

15 where, PET is the ecosystem potential ET (mm day^{-1}), h is the hours from sunrise to sunset, expressed in multiples of 12 h, calculated from date, latitude, slope and aspect of a region; d is the saturated vapor density (g m^{-3}) at daily mean temperature (T). k is the empirical coefficient to adjust PET calculated using Hamon's method to a realistic value in a range from 1.0 to 1.2 for humid and semi-humid area (Sun, et al., 2002). e_s is the saturated vapor pressure (mb).

$$20 e_s = 6.108 \cdot \exp[17.26939 \times T / (T + 273.3)] \quad (5)$$

The mean annual evapotranspiration can be modeled using Budyko method by only considering water availability and atmospheric demand as dominant controls. Zhang et al. (2001) further developed the Budyko modeling framework by introducing additional controls such as rainfall seasonality and vegetation characteristics.

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$$\frac{ET}{P} = \frac{1 + w \frac{PET}{P}}{1 + w \frac{PET}{P} + \left(\frac{PET}{P}\right)^{-1}} \quad (6)$$

where, w is the plant-available water coefficient which ranges between 0.5 and 2.0 for grassland, shrubland and forest, respectively. This model could be the most reliable one when $PET/P \approx 1$ (ranging from about 0.5 to 2). In this study, the PET/P ranged from 0.53 to 1.75 for the 12 ecosystems.

2.4 Ecosystem-specific time series and trend analysis

We first used layer stacking in ENVI (Version 4.3, ITT Industries Inc.) to build new multiband image files based on spatial data surfaces of each parameter including temperature, precipitation, NDVI, ET and PET surfaces. The 300-band stack included monthly data surfaces covering 25 yr with 8-km resolution. Spatial statistical analysis was then conducted for each vegetation type, including mean, standard deviation and range of monthly data series from the multiband images. The spatial averaged monthly data series were finally extracted from multiband images accordingly to the vegetation types. To further evaluate the time trends for different vegetation types of the NSTEC, Seasonal Mann-Kendall (SMK) test was applied to each vegetation type. The SMK test is a non-parametric test for the detection of trend in a time series. The SMK test first analyzed the data subsets based on the observation ranks of the subsets across years. The test statistic was then calculated by summing the number of times in a particular year if this sum is higher than any previous years (Beurs and Henebry, 2004; Sun et al., 2008).

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2.5 Growing season water deficit index (GWDI)

To assess the potential vegetation susceptibility to climate change and degradation risk, we defined the growing season water deficit index (GWDI) as:

$$\text{GWDI} = (\text{PET} - \text{ET}) / (P - \text{ET}) \quad (7)$$

where, the PET, ET and P were totals during the growing season. GWDI represents a balance between vegetation water demand and water availability. $\text{GWDI} < 1$ indicates that ecosystem retains more than demand green water resources which is available for plants (Calder, 2005; Liu et al., 2009). The sound water status allows ecosystem produce saturation excess runoff (Dunne and Black, 1970). $\text{GWDI} > 1$ and upward trend indicate enlarged gap between water demand and supply. Vegetation suffers from continuing water stress and appears reversal trend. Balance line ($\text{GWDI} = 1$) break suggests rising susceptibility to environmental change.

3 Results

3.1 Seasonal, growing season and annual trends

Figure 2 demonstrated the contrasting spatial patterns and change rates for mean growing season temperature (MGT), mean growing season precipitation (MGP) and time integrated NDVI for growing season (Ti-NDVI_g) during the study period (Fig. 2). The MGT showed broad increase along NSTEC with a rate of $0.04 \pm 0.02 \text{ }^\circ\text{Cyr}^{-1}$. Warming were especially remarkable within latitude $36\text{--}50^\circ \text{N}$ (Fig. 2a). The MGP showed high spatial variation along the NSTEC that decreased in the majority area of the transect by a maximum of -30% (Fig. 2a), and increased in much less areas of the mid-east and south transect by a maximum of 30% . Averagely, the entire transect experienced up to -6.3% MGP decline during the study period. Ti-NDVI_g demonstrated significant increase ($10 \sim 40\%$) in the middle of the transect within latitudes 30 to 50°N ,

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but in the lower latitude regions showed remarkable browning trends. On average, the entire transect $Ti-NDVI_g$ showed a slight increase of 1.24 % (Fig. 2c).

The time trends in MAT and AGDD for the majority vegetation types along NSTEC are consistent positive ($P < 0.01$) over the study period, except for the MAT in cold temperate coniferous forests and AGDD in subtropical evergreen-broadleaved forest (Table 2). The significant warming usually occurred in seasons from early spring to early autumn (February to September). Nine vegetation types including TCF, TMF, TDS, TGS, TG, STCF, STG, SDBF and SEBF suffered from no less than four months' significant warming every year. As for the rest three types CTCF, TDBF and TMS, there were only one or two months' significant warming in summer time (July to September) (Table 2).

The SMK test showed that the majority of vegetation types along the NSTEC experienced mean annual precipitation (MAP) decline during the study period, whereas half of them (CTCF, TMF, TDS, TMS, TG and SDBF) were statistically significant in their downward trends. Only STCF and STG showed slightly upward but insignificant trends (Table 3). The growing season precipitation (MGP) showed consistent downward trends with MAP in most vegetation types, except for STCF and SEBF that showed divergent but insignificant trends. Seasonal precipitation decline occurred during mainly from March to September, particularly in September. The precipitation in TCF, TG and STCF decreased significantly during March and in CTCF was during August, whereas most other types including TMF, TDBF, TDS, TMS, STG and SEBF decreased significantly during September.

Among the vegetation types that showed upward $Ti-NDVI_g$ trends, only the herbaceous type TG was significant ($P = 0.02$). The other two herbaceous types (TMS and TGS) and the cold temperate coniferous forest (CTCF) and temperate deciduous shrub (TDS) showed positive but insignificant trends (Table 4). All other types showed downward $Ti-NDVI_g$ trends including significant TCF ($P = 0.04$), SEBF ($P = 0.001$) and STG ($P = 0.008$), and insignificant TMF ($P = 0.24$), TDBF ($P = 0.19$), STCF ($P = 0.48$) and SDBF ($P = 0.1$). Regarding the seasonal NDVI trends, the southern subtropical types

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including STG, SDBF and SEBF showed four to five months' decrease centered in August, and the cold temperate forest types CTCF exhibited strong non-growing season decrease in November and December.

The majority of the 12 transect vegetation types showed strong increasing annual potential evapotranspiration (PET) during study period, only TMF showed insignificant positive trend. The growing season PET (PET_g) trends were consistent with that of annual PET in all vegetation types, except that STG and SEBF showed insignificant positive trend. In contrast, annual ET and growing season ET (ET_g) of most vegetation types were consistent downward. The STG was the only type showed increase trends in both ET and ET_g . Though not significant, the CTCF showed increasing ET but decreasing ET_g during the study period (Table 5).

3.2 NDVI responses across climatic gradients and vegetation types

Correlation coefficients between $Ti-NDVI_g$ and MGP (i.e. $R_{(NDVI-P)}$), $Ti-NDVI_g$ and AGDD (i.e. $R_{(NDVI-T)}$) were estimated for the 12 vegetation types using spatially-averaged 25-yr time series data. $R_{(NDVI-P)}$ by vegetation types were plotted against MGP in Fig. 3a, and $R_{(NDVI-T)}$ against AGDD in Fig. 3b.

Most ecosystems showed significant positive $R_{(NDVI-P)}$ except for subtropical evergreen-broadleaved forests (SEBF, $R = -0.09$, $P > 0.05$) and subtropical and tropical grassland (STG, $R = 0.21$, $P > 0.05$) (Fig. 3a). The $R_{(NDVI-P)}$, when pooled together across the 12 vegetation types, showed a strong linear relationship with MGP ($R^2 = 0.78$, $P < 0.01$). Collectively, the vegetation types of the NSTEC presented a significant decrease in $R_{(NDVI-P)}$ with increasing MGP. Unlike $R_{(NDVI-P)}$, $R_{(NDVI-T)}$ by all vegetation types were significantly positive. Comparatively, TGS demonstrated the lowest $R_{(NDVI-T)}$ but relatively high $R_{(NDVI-P)}$. As whole, the $R_{(NDVI-T)}$ showed insignificant negative and across-type relationship with AGDD ($R^2 = 0.13$, $P = 0.17$).

