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Response of the water use efficiency of natural vegetation to drought in Northeast China

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Abstract: Drought has become a problem that is universally faced by global terrestrial ecosystems. Northeast China is located in a region sensitive to global climate changes, and one of the main impacts of climate changes in Northeast China is manifested as drought in growing seasons. This study analyzes the spatio-temporal evolution law of the water use efficiency (WUE) of the main natural vegetation (i.e., cold-temperate coniferous forests, temperate pine-broad-leaved mixed forests, warm-temperate deciduous broad-leaved forests, and grasslands) in Northeast China based on public MODIS data products, including MCD12Q1, MOD15A2H, MOD16A2, and MOD17A3H, and meteorological data from 2002 to 2013. The influence of drought events on the WUE of different vegetation types and their response to drought events are also investigated. The study findings are as follows: (1) drought in Northeast China frequently occurs in the regions stretching from 114.55°E to 120.90°E, and the percentage of drought area among the forests is lower than that among the grasslands during these years; (2) the annual average WUE of the natural vegetation ranges from 0.82 to 1.08 $C/kg^{-1}H_2O$, and the WUE of forests (0.82 to 1.08 $C/kg^{-1}H_2O$) is universally higher than that of grasslands (0.84 to 0.99 $C/kg^{-1}H_2O$); (3) in 2008, the regions where the WUE in drought conditions is higher than that in normal water conditions account for 86.11% of the study area, and a significant linear positive correlation is found between the WUE in drought conditions and the WUE in normal water conditions, whereas the degree of drought does not influence the WUE of the natural vegetation in an obviously linear manner; and (4) the WUE for the cold-temperate coniferous forests and temperate pine-broad-leaved mixed forests with a high ET or low NPP is more likely to rise in drought conditions; the WUE for the grasslands with a low Evapotranspiration (ET), Net Primary Production (NPP), and Leaf Area Index (LAI) is more likely to rise in drought conditions; and the ET, NPP, and LAI have no significant influence on the WUE for the warm-temperate deciduous broad-leaved forests in drought conditions. This study contributes to improving the evaluation of the influence of drought on natural ecosystems.

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1 Introduction

Drought has a far-reaching influence on global terrestrial ecosystems (Yu *et al*., 2016). Both the frequency and intensity of drought increase as global climate changes are aggravated (Houghton, 1995). Therefore, the ecological academia has paid great attention to the response and adaptability of terrestrial ecosystems to drought, and studied this issue from different angles of view. Regarding the response of terrestrial ecosystems to drought, studies have reached the following consensus: (1) drought causes a decline in stomatal conductance, maximum photochemical efficiency, and quantum yield, thereby weakening the photosynthesis of plants (Hernandez *et al*., 2016; Vanlerberghe *et al*., 2016) and reducing the GPP of terrestrial ecosystems (Joo *et al*., 2016; Wang *et al*., 2017); (2) drought causes a decline in the activity of metabolic enzymes of certain plants, thereby weakening the respiratory action of their aboveground and underground parts (Zhang *et al*., 2017; Hasibeder *et al*., 2015); and (3) the respiratory action of soil microbes calls for an optimal range of moisture content, hence, the influence of drought on soil respiration is somewhat different. Drought has a negative influence on soil respiration across the world (Raich *et al*., 2002).

