Dear the Editor of Biogeosciences,

We appreciate the valuable suggestions on our manuscript. We have attempted to address all the concerns of the editor and list our responses in the reply below. All referenced changes have been implemented in the revised manuscript. A marked-up manuscript version showing the changes made was also uploaded.

Sincerely yours,

Yongguang Zhang

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Comments to the Author:

This paper has been improved in the revision and is close to being acceptable for publication. Unfortunately Reviewer #3 did not find the manuscript to present novel information, and also found the text to be difficult to read. So, although the manuscript has been much improved from previous versions, it still requires some careful proofreading. The citations are generally a bit old and could be updated. Furthermore, the authors are encouraged to highlight the novel aspects of their work in a revision.

Response: Thank you for your positive comments. Based on the editor’s suggestions, we have carefully made some proofreading through the whole manuscript and added some more new references.

Meanwhile, to highlight the novel aspects of our work, we added some more information in the Introduction in Line 69-78 as ‘Although individual grassland or forest sites have been conducted for their response to climatic warming or extremes (Wu et al., 2011; Smith, 2011), there is still no consensus on how ecosystem production will respond to temperature extremes across biomes from arid grassland to forest. Furthermore, many comparison studies of cross-site used ecosystem production from a compilation of in situ measurements from long-term experimental sites (Huxman et al., 2004). However, the measuring procedures of vegetation production are not consistent across sites, and in some cases, not consistent over time at a given site (Sala et al., 1988), and this will result in some uncertainties. As a result, we are lacking generalizations about the regional behavior of terrestrial ecosystem with more hot temperature extreme regimes.’

We also explicitly clarified the objective of our study in Line 91-97 as ‘The primary objective of this study was to examine the response of vegetation production to hot temperature extremes, with particular focus on quantifying the direction and magnitude
of ANPP long-term response across biomes from semi-arid grassland to temperate forest.

We first assessed the changes of annual ANPP due to higher temperature extremes
across biomes. Then, we examined the link between temperature extremes and annual
ANPP after controlling the effects of precipitation and low temperature.

In the Conclusion, we emphasized that ‘Our study offers a generalization of the
functional response of ecosystem to hot extreme conditions predicted with climate change
across biomes in the natural climatic conditions. ... This study also clarifies the value of
long-term experimental sites together with continuing satellite-based observations such
as EVI in future studies.’

Specific comments:

Proofread all text including figure captions.

Response: We have carefully proofread through the whole manuscript including figure
captions as shown in the marked-up manuscript version. Please check out the revised
manuscript.

Line 38: This *trend* towards hot temperature...

Response: Corrected

Line 122-123: This refers to Figure 1 which appears to be on a log-log scale. However
the equation does not reflect the logarithmic nature of the relationship. Please clarify.
Also check the formatting of the equation, because the space in front of the decimals is
strange. And furthermore, are 4 decimals on the coefficients really significant?

Response: We changed Figure 1 to linear scale to be consistent with Eq. 1. The
formatting of the equation has been modified.

Line 133: with confidence (not confident)

Response: This phrase was removed.

Line 135: Please make sure to indicate whether you are referring to direct measurements
of ANPP vs satellite derived ANPP via iEVI. To use the terms interchangeably is not
valid.

Response: This sentence was removed. We also revised the Line 132-135 as ‘Therefore,
we assumed that the iEVI can be a reasonable surrogate for ANPP interannual
variability and provide consistent sensitivity across biomes ranging from arid grassland
to forest in our analyses.’
Line 173-177, note that Smith and Knapp have some important papers indicating the importance of precipitation on grassland productivity.

Response: We have added several more references and discussion in Line 178-182, and in Line 192.

Fig 1 caption, proofread “upper lower inset” should be “upper inset” also please indicate in the caption that it is a log-log scale

Response: Corrected. Please see the response to Line 122-13.

Reviewer #3

The manuscript "Contrasting responses of terrestrial ecosystem production to hot temperature extreme regimes between grassland and forest" presents an analysis of the effects of extreme temperatures on vegetation production across a range of biomes, narrowing contrasts between grasslands and forests. The paper is poorly written and could benefit from heavy editorial help before it can really be reviewed on the merits of the work. Much of the text describing the analyses and results is unclear and there is a general lack of detail that prevents a thorough assessment of the work.