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3.3 GWDI time trends by vegetation types

The inter-annual mean GWDI of TG, TMS, TGS and TDS were significantly higher than that of other vegetation types. TGS (GWDI = 3.1 ± 1.2) was the highest among all types (Fig. 4). The average GWDI values in CTCF, TCF and SDBF were close to 1.0 as a balance line, with relatively high variations. Whereas TDBF, TMF, SEBF, STG and STCF are considerably lower than the balance line, with low variations. The sequence of bars from left to right in the graph (Fig. 4) roughly corresponds to the central latitude sequence of the vegetation types, distributing from north to south along the transect. So the figure meanwhile outlined the water deficit profile along the NSTEC.

The GWDI time series of the temperate steppes that include TGS and TMS showed not only high interannual variations but also strong increasing trends ($P < 0.01$) during the study period (Fig. 5). For temperate shrub and grassland (TDS and TG), a substantial increase in GWDI from below 1.0 to maximum 4.0 in recent years. In contrast, the GWDI time series of southern grassland (STG) was low and less variable, and the trend was not significant ($P = 0.675$).

Forests showed different patterns in GWDI time series. Among the low water deficit types (GWDI < 1.0), north TMF showed significant increase, the south STCF, TDBF and SEBF did not show any trend, but the interannual variation in GWDI for the latter three types increased in recent years (Fig. 5). The remainder of forests were water deficit types (GWDI ≥ 1.0), showed consistent increasing trends in GWDI. These important forests, including the CTCF, TCF, and SDBF changed from non-water deficit condition (GWDI < 1.0) to water deficit condition (GWDI > 1.0) during the study period of 1982–2006. Specifically, only in the 10 most recent years, these three forest types suffered from water deficit (Fig. 5).

3.4 Associating GWDI with climate and vegetation activities

GWDI was negatively and linearly related to MGP in each individual vegetation type. However, the relationship differed among precipitation regions, and the slope in dry

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regions was significantly larger than that of wet regions. When the data series of all vegetation types were pooled, GWDI decreased in a hyperbolic fashion with increasing MGP (Fig. 6a). In the low precipitation region, the GWDI decreased sharply as the MGP increased from about 200 mm to 400 mm. This region showed low variability among vegetations, including mainly herbaceous types (TGS, TMS, TDS and TG). In the medium precipitation region, where MGP ranges from 400 mm to 600 mm, the GWDI decreased with dramatic variation among the types of TMF, TDBF, TCF, SDBF and CTCF. In high precipitation region, where MAP is higher than 600 mm, the slope was significantly smaller than that of low and medium precipitation regions. The three main types including STG, STCF and SEBF, showed low variability again (Fig. 6a). The GWDI balance line of 1.0 corresponded exactly to the MGP range of 400 mm to 600 mm, with median of 500 mm.

Each individual vegetation type showed a positive relationship between GWDI and AGDD. There is no across-type trend in GWDI with increasing AGDD when the data series of all vegetation types were pooled (Fig. 6b). However, the slope coefficients of cold temperate and subtropical types are much lower than that of temperate regions. For example, there are significant larger slopes in TGS, TMS, TDS and TG as compared with those of the subtropical vegetation types such as STCF, STG and SEBF (Fig. 6b). Moreover, the GWDI for temperate types also exhibited high interannual variability during the study period (Fig. 6b).

The GWDI showed very strong relationship with $Ti-NDVI_g$ ($r^2 = 0.95$, $P < 0.001$) when spatial and interannual means for 12 vegetation types were pooled (Fig. 7). The relationship was universal and across-type, associated vegetation activities with ecosystem water status. According to the relationship, all seven forests were found within reasonable water budget ($GWDI < 1.0$) averagely during the study period. TDS, TG and TMS suffered from certain extent of water stress ($1.0 < GWDI < 2.0$). The most severe water deficit ($GWDI > 3.0$) occurred in TGS. GWDI balance line 1.0 corresponds to $Ti-NDVI_g$ value of 3.2 (Fig. 7). Therefore, the $Ti-NDVI_g$ of 3.2 can be alternatively used as a NDVI-based threshold for fast evaluation on water deficit by remote sensing.

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4.1 Climate change and growing season water deficit

In general, this study agrees with the previous assertions that warming becomes apparent with increasing latitude, but our study showed that the highest temperature increase occurred in the mid-latitude area rather than in the northernmost area of the transect (Fig. 2b). This is consistent with the warming trends presented by the 4th IPCC report chapter, during the similar time span of 1979 to 2005 (Trenberth et al., 2007). Precipitation trend along the transect agrees with a prior study in China, that showed declines in annual precipitation over the past 50 yr in Northeast and Northern China and increases in Western China, Yangtze river and along southeast coast (Zhai and Pan, 2003). As whole, the NSTEC showed significant and consistent growing season declines in precipitation during the study period (Table 3).

Some previous studies reported intensification of the water cycle in the world that attributed to warming (Held and Soden, 2000; Huntington, 2006; Zhang et al., 2009), our study also simulated the dramatic PET increase for most vegetation types either in annual or growing season. However, the ET_g decreased in the majority vegetation types, which accorded with the MGT declines along the transect (Tables 3 and 5). The result indicated that precipitation decline particularly in the growing season was the main constraint of ET. It seems more likely that the water deficit constraining on ET was more than offset by warming effect on intensifying it, particularly in the middle and northern vegetation types (Table 3).

Beside the meteorological factors, the vegetation activity change (NDVI as the proxy) has indirect effect on ET because large scale vegetation activity change is related to its water assumption (transpiration). Interestingly, for all forests types except CTCF, ET_g showed similar trend with $Ti-NDVI_g$ (Tables 4 and 5), but for non-forest types, they showed divergent trends. Specifically, the dry temperate grassland (TG), steppes (TMS, TGS) and shrubland (TDS) showed upward $Ti-NDVI_g$ but downward ET_g . These four types had long been suffered from growing season precipitation decline and were

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in high water deficit (Figs. 4 and 5), therefore the upward trend of $Ti-NDVI_g$ is obviously a result of warming effect on prolonging growing season length, which had been found by some previous studies that non-forest types phenology were more susceptible to warming compared with that of forests (Piao et al., 2006a; Yu et al., 2010). Increasing vegetation activity may not be beneficial to vegetations particularly for those in face of water deficit, which may create excessive deep soil water loss, result in decreased overall moisture availability for plants (Bradley and Mustard, 2008), and thus decrease ET. Our result on ET trend in cold temperate coniferous forests (CTCF) agreed with the recent study that showing decreasing trend in the boreal forest of Northern Mongolia (Zhang et al., 2009).

4.2 Vegetation activity and trends

The positive trend in $Ti-NDVI_g$ for the entire transect (Fig. 2c) agreed with a study by Fang et al. (2003, 2004) that suggested vegetation activity increased in China during 1982 to 1999. The increase vegetation activity became apparent in medium and higher latitude areas, and was in accord with the spatial pattern of warming (Fig. 2a). Warming played an important role in plant growth and lengthening the growing season (Piao et al., 2006a, b). Our previous research found that the growing season lengths (GSL) of most vegetation types in the NSTEC were prolonged during the period of 1982–2006 (Yu et al., 2010). As a result, the remarkable greening trend in the medium latitude can be attributed to the prolonged GSL.

However, each individual vegetation type showed differential response to environment forcing. The downward $Ti-NDVI_g$ trends in all temperate forests (TCF, TMF and TDBF) can be attributed to the MGP decline (Table 3). Regarding the cold temperate forest (CTCF), it seemed that the strong growing season warming effect on vegetation activity was more than offset by the winter cooling and precipitation decline (Tables 2–4). Despite that the $Ti-NDVI_g$ trend for the whole transect was insignificant upward during the study period, our overall result including ET and GWDI trends agreed with the recent study of boreal forests in Northern Mongolia, which showed a browning trend

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because of increasing water deficit (Zhang et al., 2009). Our findings indicate that high-latitude regions are particular susceptible to warming, which may counterbalance the effect of growing season water deficit on vegetation activities.

In addition, temperate deciduous shrub (TDS) and three non-woody types TMS, TGS and TG in the middle and higher latitude areas experienced not only warming but also growing season precipitation decline. In general, it seemed that warming played more important role than water deficit in dominating vegetation activity. Piao et al. (2006b) suggested that the TMS and TGS exhibited significant upward trends on NDVI during a shorter time span of 1982–1998. Differently, our study showed insignificant upward trends in these two types during a longer time span of 1982 to 2006. Interestingly, these two studies may indicate a slowing down pace of increasing vegetation activity as a result of warming, particularly during the most recent nine years (1998–2006) within the study period. Because the warming trends did not change during the study period (Table 2), the slowing down pace of greening in these two herbaceous types was obviously due to progressing effect of water deficit, resulted mainly from the growing season precipitation decline (Table 3).