The response of terrestrial ecosystems to drought is mainly studied by two types of methods, namely experimental and model simulations. Most of the experimental simulation methods ascertain the response of plants to water shortage through a simulation experiment on water controlling (Hoover *et al*., 2017; Ledger *et al*., 2011). Such methods can obtain accurate experimental data, which can be used to study the mechanism of the response of plants to drought. The current experimental simulation methods are mainly used to study grasslands and farmlands, but seldom used to study forest ecosystems, because of the limitations in the plant growth cycle, degree of sensitivity of plants to drought, and experimental equipment. In addition, such methods are only applicable within a small scope. Therefore, extending the applicable objects of research conclusions from individuals or groups to ecosystems is somewhat challenging. Based on a biogeochemical model, model simulation methods mainly simulate the influence of drought on the productivity of terrestrial ecosystems by adjusting the rainfall variable (PaiMazumder *et al*., 2016; Shiogama *et al*., 2013). Such methods can largely study the influence of drought on terrestrial ecosystems. However, most of these methods overlook the adaptability of terrestrial ecosystems to water shortage. Therefore, research conclusions have a certain deviation from actual ones. To address this problem, advanced remote sensing technologies can be used to inversely analyze various indices on terrestrial ecosystems, including carbon flux indices (e.g., Gross Primary Productivity (Ruehr *et al*., 2014) and Net Primary Productivity (Zhang *et al*., 2014)), biomass indices (e.g., Normal Differential Vegetation Index (Mutiibwa *et al*., 2013), Enhanced Vegetation Index (Aulia *et al*., 2016), and Leaf Area Index (Chakroun *et al*., 2014)), water utilization indices (e.g., Water Use Efficiency (Gang *et al*., 2016; da Silva *et al*., 2017)), indices used to measure the carbon sequestration and conversion capabilities (e.g., CUE (Esmaeilpour *et al*., 2016; Malone *et al*., 2016)), and certain models (Limousin *et al*., 2015; Sawada *et al*., 2014). These indices can be used to discuss the response of terrestrial ecosystems to drought. To some extent, this offsets the deficiencies of experimental and model simulations and opens a new door for studying the response of terrestrial ecosystems to drought.

Northeast China is characterized by a vast territory, a complex topography, a unique vegetation distribution, a distinctive temperature and humidity, and integrated geographical regions. Moreover, Northeast China is also located in a region sensitive to global climate changes (Zhao *et al.*, 2013). Today, Northeast China has become a hot spot for the research on global climate changes and ecogeographic process. One of the main impacts of climate changes on Northeast China is manifested as drought in growing seasons. Research data shows that the spatial distribution of drought in Northeast China is characterized by "severe in the west and slight in the east" (Xi *et al.*, 2016). For over nearly 50 years, the arid and semi-arid boundary overall tends to extend eastwards and southwards (Wang *et al.*, 2013), and drought is likely to be more severe in the forthcoming 30 years (Lu *et al.*, 2016; Ma *et al.*, 2013). Therefore, studying the response of the natural vegetation in Northeast China to drought is of great importance because it will provide a certain reference for formulating a regional sustainable development strategy, which involves issues, such as natural vegetation recovery, rational utilization of regional natural resources, and biodiversity protection. Many studies were performed in this regard. Yang Liu (2015) studied the influence of drought on the water parameters of *Larix gmelinii* by simulating the drought conditions through a water controlling experiment. Li *et al.* (2012) studied the biochemical changes of *Taxus cuspidata* in drought and rehydration conditions. By virtue of remote sensing technologies, Wang *et al.* (2016) studied the correlation between the standardized precipitation evapotranspiration index and the normalized difference vegetation index and interpreted the influence of drought on the vegetation growth from a meteorological perspective. However, their study did not consider the changes in the transpiration of plants in drought conditions, thereby ignoring the adaptability of plants to drought.

Drought inhibits the carbohydrate cycle process of ecosystems. As the productivity index of plants in certain water conditions, the WUE reflects the capability and the sensitivity of ecosystems to maintain normal production in certain water conditions. Furthermore, the WUE connects a biological process (e.g., photosynthesis and respiration) and a physical process (e.g., evapotranspiration) during the carbohydrate cycle of ecosystems (Schoo *et al.*, 2017; Anower *et al.*, 2017). In view of this, the WUE has a unique advantage in studying the response of ecosystems to drought. This study addresses the above-mentioned problem by summarizing previous research findings and acquiring the research data newly added in the last decade or so. The study object is the natural vegetation of Northeast China. This study uses the average WUE during many years based on MODIS data products and the Self-calibrating Palmer Drought Severity Index (scPDSI) to evaluate the response to drought, analyze the spatio-temporal evolution law of productivity of the natural vegetation in Northeast China since 2000, and study the quantitative influence of drought events on the productivity of natural vegetation and the response of natural vegetation to drought events. This study intends to improve the ability of evaluating the influence of drought on natural ecosystems.