Response: We disagree with Reviewer #3 who did not give any instructive and meaningful suggestions. Please see the response to the general comments of the editor.
Contrasting responses of terrestrial ecosystem production to hot temperature extreme regimes between grassland and forest

Running title: Response of ecosystem production to hot extremes

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ABSTRACT: During the past several decades, observational data has shown a faster increase in hot temperature extremes than the change in mean temperature. Increasingly high extreme temperatures are expected to affect terrestrial ecosystem function. The ecological impact of hot extremes on vegetation production, however, remains uncertain across biomes in natural climatic conditions. In this study, we investigated the effects of hot temperature extremes on vegetation production by combining MODIS EVI dataset and in situ climatic records during 2000 to 2009 from 12 long-term experimental sites across biomes and climate. Our results show that higher mean annual maximum temperatures (T_max) greatly reduced grassland production, and yet enhanced forest production after removing the effect of precipitation. The relative decrease in vegetation production was 16% for arid grassland and 7% for mesic grassland, and the increase was 5% for forest. We also observed a significantly positive relationship between interannual ANPP and T_max for forest biome (R^2 = 0.79, P < 0.001). This line of evidence suggests that hot temperature extremes lead to contrasting ecosystem-level response of vegetation production between grassland and forest biome. Given that many terrestrial ecosystem models use average daily temperature as input, predictions of ecosystem production should consider such contrasting responses to increasingly hot temperature extreme regimes associated with climate change.

Keywords: ANPP, Biomes, Hot Temperature Extremes, EVI, T_max
1. **INTRODUCTION**

The observed global temperature showed a warming of 0.85 (0.65 to 1.06) °C over the period of 1880 to 2012, and the number of warm days and nights has increased at the global scale (IPCC, 2013). Future temperature is expected to continue to warm more rapidly over land than ocean, and there will be more frequent hot and fewer cold temperature extremes over most land area (IPCC, 2013). Terrestrial ecosystems are strongly impacted by climate and climate change (Nemani et al., 2003), and hence, this trend towards hot temperature extremes would have important consequences on terrestrial ecosystems (IPCC, 2012). Numerous modeling and observational climate warming studies have shown the general enhancement of vegetation growth or increases in vegetation greenness in northern terrestrial ecosystems (e.g., Keeling, et al., 1996; Myneni, et al., 1997; Zhou et al., 2001; Neigh et al, 2008; Wu et al., 2011). However, knowing the general response of ecosystems tells us little about how the ecosystem in a particular location will respond or how different ecosystem responds to hot temperature extremes. For example, Peng et al. (2013) recently reported that the growing-season greenness was positively correlated with the maximum daily temperature ($T_{\text{max}}$) in northwestern North America and Siberia while negatively correlated in drier temperate regions such as western China, central Eurasia, central and southwestern North America.

Usually, field manipulated experiments were conducted to investigate the effects of climatic warming on ecosystem (Alward et al., 1999; Shaver et al., 2000; Wu et al., 2011). Such experimental manipulations are important to understand and quantify the individual contribution of climatic warming on vegetation growth by controlling other global change factors. However, these studies usually have been conducted either on an
individual ecosystem, or over short-term periods, which render the comparisons across biomes that may differ between regions and ecosystem difficult. A main problem with these experiments is that they do not incorporate the entire micro- and macro-environmental aspects of variable weather. In addition, the long-term responses of ecosystem function are difficult to capture in warming experiments most of which were short term (<5 years) (Wu et al., 2011). In other words, manipulated experiments are spatially and temporally restricted. The results from these manipulated studies are needed to understand in the context of long-term experiments in the natural field settings. An alternative to manipulated experiments is to analyze these effects on ecosystem processes in natural field settings with long-term measurements across biomes (Huxman et al., 2004).

Although individual grassland or forest sites have been conducted for their response to climatic warming or extremes (Wu et al., 2011; Smith, 2011), there is still no consensus on how ecosystem production will respond to temperature extremes across biomes from arid grassland to forest. Furthermore, many comparison studies of cross-site used ecosystem production from a compilation of in situ measurements from long-term experimental sites (Huxman et al., 2004). However, the measuring procedures of vegetation production are not consistent across sites, and in some cases, not consistent over time at a given site (Sala et al., 1988), and this will result in some uncertainties. As a result, we are lacking generalizations about the regional behavior of terrestrial ecosystem with more hot temperature extreme regimes.