Subtropical types including STCF, STG, SDBF and SEBF demonstrated consistent summer decline in $Ti-NDVI_g$, from roughly June to August (Table 4). The STG, SDBF and SEBF meanwhile showed consistent precipitation increase in summer (Table 3). The summer browning was most likely due to decreases in surface solar radiation associated with significant decline in sunshine duration (Wang et al., 2009). Similarly, Ren et al. (2005) also suggested a decline in sunshine duration in South East China during the past 50 yr since 1951. It is worthy to note that the significant browning trends in STG and SEBF were suggestive of decreasing potential of carbon sequestration in these areas, where were usually identified as the most significant natural carbon sinks in China.

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4.3 Ti-NDVI_g responses to MGP and AGDD gradients

Linear decrease in $R_{(NDVI-P)}$ with increasing MGP ($R^2 = 0.78$, $P < 0.01$) was found across vegetation types that distribute from dry to wet regions along the NSTEC (Fig. 3a). The across-type “gradient effect” indicated a decrease effect that precipitation exerting controls on vegetation activity. The result agreed with previous study in the semiarid area that suggested the NDVI-rainfall relationship was linear in 200–600 mm annual precipitation, and changes from the scattered to disperse when rainfall was higher than 600 mm (Martiny et al., 2006). In our study, Ti-NDVI_g for ten vegetation types had been found significantly correlated with growing season precipitation that within 750 mm, and poorly correlated when MGP was above 1000 mm. In contrast, there was no significant “gradient effect” in temperature affecting on NDVI, despite that there was likely downward trend in $R_{(NDVI-T)}$ with the latitude changed from about 18° N to 53° N, and the AGDD varied from 1800 degrees to 4300 degrees (Fig. 3b). There were no statistically difference in the warming effects on north and south vegetations along the transect. In fact, warming exerted broad and profound impacts on either north or south vegetations, due mainly to its strong controls on vegetation phenological events (Piao et al., 2006a; Yu et al., 2010) and production (Fang et al., 2003). We speculate that vegetation activity in wet south transect would increase much more than that of the dry north transect, given suffering from the same manner of temperature increase. For most north vegetation types, the growing season water deficit counteracts the warming effect on vegetation, for instance, the $R_{(NDVI-T)}$ in dry TGS was much lower than other types (Fig. 3b).

4.4 GWDI and ecosystem susceptibility

To identify the vegetation types that potentially susceptible to climate change, we formulated the growing season water deficit index (GWDI). It is a composite indicator that integrates the effects of temperature and precipitation, which exerted counteracting controls on vegetation activities. Therefore the index allows for better diagnose of

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ecosystem water balance status which may suggest of long term vegetation change. Unlike the wetness index (WEI) defined as the ratio of total precipitation (P) to total potential evaporation (PET) during the warmest seven months (Suzuki et al., 2006), the GWDI takes into account not only P and PET during the growing season, but also the very important ET, which associates mainly with ecosystem green water (Liu et al., 2009; Liu and Yang, 2010). Therefore the GWDI reflects the balance between evaporative water demand and green water. In addition, this index enables us to fast evaluate the possibility that ecosystem produces blue water (Calder, 2005).

The extreme high GWDI and dramatic upward trend in TGS strongly indicated the unbalanced water budget during the study period. The continuing decrease of overall moisture availability may lead to lower vegetation activity and ecosystem degradation. The speculation has been evidenced by some previous findings that suggested the grass land desertification within the region of temperate grass steppe (TGS) (e.g., Tong et al., 2002). However, based only on NDVI trend analysis, few earlier studies suggested a reverse desertification process in Chinese arid and semiarid regions, which include our study region of TGS (Runnström et al., 2000; Zhong and Qu, 2003). Similarly, we also found a similar upward though not significant trend of the NDVI in TGS during our study period (Table 4), but its GWDI time series suggested different trend. Averagely, the TGS is the most stressed ($GWDI = 3.1 \pm 1.2$) type in the NSTEC, and the extreme high GWDI and dramatic interannual variability occurred since the year 1999. Therefore, it is more likely that the desertification reversal process only reflected the provisional phenomenon of plant phenological response to warming. The abrupt greening may accelerate water loss through plant transpiration given the water deficit status continued. Inferred from their upward trends in GWDI (Fig. 5), the shrub land (TDS) and three non-woody types (TG, TMS, TGS) will be susceptible to future climate change, particularly the precipitation decline, evidenced by the slowing down of NDVI increasing (discussed above). These results are quite similar to a recent study in shrubland and grassland biomes where abrupt greening was often followed by gradual browning (De Jong et al., 2012). Sound water condition was found in TDBF, TMF,

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SEBF, STCF and STG according to their far below 1.0 GWDI. However, the increasing interannual variation in temperate types (TDBF and TMF) can be attributed to stronger effect of MGP decline than warming. Through the GWDI and MGP trends analysis, the CTCF, TCF and SDBF were identified as facing progressive risk of water deficit, because their GWDI broken the balance line 1.0 and became variable.

The strong intra- and across-type relationships between GWDI and MGP reflected the dominative effect of precipitation on ecosystem water deficit, but the hyperbolic fashion meanwhile indicated a fast decreasing of the effect. Comparatively, the dry region showed higher interannual variation in GWDI than wet region, indicated an increasing uncertainty in ET that attribute to drought. Regarding the inter-type variation, herbaceous types either in dry or wet regions demonstrated higher GWDI than forests. This phenomenon was likely a result of ET overestimating for low coverage vegetations. The MGP median of 500 mm can be a baseline to differentiate between water deficit and water abundant types or conditions. By contrast, there was no significant across-type GWDI-AGDD relationship, despite that each individual vegetation type showed significant linear relationship between AGDD and GWDI (Fig. 6b). However, the dry region types showed much higher slope coefficients than those of wet region (Fig. 6b). This interesting phenomenon implied that the water deficit situation in dry areas was more easily accelerated by warming than that of wet region.

The sound relationship between $Ti-NDVI_g$ and GWDI reflected the strong interaction between ecosystem water balance and its vegetation activity. In addition, base on the consumptive vegetation water use, GWDI was proved to be effective in indicating vegetation activities for diverse vegetation types in broad environment conditions. The baselines in both $Ti-NDVI_g$ (3.2) and GWDI (1.0) can be used to evaluate water status for the different vegetation types. Through the baseline, we identified that the TDS, TG and TMS had suffered from certain extent of water deficit, and severe drought occurred in TGS (Fig. 7). Averagely, forests were in sound water status during the study period. However, the increasing water deficit and decreasing vegetation activity in temperate forest CTCF, TCF TDBF, suggested their rising susceptibility to future climate change,

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in which water deficit exerted substantial effect and warming exerted counteracting effect. It seemed that warming effect on vegetation became variable and uncertain because of seasonal water deficit.

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5 The whole transect exhibited high spatial heterogeneity and interannual variability in terms of climate change pattern during the entire study period of 1982–2006. This study found significant warming trends in most vegetation types, and the majority of vegetation types along the transect have experienced growing season precipitation decline. Warming and precipitation decline showed counteracting effect in controlling
10 vegetation activity. Our study found insignificant greening trends in the northernmost forest type (CTCF), three temperate herbaceous types (TGS, TMS, TG) and temperate shrub (TDS), where the growing season warming exerted more than offset effect on vegetation activity (phenology) than growing season water deficit. For the three temperate forest (TMF, TCF, and TDBF), growing season water deficit was still the main
15 constraint on vegetation activity. Differently, the growing season browning in subtropical types (STCF, STG, SDBF and SEBF) were likely attributed to decline in sunshine duration due to increased summer cloudiness.

Through the GWDI time series and its relationship with $Ti\text{-}NDVI_g$, we have identified growing season water deficit in TDS, TG and TMS, and severe drought in TGS.
20 Averagely, forests were in sound water status during the study period. However, the emerging water deficit and browning in temperate forest CTCF, TCF TDBF, suggested their rising susceptibility to future climate change.