2 The study area

Northeast China comprises three provinces of Heilongjiang, Jilin, and Liaoning, and some regions, including cities of Chifeng, Tongliao, Hulun Buir, and Xing'an League, in the east of Inner Mongolia Autonomous Region (Wang *et al.*, 2006). Northeast China stretches from

111.15°E to 135.09°E and from 37.95°N to 53.56°N. Its north borders on Russia; its south is adjacent to the Yellow Sea and Bohai Sea; its east and north are surrounded by the Yalu River, Tumen River, Wusuli River, and Heilongjiang River; and its west borders on Mongolia. Northeast China covers a total area of 787,000 km^2. The Northeast China territory includes the Greater Khingan Mountains, Lesser Khingan Mountains, Changbai Mountains, and Northeast China Plain (comprising the Songliao Plain, Liaohe Plain, and Three River Plain). Its altitude ranges from 2 to 2,667 m. Northeast China is dominated by a temperate monsoon climate, specifically cold and dry in winter and hot and rainy in summer. The annual average temperature over the past 30 years (1981 to 2010) has ranged from –4.08 °C to 11.34 °C. The annual rainfall ranges from 199.53 mm to 1170.60 mm. The daily average sunshine duration ranges from 5.26 h to 9.21 h.

Northeast China falls in the Eurasian forest–grass plant subregion and the China–Japan forest plant subregion. Cold-temperate coniferous forests, temperate pine-broad-leaved mixed forests, warm-temperate deciduous broad-leaved forests, and vast grasslands can be found in the Northeast China territory (Xu *et al*., 1986). Cold-temperate coniferous forests comprise frost-resisting evergreen or deciduous coniferous trees, and are a type of zonal vegetation in the north of the Greater Khingan Mountains. They are distributed from 50°N to 53°N and at the altitude of 300 to 1,400 m. Temperate pine-broad-leaved mixed forests comprise evergreen needle-leaved trees, deciduous needle-leaved trees, and deciduous broad-leaved trees. They are distributed in the south of the Greater Khingan Mountains, and most parts of the Lesser Khingan Mountains and Changbai Mountains, or specifically distributed from 40°N to 50° and at the altitude of 100 to 1600 m. Meanwhile, warm-temperate deciduous broad-leaved forests are distributed within a small area, specifically only in the regions south of the Changbai Mountains below an altitude of 500 m. Grasslands are mainly distributed inside Inner Mongolia located in the west of Northeast China, or specifically from 41°N to 50°N and from 110°E to 125°E at the altitude of 150 to 1300 m.

3 Data source and processing

3.1 Geographic information data

The digital elevation model (DEM) is a Shuttle Radar Topography Mission product (V4.1) with a spatial resolution of 90 m. The DEM data is available from the international scientific data mirroring website (http://www.gscloud.cn) of the Computer Network Information Center in the Chinese Academy of Sciences.

The data on the prefecture/provincial-level administrative division is available from the basic geographic information (scale: 1:250,000) released by the China Meteorological Administration. A topological check was conducted for all data.

3.2 Remote sensing data

The remote sensing data used in this study, except for the MOD16A2 data product available from the Numerical Terradynamic Simulation Group of The University of Montana, are all available from the DOS data center of The Land Processes Distributed Active Archive Center in NASA. All remote sensing data (e.g., image stitching, resampling (unified spatial resolution: 500 m), and projection transformation (sinusoidal projection is transformed into longitude-latitude projection)) were preprocessed using the MODIS Reprojection Tool (MRT 4.0) software. The time range was from 2002 to 2013, and the spatial range was Northeast China.

3.2.1 MCD12Q1 data product

This study extracted the data on the natural vegetation distribution in the study area based on the classification results under the IGBP Global Vegetation Classification Scheme specified by the MCD12Q1 data product (land cover classification product) of the MODIS. The original spatial resolution of the data was 500 m.

The MCD12Q1 data product tried to control the errors in classification by various means (e.g., introducing the surface temperature variable and using the data of the recent three years), but it still encountered certain difficulties in distinguishing the similar land types (Friedl *et al*., 2010). In this study, the classification results of the MCD12Q1 data were combined into forests, shrublands, grasslands, wetlands, and non-natural vegetation, including urban lands, farmlands, waters, and snowfields, because the changes in the vegetation types will largely influence the degree of response of plants to climate changes. Therefore, this study only retained the natural ecosystems, in which the vegetation types were not changed during 2002 to 2013, for use as the study object. Figure 1 shows the distribution of the study object. The shrublands and the wetlands in the study area accounted for a very small proportion (≤0.01%). Therefore, this study only discussed the response of forests and grasslands to drought. The forests of Northeast China were classified herein into cold-temperate coniferous forests, temperate pine-broad-leaved mixed forests, and warm-temperate deciduous