The last decade has witnessed dramatic global warming: 9 of the 10 warmest years on record have occurred during the 21st century (NOAA, 2013). These conditions are
similar to those expected due to climate change (IPCC, 2013). In particular, the United States has warmed faster than the global rate since the late 1970s, and heat waves in 2005, 2006 and 2007 broke all-time records for high maximum and minimum temperature (NOAA, 2013). Therefore, this recent climatic condition provides an opportunity to study the functional response of biomes to hot temperature extremes with respect to future climate change.

In this study, we used a 10-year dataset of MODerate resolution Imaging Spectroradiometer (MODIS) Enhanced Vegetation Index (EVI) (Huete et al., 2002) as an indicator of aboveground net primary production (ANPP), in combination with field observations from 12 long-term experimental sites in the conterminous United States. The primary objective of this study was to examine the response of vegetation production to hot temperature extremes, with particular focus on quantifying the direction and magnitude of ANPP long-term response across biomes from semi-arid grassland to temperate forest. We first assessed the changes of annual ANPP due to higher temperature extremes across biomes. Then, we examined the link between temperature extremes and annual ANPP after controlling the effects of precipitation and low temperature.

2. MATERIALS AND METHODS

2.1. Study Sites and Meteorological Data

Twelve USDA experimental sites across the conterminous United States were used. These sites included different precipitation regimes and biomes representative of ecosystems ranging from arid grassland to temperate forest. They represent a broad range
of production, climatic and soil conditions, and life history characteristics of the
dominant species. At each site, a location was selected in an undisturbed vegetated area
of size at least 2.25 km × 2.25 km (Table 1). According to Köppen-Geiger climate
classification (Peel et al., 2007), arid grassland (DE, JE, WG, and SR) and Mediterranean
forest (CC) sites experience a climate with a dry season and are seasonally water-limited,
whereas mesic grassland (CP, SP, and LW) and temperate forest (LR, MC, BC and CF)
sites experience humid climate and can be temperature-limited.

The climate dataset used in this study was from in situ daily precipitation, maximum
and minimum air temperature measured at the local weather station representative of each
site from 1970-2009 except for JE, for which data was available from 1978-2009. Long-
term (40 years) in situ temperature datasets were used to identify climate extremes within
the past decade. In this study, we considered two extreme temperature indices. Maximum
temperature index (T_{max}) represents annual mean daily maximum temperature, and
minimum temperature index (T_{min}) represents annual mean daily minimum temperature.
Annual values were based on the hydrologic year extending from 1 October to 30
September. The interannual variability of temperature extremes was represented by the
anomaly, which was calculated as the departure of a given year from the mean of 1970-
2009 periods, divided by the standard deviation. Positive anomaly means higher T_{max}
above the long-term average, and vice versa for negative anomaly.

2.2. **Satellite Data**

We used satellite observations of the EVI from the MODIS as a proxy for annual
ANPP. The EVI dataset was derived from the MODIS land product subset (MOD13Q1)
with 16-day and 250-m resolutions for the period of 2000-2009. To compare EVI with in
situ climalc measurements, we averaged the EVI data over an area of ~2.25×2.25 km
(9×9 pixels) based on the coordinates for each site in Table 1. A total of 230 scenes
(23/year *10 years) was obtained for each of the 12 sites. In order to eliminate the noise
of low quality, cloud and aerosol contaminated pixels, a pixel-based quality assurance
(QA) control was applied to generate a less noisy time series dataset based on the quality
flag in MOD13Q1 product (Ponce-Campos et al. 2013). Then the software TIMESAT
was used to smooth the QA-filtered time series of EVI as well as to estimate the
vegetation parameters such as EVI integrals of the growing season (Jönsson & Eklundhl,
2004). The large integral of MODIS EVI measurements (referred to as iEVI hereafter)
over the whole year was used as our surrogate measure of ANPP (Fig. 1). The MODIS
iEVI has been used to quantify the dynamics of ANPP across biomes ranging from arid
grassland to forest (Zhang et al. 2013; Ponce-Campos et al. 2013). For this study, to
validate the relation between iEVI and annual ANPP for the dataset in this study, ground
measurements of ANPP (ANPP_G) during the period 2000-2009 were compiled for 9 sites
(53 years totally) across the United States (Table 2). A strong relationship (Eq.1) between
ANPP_G and the corresponding iEVI was derived across biomes for these long-term
experimental sites (Fig. 1):

\[
ANPP_G = 100.97 \times iEVI - 85.28
\]

\[R^2 = 0.90 \quad P < 0.001 \quad (n = 53)\]