Acknowledgements. This research was jointly supported by Special Research Program for Public-welfare Forestry (No. 200804001 and No. 201104006), Chinese Academy of Forestry Foundation (CAFYBB2008007), National Nature Science Foundation of China (30590383) and the key Laboratory of Forest Ecology and Environment of State Forestry Administration.
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- Andréassian, V.: Waters and forests: from historical controversy to scientific debate, *J. Hydrol.*, 291, 1–27, 2004.
- Arora, V. K.: The use of the aridity index to assess climate change effect on annual runoff, *J. Hydrol.*, 265, 164–177, 2002.
- Beurs, K. M. and Henebry, G. M.: Trend analysis of the Pathfinder AVHRR Land (PAL) NDVI data for the deserts of Central Asia, *IEEE Geosci. Remote S.*, 1, 282–286, 2004.
- Bradley, B. A. and Mustard, J. F.: Comparison of phenology trends by land cover class: a case study in the Great Basin, USA, *Global Change Biol.*, 14, 334–346, doi:10.1111/j.1365-2486.2007.01479.x, 2008.
- Brown, A. E., Zhang L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *J. Hydrol.*, 310, 28–61, 2005.
- Brown, T. C., Hobbins, M. T., and Ramirez, J. A.: Spatial distribution of water supply in the coterminous United States, *J. Am. Water Resour. As.*, 44, 1474–1487, 2008.
- Calder, I. R.: *Blue Revolution: Integrated Land and Water Resource Management*, Earthscan, London, 2005.
- Chen, J., Wang, C., Jiang, H., Mao, L., and Yu, Z.: Estimating soil moisture using Temperature-vegetation Dryness Index (TVDI) in the Huang-huai-hai (HHH) plain, *Int. J. Remote Sens.*, 32, 1165–1177, 2011.
- De Jong, R., Verbesselt, J., Schaepman, M. E., and De Bruin, S.: Trend changes in global greening and browning: contribution of short-term trends to longer-term change, *Global Change Biol.*, 18, 642–655, 2012.
- Donohue, R. J., McVicar, T. R., and Roderick, M. L.: Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006, *Global Change Biol.*, 15, 1025–1039, 2009.
- Dragoni, D., Schmid, H. P., Wayson, C. A., Potter, H., Grimmond, C. S. B., and Randolph, J. C.: Evidence of increased net ecosystem productivity associated with a longer vegetated season in a deciduous forest in South-Central Indiana, USA, *Global Change Biol.*, 17, 886–897, 2011.
- Dunne, T. and Black, R. D.: Partial area contributions to storm runoff in a small New England watershed, *Water Resour. Res.*, 6, 1296–1311, 1970.

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- Fang, J. Y., Piao, S. L., and Field, C. B.: Increasing net primary production in China from 1982 to 1999, *Front. Ecol. Environ.*, 1, 293–297, 2003.
- Fang, J. Y., Piao, S. L., He, J. S., and Ma, W. H.: Increasing terrestrial vegetation activity in China, 1982–1999, *Sci. China Ser. C*, 47, 229–240, 2004.
- 5 Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., and Sitch, S.: Terrestrial vegetation and water balance – hydrological evaluation of a dynamic global vegetation model, *J. Hydrol.*, 286, 249–270, 2004.
- Held, I. M. and Soden, B. J.: Water vapor feedback and global warming, *Annu. Rev. Energ. Env.*, 25, 441–475, 2000.
- 10 Huemmrich, K. F., Black T. A., and Jarvis P. G.: High temporal resolution NDVI phenology from micrometeorological radiation sensors, *J. Geophys. Res.-Atmos.*, 104, 27935–27944, 1999.
- Hundecha, Y. and Bárdossy, A.: Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model, *J. Hydrol.*, 292, 281–295, 2004.
- 15 Huntington, T. G.: Evidence for intensification of the global water cycle: review and synthesis, *J. Hydrol.*, 319, 83–95, 2006.
- Hutchinson, M. F. and Gessler, P. E.: Splines-more than just a smoothinterpolator, *Geoderma*, 62, 45–67, 1994.
- IPCC: Climate Change 2007: Mitigation, in: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Metz, B., Davidson, O. R., Bosch, P. R., Dave, R., and Meyer L. A., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.
- 20 Jia, G. J., Epstein, H. E., and Walker, D. A.: Spatial heterogeneity of tundra vegetation response to recent temperature changes, *Global Change Biol.*, 12, 42–55, 2006.
- 25 Lavabre, J., Sempere, D., and Cernesson, F.: Changes in the hydrological response of a small Mediterranean basin a year after a wildfire, *J. Hydrol.*, 142, 273–299, 1993.
- Liu, J. and Yang, H.: Spatially explicit assessment of global consumptive water uses in cropland: green and blue water, *J. Hydrol.*, 384, 187–197, 2010.
- Liu, J., Zehnder, A. J. B., and Yang H.: Global consumptive water use for crop production: the importance of green water and virtual water, *Water Resour. Res.*, 45, W05428, doi:10.1029/2007WR006051, 2009.
- 30 Martiny, N., Camberlin, P., Richard, Y., and Philippon, N.: Compared regimes of NDVI and rainfall in semi-arid regions of Africa, *Int. J. Remote Sens.*, 27, 5201–5223, 2006.

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- McVicar, T. R. and Bierwirth, P. N.: Rapidly assessing the 1997 drought in Papua New Guinea using composite AVHRR imagery, *Int. J. Remote Sens.*, 22, 2109–2128, 2001.
- McVicar, T. R. and Jupp, D. L. B.: The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review, *Agr. Syst.*, 57, 399–468, 1998.
- McVicar, T. R., Niel, T. G. V., Li, L., Hutchinson, M. F., Mu, X., and Liu, Z.: Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences, *J. Hydrol.*, 338, 196–220, 2007.
- Méndez-Barroso, L. A., Vivoni, E. R., Watts, C. J., and Rodríguez, J. C.: Seasonal and interannual relations between precipitation, surface soil moisture and vegetation dynamics in the North American monsoon region, *J. Hydrol.*, 377, 59–70, 2009.
- Milly, P. C. D., Dunne, K. A., and Vecchia, A. V.: Global pattern of trends in streamflow and water availability in a changing climate, *Nature*, 438, 437–350, 2005.
- Mu, Q., Heinsch, F. A., Zhao, M., and Running, S. W.: Development of a global evapotranspiration algorithm based on MODIS and global meteorology data, *Remote Sens. Environ.*, 111, 519–536, 2007.
- Niehoff, D., Fritsch, U., and Bronstert, A.: Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany, *J. Hydrol.*, 267, 80–93, 2002.
- Patel, N. R., Anapashsha, R., Kumar, S., Saha, S. K., and Dadhwal, V. K.: Assessing potential of MODIS derived temperature/vegetation condition index (TVDI) to infer soil moisture status, *Int. J. Remote Sens.*, 30, 23–39, 2009.
- Piao, S., Fang, J., Zhou, L., Ciais, P., and Zhu, B.: Variations in satellite-derived phenology in China's temperate vegetation, *Global Change Biol.*, 12, 672–685, 2006a.
- Piao, S., Mohammat, A., Fang, J., Qiang, C., and Feng, J.: NDVI-based increase in growth of temperate grasslands and its responses to climate changes in China, *Global Environ. Chang.*, 16, 340–348, 2006b.
- Prasad, A. K., Sarkar, S., Singh, R. P., and Kafatos, M.: Inter-annual variability of vegetation cover and rainfall over India, *Adv. Space Res.*, 39, 79–87, 2006.
- Prasad, A. K., Singh, R. P., Tare, V., and Kafatos, M.: Use of vegetation index and meteorological parameters for the prediction of crop yield in India, *Int. J. Remote Sens.*, 28, 5207–5235, 2007.

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- Reed, B. C., Brown, J. F., VanderZee, D., Loveland, T. R., Merchant, J. W., and Ohlen, D. O.: Measuring phenological variability from satellite imagery, *J. Veg. Sci.*, 5, 703–714, 1994.
- Ren, G. Y., Guo, J., Xu, M. Z., Chu, Z. Y., Zhang, L., Zou, X. K., Li, Q. X., and Liu, X. N.: Climate changes of mainland China over the past half century, *Acta Meteorol. Sin.*, 63, 942–956, 2005 (in Chinese).
- Rhee, J., Im, J., and Carbone, G. J.: Monitoring agricultural drought for arid and humid regions using multi-sensor remote sensing data, *Remote Sens. Environ.*, 114, 2875–2887, 2010.
- Runnström, M. C.: Is Northern China winning the battle against desertification? Satellite remote sensing as a tool to study biomass trends on the Ordos plateau in semiarid China, *Ambio*, 29, 468–476, 2000.
- Scheiter, S. and Higgins, S. I.: Impacts of climate change on the vegetation of Africa: an adaptive dynamic vegetation modelling approach, *Global Change Biol.*, 15, 2224–2246, 2009.
- Sun, G., McNulty, S. G., Amatya, D. M., Skaggs, R. W., Swift Jr., L. W., Shepard, J. P., and Riekerk, H.: A comparison of the watershed hydrology of coastal forested wetlands and the mountainous uplands in the Southern US, *J. Hydrol.*, 263, 92–104, 2002.
- Sun, G., McNulty, S. G., Lu, J., Amatya, D. M., Liang, Y., and Kolka, R. K.: Regional annual water yield from forest lands and its response to potential deforestation across the Southeastern United States, *J. Hydrol.*, 308, 258–268, 2005.
- Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S. G., and Vose, J. M.: Potential water yield reduction due to forestation across China, *J. Hydrol.*, 328, 548–558, 2006.
- Sun, G., McNulty, S. G., Myers, J. A. M., and Cohen E. C.: Impacts of multiple stresses on water demand and supply across the Southeastern United States, *J. Am. Water Resour. As.*, 44, 1441–1457, 2008.
- Sun, G., Caldwell, P., Noormets, A., McNulty, S. G., Cohen, E., Myers, J. M., Domec, J., Treasure, E., Mu, Q., Xiao, J., Ranjeet, J., and Chen J.: Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model, *J. Geophys. Res.*, 116, 1–16, 2011.
- Sun, P., Liu, S., Jiang, H., Lü, Y., Liu, J., Lin, Y., and Liu, X.: Hydrologic effects of NDVI time series in a context of climatic variability in an Upstream Catchment of the Minjiang River, *J. Am. Water Resour. As.*, 44, 1132–1143, 2008.
- Suzuki, R., Xu, J., and Motoya, K.: Global analyses of satellite-derived vegetation index related to climatological wetness and warmth, *Int. J. Climatol.*, 26, 425–438, 2006.

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Suzuki, R., Masuda, K., and Dye, D. G.: Interannual covariability between actual evapotranspiration and PAL and GIMMS NDVIs of Northern Asia, *Remote Sens. Environ.*, 106, 387–398, 2007.

Tan, S. Y.: The influence of temperature and precipitation climate regimes on vegetation dynamics in the US Great Plains: a satellite bioclimatology case study, *Int. J. Remote Sens.*, 28, 4947–4966, 2007.

Tong, C., Hao, D. Y., Gao, X., Jiang, Q. H., and Yong, S. P.: Forecast on changes of steppe degradation patterns in the Xilin River Basin, Inner Mongolia: an application of Markov process, *J. Nat. Res.*, 17, 488–493, 2002 (in Chinese).

Trenberth, K. E., Jones, P. D., Ambenje, P., Bojariu, R., Easterling, D., Klein Tank, A., Parker, D., Rahimzadeh, F., Renwick, J. A., Rusticucci, M., Soden, B., and Zhai, P.: Observations: surface and atmospheric climate change, in: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Tucker, C. J. and Sellers, P. J.: Satellite remote sensing of primary vegetation, *Int. J. Remote Sens.*, 7, 1395–1416, 1986.

Tucker, C. J., Slayback, D. A., and Pinzon, J. E.: Higher northern latitude normalized difference vegetation index and growing season trends from 1982 to 1999, *Int. J. Biometeorol.*, 45, 184–190, 2001.

Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, D. A., Pak, E. W., Mahoney, R., Vermote, E. F., and El Saleous, N.: An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data, *Int. J. Remote Sens.*, 26, 4485–4498, 2005.

Wang, Y. J., Huang, Y., and Zhang, W.: Changes in surface solar radiation in mainland China over the period from 1961 to 2003, *Clim. Environ. Res.*, 14, 405–413, 2009 (in Chinese).

Wei, X. and Zhang, M.: Quantifying stream flow change caused by forest disturbance at a large spatial scale: a single watershed study, *Water Resour. Res.*, 46, W12525, doi:10.1029/2010WR009250, 2010.

White, M. A., Thornton, P. E., and Running, S. W.: A Continental phenology model for monitoring vegetation responses to interannual climatic variability, *Global Biogeochem. Cy.*, 11, 217–234, 1997.

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- White, M. A., Hoffman, F., and Hargrove, W.: A global framework for monitoring phenological response to climate change, *Geophys. Res. Lett.*, 32, L04705, doi:10.1029/2004GL021961, 2005.
- 5 Yu, Z., Sun, P. S., and Liu, S. R.: Phenological change of main vegetation types along a north-south transect of Eastern China, *Chinese J. Plant Ecol.*, 34, 316–329, 2010 (in Chinese).
- Zhai, P. and Pan, X.: Trends in temperature extremes during 1951–1999 in China, *Geophys. Res. Lett.*, 30, 1913, doi:10.1029/2003GL018004, 2003.
- 10 Zhang, K., Kimball, J. S., Mu, Q., Jones, L. A., Goetz, S. J., and Running, S. W.: Satellite based analysis of northern ET trends and associated changes in the regional water balance from 1983 to 2005, *J. Hydrol.*, 379, 92–110, 2009.
- Zhang, L., Dawes, W. R., and Walker, G. R.: Predicting the effect of vegetation changes on catchment average water balance, Cooperative Research Centre for Catchment Hydrology, Technical Report 99/12, 1–2, 1999.
- 15 Zhang, L., Dawes, W. R., and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, *Water Resour. Res.*, 37, 701–708, 2001.
- Zhang, Y. K. and Schilling, K. E.: Increasing stream flow and base flow in Mississippi river since the 1940s: effect of land use change, *J. Hydrol.*, 24, 412–422, 2006.
- Zhao, M. and Running, S. W.: Drought-induced reduction in global terrestrial net primary production from 2000 through 2009, *Science*, 329, 940–943, doi:10.1126/science.1192666, 2010.
- 20 Zhao, M., Fu, C., Yan, X., and Wen, G.: Study on the relationship between different ecosystems and climate in China using NOAA/AVHRR data, *Acta Geogr. Sin.*, 56, 287–296, 2001.
- Zhong, D. C. and Qu J. J.: Recent developmental trend and prediction of sand deserts in China, *J. Arid. Environ.*, 53, 317–329, 2003.
- 25 Zhou, L. M., Tucker, C. J., and Kaufmann, R. K.: Variations in northern vegetation activity inferred from satellite data of vegetation index during 1981 to 1999, *J. Geophys. Res.-Atmos.*, 106, 20069–20083, 2001.

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Table 1. Statistics for the twelve vegetation types that distribution along the north-south transect of Eastern China (NSTEC). Phenology events (onset dates of greening and dormancy) are derived from their respective seasonal dynamic curves of NDVI (Yu et al., 2010).

| Vegetation type | Short name | Latitude range | Onset date of greening (DOY) | Onset date of dormancy (DOY) | Growing season length (months) |
|--|------------|----------------|------------------------------|------------------------------|--------------------------------|
| Cold temperate coniferous forest | CTCF | 48°–53° N | 123 | 250 | 4.2 |
| Temperate coniferous forest | TCF | 32°–42° N | 118 | 268 | 5.0 |
| Temperate mixed forest | TMF | 40°–47° N | 119 | 260 | 4.7 |
| Temperate deciduous-broadleaved forest | TDBF | 32°–53° N | 117 | 262 | 4.8 |
| Temperate deciduous shrub | TDS | 30°–50° N | 127 | 260 | 4.5 |
| Temperate meadow steppe | TMS | 35°–53° N | 138 | 254 | 3.9 |
| Temperate grass steppe | TGS | 36°–50° N | 145 | 260 | 3.8 |
| Temperate grassland | TG | 30°–42° N | 122 | 265 | 4.8 |
| Subtropical deciduous broadleaved forest | SDBF | 25°–35° N | 100 | 277 | 5.9 |
| Subtropical evergreen-broadleaved forest | SEBF | 22°–31° N | 119 | 316 | 6.6 |
| Subtropical and tropical coniferous forest | STCF | 21°–34° N | 108 | 270 | 5.4 |
| Subtropical and tropical grassland | STG | 18°–34° N | 114 | 297 | 6.1 |

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Table 2. Seasonal Mann-Kendall (SMK) trend tests of temperature by vegetation types from 1982 to 2006.