It should be noted that Eq. 1 is a spatio-temporal relationship between ANPP_G and
iEVI across biomes. At the site scale, the temporal relationship between ANPP_G and iEVI
is not as strong as Eq.1, but the site-specific comparison with ANPP_G from the plot-scale
ground measurements at two sites in Table 1 (CP and JN) showed generally good
agreement during 2000-2009 periods (Fig. 1 inset, $R^2=0.70$, $P<0.01$) in spite of the scale differences between measurements of iEVI and ANPP$_G$. Hence iEVI could show the inter-annual variability of vegetation growth. On the other hand, the spatial correlation is also significantly positive between ANPP$_G$ and the corresponding iEVI as shown in Fig. 1 (inset) for the year of 2001 across biomes ($R^2=0.88$, $P<0.001$). Therefore, we assumed that the iEVI can be a reasonable surrogate for ANPP interannual variability and provide consistent sensitivity across biomes ranging from arid grassland to forest in our analyses.

2.3. **Data Analysis**

To investigate the sensitivity of ANPP to temperature extreme ($T_{\text{max}}$) across biomes, we compared the iEVI measured during years with extremely high temperatures with the mean iEVI of all other years during 2000-2009 for each site. Years with extremely high temperatures were defined as those for which the $T_{\text{max}}$ anomaly ≥1 or the maximum anomaly year when there is no anomaly > 1 during 2000-2009. Since both precipitation and temperature ($T_{\text{max}}$ and $T_{\text{min}}$) have limitations on vegetation production (iEVI) and they covary with one another, we also used partial correlation analysis to assess the relationship between iEVI and $T_{\text{max}}$ by removing the effects of precipitation and $T_{\text{min}}$. Partial correlation analysis is widely used to isolate the relationship between two variables by removing the effects of many correlated variables. A Duncan multiple range test was used to determine significant differences in temperature and iEVI among groups.

3. **Results and Discussion**
3.1. Long-term trends of the anomaly of $T_{\text{max}}$

Figure 2 shows the long-term trends of $T_{\text{max}}$ for the four biome types (Table 1). For desert grassland, annual mean maximum temperature increased by 1.66°C ($P<0.0001$) during the 40-year period from 1970 to 2009 (Fig. 2). For mesic grassland, $T_{\text{max}}$ increased by 1.21°C ($P<0.0001$) during 1970-2009 (Fig. 2). There was no significant trend for $T_{\text{max}}$ for temperate forest sites. In contrast, $T_{\text{max}}$ decreased slightly for Mediterranean forest even though not statistically significant for the whole 40-year period (Fig. 2, $P>0.1$).

However, Figure 2 shows that there were two different periods for $T_{\text{max}}$ at the Mediterranean forest site (CC in Table 1). $T_{\text{max}}$ increased by 1.86 °C ($P<0.0001$) before the earlier 1990s but then dropped dramatically by -3.46°C ($P<0.0001$) after 1992 (Fig. 2).

The temperature rises observed in desert and mesic grassland are consistent with the observation in the southwestern US and the Great Plains (USGCRP, 2009; MacDonald, 2010). However, the unchanged annual mean $T_{\text{max}}$ in the temperate forest sites is not consistent with the regional temperature rise in the eastern US (USGCRP, 2009).