| Season | CTCF | TCF | TMF | TDBF | TDS | TMS | TGS | TG | STCF | STG | SDBF | SEBF |
|----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| Seasonal | | | | | | | | | | | | |
| Jan | 0.3 | 1.0 | 1.4 | 1.3 | 1.1 | 0.7 | 0.8 | 1.9 | 1.4 | 1.3 | 0.3 | 1.3 |
| Feb | 1.5 | 3.5 ^b | 2.2 ^a | 2.0 ^a | 2.8 ^b | 1.8 | 2.7 ^b | 3.6 ^b | 3.0 ^b | 2.1 ^a | 2.9 ^b | 2.0 ^a |
| Mar | 1.1 | 3.7 ^b | 1.3 | 1.0 | 2.0 ^a | 0.8 | 1.7 | 3.3 ^b | 3.4 ^b | 2.8 ^b | 3.4 ^b | 2.0 ^a |
| Apr | 0.4 | 2.2 ^a | 1.3 | 0.9 | 1.5 | 1.5 | 1.8 | 2.2 ^a | 1.9 | 2.6 ^b | 2.2 ^a | 2.7 ^b |
| May | 0.5 | 1.6 | 1.3 | 1.3 | 2.0 ^a | 1.4 | 2.0 ^a | 2.0 ^a | 0.8 | 0.9 | 1.0 | 1.5 |
| Jun | 0.4 | 3.1 ^b | 3.0 ^b | 1.7 | 2.4 ^a | 1.5 | 2.5 ^b | 3.1 ^b | 3.3 ^b | 2.0 ^a | 3.3 ^b | 0.8 |
| Jul | 2.5 ^b | 3.1 ^b | 3.1 ^b | 2.1 ^a | 2.8 ^b | 2.9 ^b | 3.6 ^b | 3.0 ^b | 3.5 ^b | 1.7 | 2.4 ^a | 0.1 |
| Aug | 1.3 | 1.7 | -0.3 | -0.7 | 0.7 | 1.8 | 2.2 ^a | 1.5 ^b | 0.4 | 0.6 | -0.2 | 0.1 |
| Sep | 1.4 | 1.7 | 3.2 ^b | 3.1 ^b | 3.1 ^b | 3.3 ^b | 3.5 ^b | 2.6 ^b | 1.7 | 1.8 | 1.5 | 0.8 |
| Oct | 1.1 | 0.4 | 1.5 | 1.0 | 1.1 | 1.5 | 0.9 | 1.2 | 0.4 | 0.5 | 0.7 | 0.6 |
| Nov | -0.6 | 1.8 | 1.1 | 0.7 | 0.8 | -0.3 | 0.5 | 1.9 | 1.4 | 1.6 | 0.7 | 2.0 ^a |
| Dec | -0.6 | 1.3 | -0.3 | -0.4 | -0.2 | -1.5 | -0.2 | 1.5 | 0.9 | 0.9 | 0.6 | 0.8 |
| Growing season | | | | | | | | | | | | |
| AGDD | 2.1 ^a | 3.5 ^b | 3.8 ^b | 2.9 ^b | 3.4 ^b | 4.0 ^b | 4.2 ^b | 3.2 ^b | 3.0 ^b | 2.1 ^a | 2.6 ^b | 1.6 |
| Annual | | | | | | | | | | | | |
| MAT | 1.1 | 4.0 ^b | 2.7 ^b | 4.2 ^b | 4.1 ^b | 3.7 ^b | 2.6 ^b | 3.5 ^b | 3.5 ^b | 3.7 ^b | 4.1 ^b | 3.7 ^b |

^a Significant at $P < 0.05$.

^b Significant at $P < 0.01$.

A positive SMK statistic value denotes an upward trend and a negative one denotes a downward trend.



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Table 3. Seasonal Mann-Kendall (SMK) trend tests of precipitation by vegetation types from 1982 to 2006.

| Vegetation | CTCF | TCF | TMF | TDBF | TDS | TMS | TGS | TG | STCF | STG | SDBF | SEBF |
|----------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Seasonal | | | | | | | | | | | | |
| Jan | -0.3 | 0.8 | 0.0 | 0.4 | 0.0 | 1.0 | 0.9 | 0.7 | 0.0 | 1.0 | 0.5 | 0.4 |
| Feb | 0.1 | 0.8 | -0.8 | -1.3 | -0.3 | -0.5 | -0.1 | 0.1 | 0.8 | -1.9 | 0.7 | -1.3 |
| Mar | 0.2 | -2.5 ^b | 0.0 | 1.1 | -1.5 | 0.8 | -0.9 | -2.2 ^a | -2.2 ^a | 0.3 | -1.2 | -1.3 |
| Apr | -0.2 | 0.1 | -0.8 | -0.7 | -0.4 | 0.4 | 0.2 | 0.1 | -0.7 | -0.5 | 0.6 | 0.0 |
| May | 0.5 | -1.7 | 0.0 | -0.5 | -1.4 | -0.6 | -0.4 | -1.1 | -0.6 | 1.4 | -0.9 | 0.4 |
| Jun | -0.5 | 0.5 | -0.7 | -0.3 | 0.6 | -0.9 | -0.7 | 0.7 | -0.6 | 1.4 | 0.5 | 1.8 |
| Jul | -1.0 | -0.3 | -0.7 | -0.2 | -0.5 | -1.0 | -1.4 | -0.7 | -1.0 | 0.7 | 0.7 | 2.1 ^a |
| Aug | -2.7 ^b | -0.4 | -1.4 | -0.9 | -1.6 | -1.8 | -1.9 | -0.7 | -0.8 | 0.5 | -0.2 | 1.1 |
| Sep | -1.5 | 0.1 | -2.4 ^a | -2.6 ^b | -2.8 ^b | -2.6 ^b | -1.7 | -0.8 | -1.0 | -2.0 ^a | -0.4 | -2.3 ^a |
| Oct | 0.3 | -0.6 | 0.9 | 1.3 | 0.6 | 0.5 | -0.1 | -0.2 | 0.1 | -0.4 | -0.6 | -1.3 |
| Nov | 0.4 | -0.6 | -0.7 | -0.3 | -0.4 | 0.0 | 0.1 | -0.2 | -1.4 | -1.3 | -0.3 | 0.5 |
| Dec | 0.5 | 0.5 | -0.2 | 0.3 | 0.6 | 0.8 | 1.1 | 0.3 | 0.1 | 1.1 | 0.6 | -0.3 |
| Growing season | | | | | | | | | | | | |
| MGP | -2.1 ^a | -1.0 | -2.6 ^b | -1.0 | -1.7 | -2.3 ^a | -2.3 ^a | -0.9 | -1.6 | 0.0 | -0.7 | 1.3 |
| Annual | | | | | | | | | | | | |
| MAP | -2.2 ^a | -1.7 | -2.1 ^a | -1.3 | -2.2 ^a | -2.2 ^a | -1.1 | -2.4 ^a | 0.9 | 0.2 | -2.1 ^a | -0.8 |

^a Significant at $P < 0.05$.

^b Significant at $P < 0.01$.

A positive SMK statistic value denotes an upward trend and a negative one denotes a downward trend.



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Table 4. Seasonal Mann-Kendal (SMK) trend tests of NDVI by vegetation types from 1982 to 2006.

| | CTCF | TCF | TMF | TDBF | TDS | TMS | TGS | TG | STCF | STG | SDBF | SEBF |
|----------------------|-------------------|-------------------|-------------------|-------------------|------------------|------------------|------------------|------------------|------------------|-------------------|-------------------|-------------------|
| Seasonal | | | | | | | | | | | | |
| Jan | -1.7 | 0.1 | -0.4 | -0.2 | 0.7 | -0.1 | -1.0 | -0.2 | 1.7 | -2.1 | 1.2 | -0.8 |
| Feb | -0.9 | 0.8 | -0.2 | -0.1 | 0.8 | 0.1 | 0.1 | -0.1 | 1.5 | 0.3 | 0.9 | 0.0 |
| Mar | -1.6 | 1.0 | -3.0 ^b | 0.1 | 2.2 ^a | 1.6 | 1.5 | 0.5 | 1.1 | 0.6 | 0.2 | 0.1 |
| Apr | 0.2 | 1.4 | -1.6 | -2.1 ^a | 0.6 | 1.8 | 1.2 | 1.4 | 3.2 ^b | 1.8 | 3.3 ^b | 1.3 |
| May | -0.2 | 2.2 ^a | -0.3 | 1.7 | 1.9 | -0.6 | 0.2 | 3.6 ^b | 1.5 | 1.3 | 1.4 | 0.9 |
| Jun | -0.7 | -1.0 | -1.7 | -2.2 ^a | -0.7 | -0.9 | -1.3 | 0.7 | 0.3 | -1.7 | -0.6 | -1.9 |
| Jul | -0.9 | -2.4 ^a | -0.7 | -2.1 ^a | 0.0 | 0.2 | 0.7 | 1.2 | -1.6 | -1.7 | -1.5 | -2.3 ^a |
| Aug | 0.5 | -1.9 | -1.0 | -1.2 | 0.5 | 2.4 ^a | 2.9 ^b | 0.8 | -0.9 | -2.8 ^b | -2.5 ^a | -3.5 ^b |
| Sep | 1.7 | -0.9 | 1.2 | 0.8 | 1.4 | 0.1 | 1.2 | 1.9 | -0.7 | -1.5 | -0.2 | -2.2 ^a |
| Oct | 1.5 | 1.0 | -1.5 | 0.1 | 0.5 | -0.2 | -0.4 | 1.2 | 1.1 | -1.9 | 1.0 | -1.6 |
| Nov | -2.2 ^a | 0.5 | -0.6 | -0.1 | 0.6 | -0.2 | 1.2 | -0.4 | 1.0 | 0.4 | 0.3 | 0.3 |
| Dec | -2.1 ^a | 1.5 | -1.8 | -0.5 | 0.8 | -0.5 | 0.8 | 0.6 | 1.3 | 0.1 | -0.1 | 0.5 |
| Growing season | | | | | | | | | | | | |
| Ti-NDVI _g | 0.9 | -2.0 ^a | -1.2 | -1.3 | 1.4 | 0.3 | 1.1 | 2.2 ^a | -0.7 | -2.6 ^b | -1.6 | -3.3 ^b |
| Annual | | | | | | | | | | | | |
| Mean | -1.7 | 0.4 | -2.8 ^b | -1.3 | 1.6 | 1.0 | 1.6 | 1.8 | 2.1 ^a | -1.8 | 0.6 | -2.2 ^a |