3.2. Contrasting responses to $T_{\text{max}}$ between grassland and forest biomes

Figure 3 shows that annual iEVI was significantly correlated with $T_{\text{max}}$ ($R^2 = 0.79$, $P < 0.001$) across the temperature gradient of forested sites, and a stronger relation was identified between the decadal maximum $T_{\text{max}}$ and corresponding iEVI ($R^2 = 0.95$, $P < 0.005$; Fig. 3). Because the slopes of these two relations are not significantly different (F-test, $P > 0.05$; Fig. 3), this confirms that forest production increases with elevated temperature across temperature gradient (Magnani et al., 2001; Wullschleger et al., 2003; Huxman et al., 2004). This also suggests that the decadal maximum $T_{\text{max}}$ may not affect
the overall sensitivity of interannual ANPP to mean annual temperature. Figure 3 also
suggests that maximum temperature can explain 80% of the variability of vegetation
production across these forest sites. For the grassland sites, however, there is no
significant correlation between mean annual iEVI and $T_{\text{max}}$ ($R^2 = 0.05, P = 0.64$). This is
consistent with that vegetation production is more controlled by water availability for
grasslands in arid and semi-arid regions and interannual ANPP was related to soil
moisture variability (Knapp and Smith, 2001; Knapp et al., 2002; Cherwin and Knapp,
2012). On the other hand, forest biome is more temperature-limited on productivity,
particularly in regions that are not constrained by water, and climatic warming can
stimulate vegetation growth through enhancing summer photosynthesis (Churkina and
Running, 1998; Nemani et al., 2003; Piao et al., 2007).

Within sites, however, the interannual iEVI was not correlated with interannual
variations in $T_{\text{max}}$ at any forest site ($P > 0.05$). The differences between spatial and
temporal patterns of forest ANPP responses to $T_{\text{max}}$ reflect different underlying
mechanisms at regional and local scale. The regional pattern of forest ANPP is
determined primarily by temperature, while the temporal pattern for a given ecosystem is
most likely affected by interactions between temperature and nutrient availability.
Several studies have found limited forest production response to warming alone, but
significant response to warming with fertilization (Parsons et al., 1994; Press et al., 1998;
Rustad et al. 2001; Strömgren and Linder 2002; Xu et al. 2011).

Among biomes, higher $T_{\text{max}}$ with anomaly > 1 had a direct negative effect on
vegetation production in grassland ecosystems, especially for arid grassland, but a
positive effect on forest ecosystems (Fig. 4; $P<0.05$). On average, the decreases of iEVI
were up to 7% for mesic grassland, and 16% for arid grassland (Fig. 4, inset). This may be attributed to the negative effects of warming temperatures on water availability through enhanced evapotranspiration (Seager and Vecchi, 2010). In contrast, higher $T_{\text{max}}$ enhanced mean annual iEVI by 5% for both temperate and Mediterranean forest sites (Fig. 4). There were larger, positive responses of ANPP to higher temperature for forested sites in colder environments which are the sites of BC and MC (Fig. 4).

The results stated above demonstrated the effects of hot temperature extreme on vegetation production without considering the confounding effects of other variables such as precipitation and $T_{\text{min}}$. There is a highly positive correlation between $T_{\text{max}}$ and $T_{\text{min}}$. To isolate the role of $T_{\text{max}}$ from precipitation and $T_{\text{min}}$, we alternately investigated the apparent responses of iEVI to $T_{\text{max}}$ with partial correlation analyses to remove the confounding effects. Figure 5 shows how interannual iEVI respond to variations of interannual $T_{\text{max}}$ across sites. After removing the effects of $T_{\text{min}}$ and precipitation in the partial correlation analyses, the individual $T_{\text{max}}$ interannual changes again show the contrasting effects on the interannual iEVI between grassland and forest sites (Fig. 5).

For desert grassland sites, interannual iEVI is negatively correlated with interannual $T_{\text{max}}$ with statistical significance at the 0.05 level ($R = 0.35$). There is no significantly partial correlation between $T_{\text{max}}$ and annual iEVI for mesic grassland sites (Fig. 5), implying little or no response of ecosystem production to $T_{\text{max}}$ after removing the effects of $T_{\text{min}}$ and precipitation. In contrast, interannual $T_{\text{max}}$ variations exhibits significantly positive partial correlations with interannual iEVI changes for temperate forest sites ($R = 0.57; P < 0.001$). For the Mediterranean forest site of Caspar Creek, it also shows positive partial correlations between interannual $T_{\text{max}}$ and iEVI but without statistical significance ($R =$
0.49; P = 0.22) due to fewer data set from only site. This opposite response of interannual
iEVI to T$_{\text{max}}$ between wet and dry temperate regions of the North America agrees well
with a recent global study (Peng et al., 2013), in which they showed remarkable spatial
patterns of the partial correlations between growing-season greenness and T$_{\text{max}}$ over
Northern Hemisphere.

In all, the two approaches in the present study suggest that hot temperature extreme
imposed a negative effect on vegetation production for grassland, especially desert
grassland in the southwestern US, while it has a positive effect on forest (Fig. 4 and 5).
This difference in response between grassland versus forest may be related to the
adaptations of dominant species in terms of their response to warming temperature.
Higher T$_{\text{max}}$ and warming climate would imply drier soils through increased evaporative
demand (Manabe and Wetherald, 1986) and decreased production due to decreases in
stomatal conductivity, down-regulation of the photosynthetic processes and increased
allocation to roots in arid and semi-arid regions (Chaves et al., 2002). Our results agree
well with the results of previous studies (Braswell et al., 1997; Piao et al., 2006; Munson
et al., 2012) that higher temperature may have directly negative effects on vegetation
growth in arid and semi-arid grassland. With more atmospheric carbon dioxide in the
future, however, such warming desiccation effects would be likely modified at least for
arid grasslands as shown by Morgan et al. (2011). For forest, the positive effect is
consistent with the results reported by Rustad et al. (2001) and McMahon et al. (2010)
for ANPP in ecosystem warming experiments that higher T$_{\text{max}}$ would have a positive
impact on forest production (Boisvenue and Running, 2006). Previous studies have also
shown that higher temperatures favor tree growth by enhancing photosynthesis (Lukac et
and nutrient uptake (Weih and Karlsson, 2002), especially in sites where trees were not typically constrained by moisture stress. Thus, these contrasting responses to $T_{\text{max}}$ in different ecosystems could have different effects on regional vegetation carbon uptake (Braswell et al., 1997). It should be noted that, however, due to data limitations, only 12 sites were used in this study. We need more data from all terrestrial ecosystems to test whether the contrasting effect of temperature extremes is a general behavior on forest and grassland ecosystem. Furthermore, the results reported here may be temporal, and the long-term impact of temperature extremes on ecosystem functional integrity across biomes is yet unknown. The ongoing field measurements of carbon flux and meteorological data from eddy covariance flux method for different ecosystem may provide an opportunity to validate the assumption in this study.

4. Conclusions

Understanding how vegetation production responds to extreme warm temperature regimes is crucial for assessing the impacts of climate change on terrestrial ecosystem. Recent breaking-record high temperature in the contiguous US provides the opportunity to study such effect. Our study offers a generalization of the functional response of ecosystem to hot extreme conditions predicted with climate change across biomes in the natural climatic conditions. By using satellite and in situ meteorological data, we found a contrasting response of terrestrial ecosystem to extreme warm temperature anomalies between grassland and forest biomes in natural settings. The opposite direction and magnitude of response indicates different sensitivities across ecosystems to hot temperature extremes. Recent study shows that there is a continuous increase of hot extremes over land, despite the slowed rate of increase in annual global mean temperature.
Hence, the sensitivity of ecosystem production in response to hot extremes across biomes found here has important implications. Current terrestrial ecosystem models usually utilize daily mean or monthly temperature data as input, and hence they may neglect the response of vegetation to extreme warm temperature (T$_{max}$). To some extent, the effects of hot extremes are more relevant for climate change impacts than global mean temperature on ecosystems (IPCC, 2012; 2013). Hence, this work further strengthens our understandings of the ecosystem-level response to extreme warm temperature across biomes. This study also clarifies the value of long-term experimental sites together with continuing satellite-based observations such as EVI in future studies. This compelling result in a natural setting at the ecosystem level should play a role in future climate change impacts studies.

ACKNOWLEDGMENTS

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information managers, scientists and technicians responsible for measuring ANPP at the LTER sites. The authors also gratefully acknowledge the valuable suggestions made by Dr. Christopher Kyba at Freie Universität Berlin.

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Table 1. Descriptions of the sites in this study.