^a Significant at $P < 0.05$.

^b Significant at $P < 0.01$.

A positive SMK statistic value denotes an upward trend and a negative one denotes a downward trend.



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Table 5. Seasonal Mann-Kendal (SMK) trend tests of PET and ET by vegetation types from 1982 to 2006.

| | CTCF | TCF | TMF | TDBF | TDS | TMS | TGS | TG | STCF | STG | SDBF | SEBF |
|------------------|------------------|------------------|------------------|------------------|------------------|-------------------|------------------|------------------|------------------|-------------------|------------------|------------------|
| Annual | | | | | | | | | | | | |
| PET | 2.3 ^a | 3.8 ^b | 1.7 | 2.4 ^a | 3.0 ^b | 3.9 ^b | 4.0 ^b | 3.1 ^b | 3.8 ^b | 3.8 ^b | 3.4 ^b | 3.4 ^b |
| ET | 0.47 | -0.98 | -1.26 | -0.05 | 0.05 | -1.73 | -0.79 | -0.09 | -0.56 | 2.24 ^a | -0.19 | -0.84 |
| Growing season | | | | | | | | | | | | |
| PET _g | 2.3 ^a | 3.0 ^b | 2.4 ^a | 2.6 ^b | 2.7 ^b | 3.9 ^b | 4.3 ^b | 3.2 ^b | 2.8 ^b | 1.4 | 2.5 ^a | 1.2 |
| ET _g | -1.50 | -0.51 | -1.59 | -0.65 | -1.31 | -2.2 ^a | -1.63 | -0.14 | -0.93 | 0.09 | -0.42 | -0.05 |

^a Significant at $P < 0.05$.

^b Significant at $P < 0.01$.

A positive SMK statistic value denotes an upward trend and a negative one denotes a downward trend.

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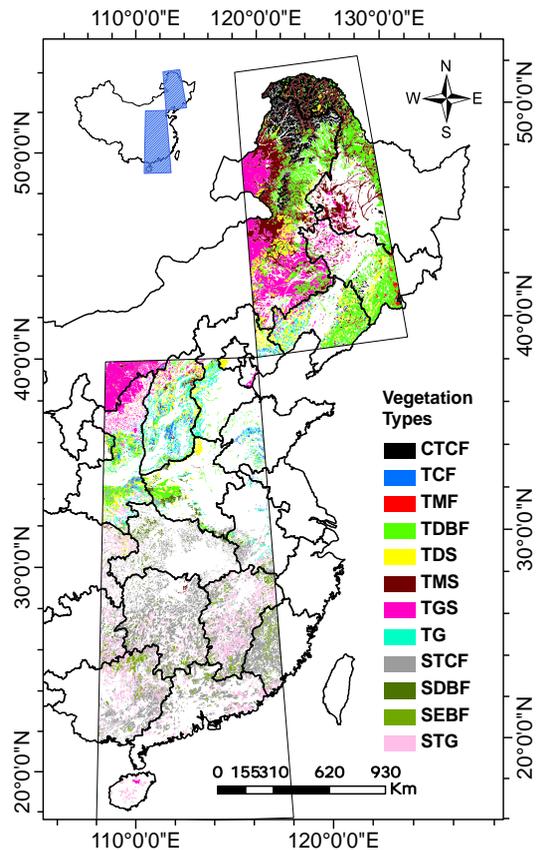


Fig. 1. Twelve major natural vegetation types and their spatial distribution along the north south transect of Eastern China (NSTEC).

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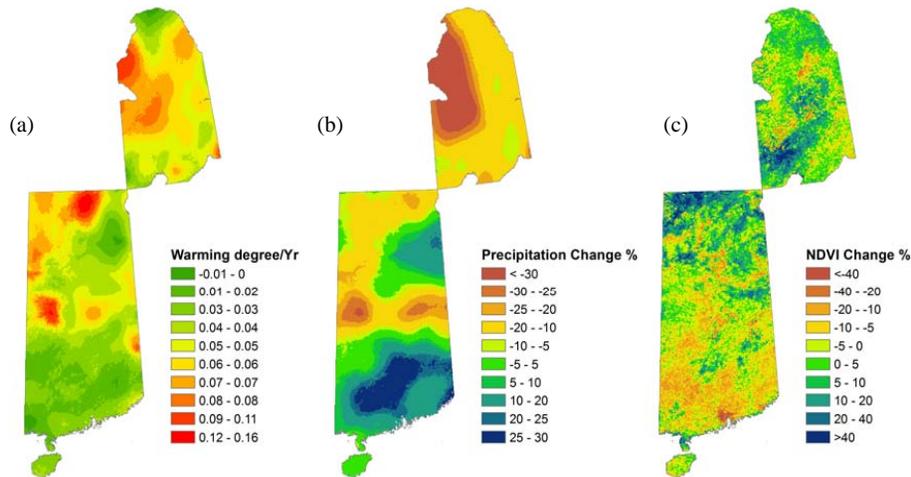


Fig. 2. (a) Averaged change rate (degree yr^{-1}) of mean growing season temperature (MGT) from 1982 to 2006. (b) Averaged change rate (%) of mean growing season precipitation (MGP) from 1982 to 2006. (c) Averaged change rate (%) of time integrated NDVI for growing season (Ti-NDVI_g) from 1982 to 2006.

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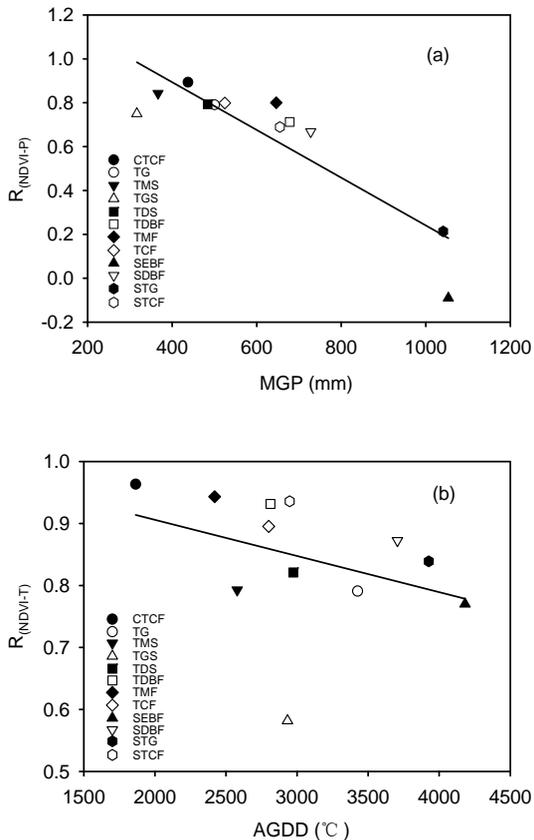


Fig. 3. (a) Relationship between mean growing season precipitation (MGP) and $R_{(NDVI-P)}$ (correlation coefficients between Ti-NDVI_g and MGP) ($R^2 = 0.78$, $P < 0.01$). Data are spatial means by vegetation types for the period of 1982–2006. **(b)** Relationship between accumulated growing degree days (AGDD) and $R_{(NDVI-T)}$ (correlation coefficients between Ti-NDVI_g and AGDD) ($R^2 = 0.13$, $P = 0.19$). Data are spatial means by vegetation types for the period of 1982–2006.