Table 2. Sites with “in-situ” ANPP measurements within the period of 2000-2009 for validation with iEVI.
Figure 1. Relationship between annual ground measurements of ANPP (ANPP$_G$) and the corresponding iEVI derived from MODIS data during 2000-2009 periods for 9 selected sites across biomes ($R^2=0.90$, $P<0.0001$; Table 2). The upper inset shows the relationship at two sites of CP and JE ($R^2=0.63$ and 0.74, respectively, $P<0.01$). The lower inset shows the relationship between ANPP$_G$ and iEVI for the year 2001 across the 9 sites ($R^2=0.88$, $P<0.001$).

Figure 2. Long-term trends of the anomaly of $T_{\text{max}}$ during 1970-2009 for different biome types. DG, arid grassland sites (DE, JE, WG, SR, and CP in Table 1); MG, mesic grassland sites (SP and LW in Table 1); TF, temperate forested sites (LR, MC, BC, and CF in Table 1); MF, Mediterranean forested site (CC). The dotted line shows the year of 2000 for the starting year of the MODIS EVI dataset.

Figure 3. Relationship between iEVI and $T_{\text{max}}$ and their maximum-year $T_{\text{max}}$ -iEVI relationship for 5 forested sites. Dotted line shows the linear relationship between maximum-year $T_{\text{max}}$ and the relevant iEVI for all the sites.

Figure 4. Comparison of iEVI differences between the extreme years and average of all other years of $T_{\text{max}}$ across sites. Extreme years mean that the years of $T_{\text{max}}$ anomaly is ≥1. The inset denotes the average differences by biome type. DG, arid grassland sites (DE, JE, WG, and SR in Table 1); MG, mesic grassland sites (CP, SP, and LW in Table 1); TF, temperate forested sites (LR, MC, BC, and CF in Table 1); MF, Mediterranean forested site (CC). Different letters indicate significant differences at $P < 0.05$.

Figure 5. Partial correlations between iEVI and $T_{\text{max}}$ after controlling for $T_{\text{min}}$ and precipitation across sites. * Statistically significant at the 95% ($P<0.05$) level; ** statistically significant at the 99.9% ($P<0.001$) level.
Table 1 Descriptions of the sites in this study.

<table>
<thead>
<tr>
<th>Site and location</th>
<th>Latitude (degree)</th>
<th>Longitude (degree)</th>
<th>Land cover</th>
<th>MAP (mm)**</th>
<th>Max. Temperature (°C)</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert Exp. Range, UT</td>
<td>38.547</td>
<td>-113.712</td>
<td>Arid grassland</td>
<td>216 (65)</td>
<td>19 (1.1)</td>
<td>DE</td>
</tr>
<tr>
<td>Jornada Exp. Range, NM</td>
<td>32.589</td>
<td>-106.844</td>
<td>Arid grassland</td>
<td>242 (78)</td>
<td>25 (0.7)</td>
<td>JE</td>
</tr>
<tr>
<td>Walnut Gulch Exp. Watershed, AZ</td>
<td>31.736</td>
<td>-109.938</td>
<td>Arid grassland</td>
<td>311 (85)</td>
<td>25 (1.0)</td>
<td>WG</td>
</tr>
<tr>
<td>Santa Rita Exp. Range, AZ</td>
<td>31.846</td>
<td>-110.839</td>
<td>Arid grassland</td>
<td>447 (129)</td>
<td>29 (0.7)</td>
<td>SR</td>
</tr>
<tr>
<td>Central Plains Exp. Range, CO</td>
<td>40.819</td>
<td>-104.748</td>
<td>Arid grassland</td>
<td>381 (91)</td>
<td>16 (1.4)</td>
<td>CP</td>
</tr>
<tr>
<td>Southern Plains Exp. Range, OK</td>
<td>36.614</td>
<td>-99.576</td>
<td>Mesic grassland</td>
<td>586 (153)</td>
<td>22 (0.9)</td>
<td>SP</td>
</tr>
<tr>
<td>Little Washita Creek, OK</td>
<td>34.918</td>
<td>-97.956</td>
<td>Mesic grassland</td>
<td>796 (195)</td>
<td>24 (1.2)</td>
<td>LW</td>
</tr>
<tr>
<td>Little River Watershed, GA</td>
<td>31.537</td>
<td>-83.626</td>
<td>Temperate Conifer Forest</td>
<td>1148 (257)</td>
<td>25 (0.6)</td>
<td>LR</td>
</tr>
<tr>
<td>Mahatango Creek, PA</td>
<td>40.731</td>
<td>-76.592</td>
<td>Temperate Broadleaf Forest</td>
<td>1058 (179)</td>
<td>16 (0.9)</td>
<td>MC</td>
</tr>
<tr>
<td>Cutfoot Experimental Forest, MN</td>
<td>47.4264</td>
<td>-94.0141</td>
<td>Temperate Broadleaf Forest</td>
<td>665(101)</td>
<td>11(1.1)</td>
<td>CF</td>
</tr>
<tr>
<td>Bent Creek Exp. Forest, NC</td>
<td>35.500</td>
<td>-82.624</td>
<td>Temperate Mixed forest</td>
<td>1227 (239)</td>
<td>19 (0.6)</td>
<td>BC</td>
</tr>
<tr>
<td>Caspar Creek, CA</td>
<td>39.337</td>
<td>-123.748</td>
<td>Mediterranean forest</td>
<td>1054 (301)</td>
<td>16 (0.7)</td>
<td>CC</td>
</tr>
</tbody>
</table>

* Precipitation and temperature for the 40-year period 1970-2009 were available for all sites except JE, for which data were available for a 32-year period 1978-2009. **Average annual sum of precipitation (MAP) and average annual mean max temperature with standard deviation in parentheses.
Table 2 Sites with “in-situ” ANPP measurements within the period of 2000-2009 for validation with iEVI.

<table>
<thead>
<tr>
<th>Site</th>
<th>Biome and Location</th>
<th>Period</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cedar Creek LTER</td>
<td>Grassland, Minnesota</td>
<td>2000-2007</td>
<td><a href="http://www.lternet.edu/sites/">http://www.lternet.edu/sites/</a></td>
</tr>
<tr>
<td>Ohio Hills FFs</td>
<td>Mixed Forest, Ohio</td>
<td>2001-2002</td>
<td>Chiang et al. 2008</td>
</tr>
<tr>
<td>University of Michigan Biological Station</td>
<td>Deciduous broadleaf forest, Michigan</td>
<td>2000-2006</td>
<td>Gough et al. 2008</td>
</tr>
</tbody>
</table>
Figure 1. Relationship between annual ground measurements of ANPP (ANPP\(_G\)) and the corresponding iEVI derived from MODIS data during 2000-2009 periods for 9 selected sites across biomes (\(R^2=0.90, P<0.0001\); Table 2). The upper inset shows the relationship at two sites of CP and JE (\(R^2=0.63\) and 0.74, respectively, \(P<0.01\)). The lower inset shows the relationship between ANPP\(_G\) and iEVI for the year 2001 across the 9 sites (\(R^2=0.88, P<0.001\)).
Figure 2. Long-term trends of the anomaly of $T_{\text{max}}$ during 1970-2009 for different biome types. DG, arid grassland sites (DE, JE, WG, SR, and CP in Table 1); MG, mesic grassland sites (SP and LW in Table 1); TF, temperate forested sites (LR, MC, BC, and CF in Table 1); MF, Mediterranean forested site (CC). The dotted line shows the year of 2000 for the starting year of the MODIS EVI dataset.
Figure 3. Relationship between iEVI and $T_{\text{max}}$ and their maximum-year $T_{\text{max}}$-iEVI relationship for 5 forested sites. Dotted line shows the linear relationship between maximum-year $T_{\text{max}}$ and the relevant iEVI for all the sites.
Figure 4. Comparison of iEVI differences between the extreme years and average of all other years of $T_{\text{max}}$ across sites. Extreme years mean that the years of $T_{\text{max}}$ anomaly is $\geq 1$. The inset denotes the average differences by biome type. DG, arid grassland sites (DE, JE, WG, and SR in Table 1); MG, mesic grassland sites (CP, SP, and LW in Table 1); TF, temperate forested sites (LR, MC, BC, and CF in Table 1); MF, Mediterranean forested site (CC). Different letters indicate significant differences at $P < 0.05$. 
Figure 5. Partial correlations between iEVI and $T_{\text{max}}$ after controlling for $T_{\text{min}}$ and precipitation across sites. * Statistically significant at the 95% (P<0.05) level; ** statistically significant at the 99.9% (P<0.001) level.