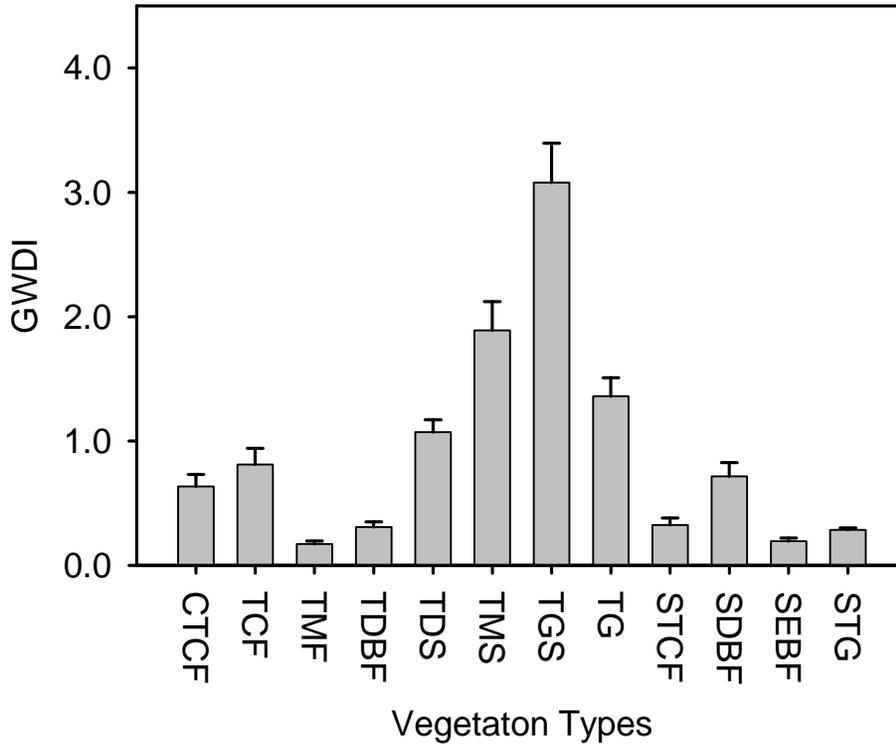


Fig. 4. Growing season water deficit index (GWDI) of different vegetation types. Data are spatial means for the period of 1982–2006.

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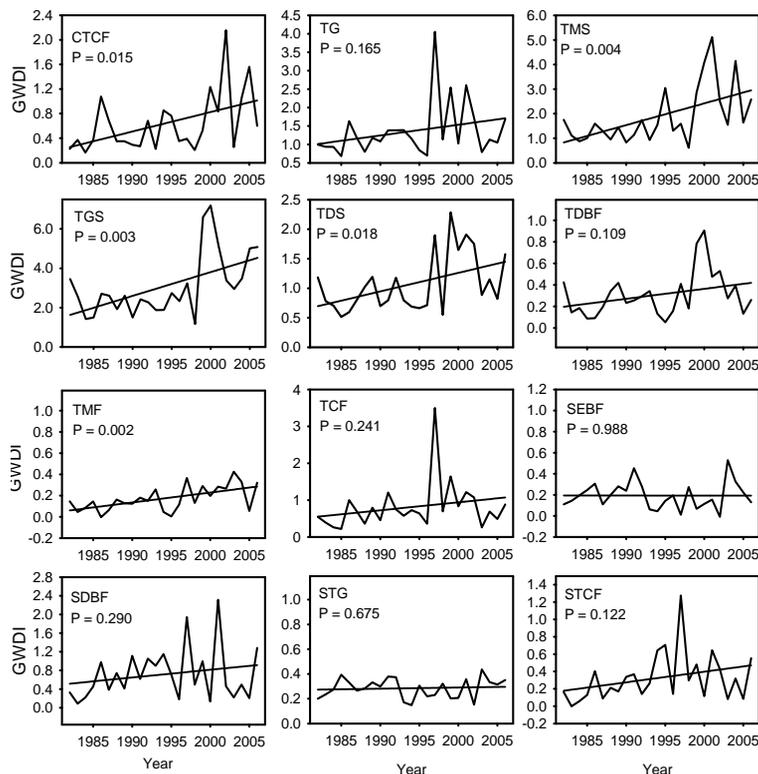


Fig. 5. Time trends of growing season water deficit index (GWDI) for twelve vegetation types during 1982–2006. Data are spatial means by vegetation type. P is the significance probability of the Mann-Kendal trend test.

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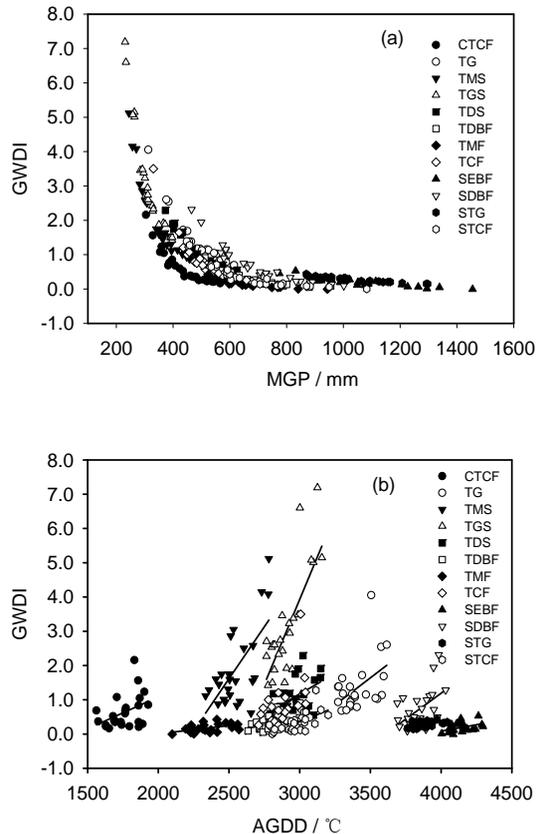


Fig. 6. The growing season water deficit index (GWDI) vs. **(a)** Mean growing season precipitation (MGP) and **(b)** Accumulated growing degree days (AGDD). All data are spatially averaged.

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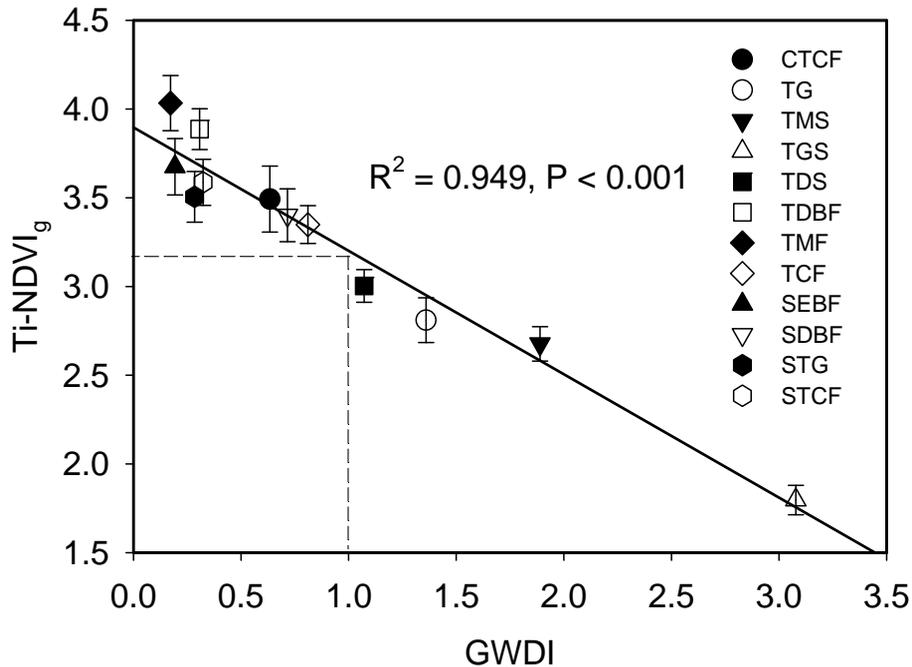


Fig. 7. Relationship between time-integrated growing season NDVI ($Ti-NDVI_g$) and growing season water deficit index (GWDI). Data are spatial averaged by vegetation types for the period of 1982–2006.

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