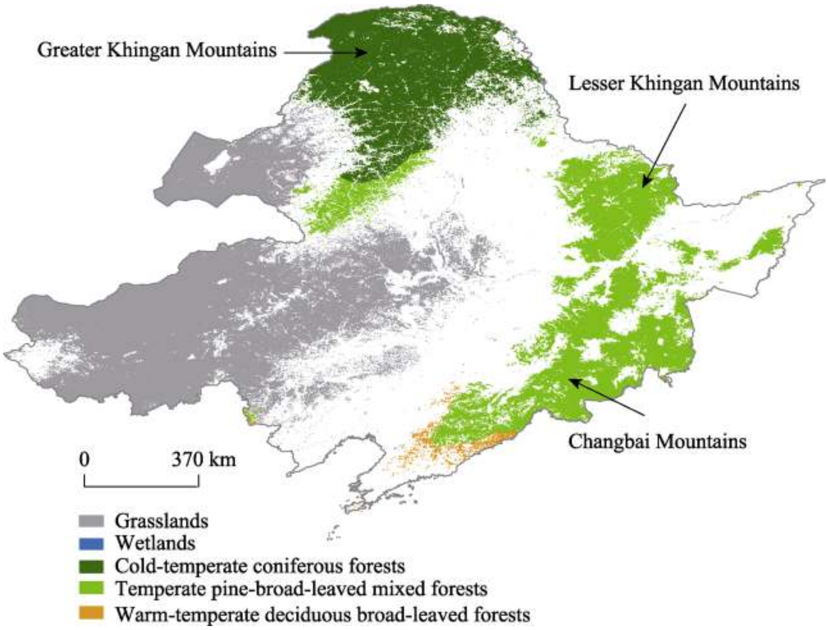


Figure 1 Natural vegetation distribution in Northeast China. The white areas represent the non-vegetation regions and the regions with changes in land cover types from 2000 to 2013. The vegetation regions are arranged in a descending order as follows: grasslands (accounting for 20.45% of the total area of Northeast China), temperate pine-broad-leaved mixed forests (11.19%), cold-temperate coniferous forests (7.22%), warm-temperate deciduous broad-leaved forests (0.32%), and wetlands (<0.01).

broad-leaved forests according to the Chinese vegetation regionalization data available from the Data Center for Resources and Environmental Sciences in the Chinese Academy of Sciences (http://www.resdc.cn).

3.2.2 MOD15A2H data product

The leaf area index (LAI) is an important characteristic index of vegetation growth (Iio *et al.*, 2014). This study selects the MOD15A2H data product (MODIS/Terra Leaf Area Index/FPAR) to analyze the response of the vegetation growth to climate changes. The data is an eight-day synthetic product with an original spatial resolution of 500 m. The LAI is a dimensionless index. The data incorporates the fraction of photosynthetically active radiation (FPAR) and the LAI. Compared with the MOD15A2, the MOD15A2H uses the L2G-lite apparent reflectance instead of the MODIS apparent reflectance product (MODAGAGG). In the calculation process, the MOD15A2H cites the improved multi-year land cover classification product, thereby improving the spatial resolution from 1 km to 500 m (Myneni *et al.*, 2015).

3.2.3 MOD16A2 data product

Evapotranspiration (EI) is an important link in the water migration in the soil–plant–atmosphere continuum (Hobbins *et al.*, 2001). This study used the MOD16A2_MONTHLY data product (MODIS Global Evapotranspiration Project) to analyze the response of the EI of ecosystems to climate changes. The data is a part of the NASA/EOS program and intends to monitor the EI of the global land surface through satellite remote sensing. The data is a monthly synthetic product with an original spatial resolution of 1 km (unit: 0.1 mm/month). The data product uses an improved ET algorithm (Mu *et al.*, 2011) to synthesize monthly data based on the calculated eight-day data.

3.2.4 MOD17A3H data product

The net primary productivity (NPP) is an important part of the carbon cycle on the Earth surface. It is also a characteristic index of the quality of terrestrial ecosystems (Murray *et al.*, 2016). This study used the MOD17A3H data product (MODIS/Terra Net Primary Production) to analyze the spatio-temporal characteristics of the carbon allocation of ecosystems. The data is an annual synthetic product with an original spatial resolution of 500 m (unit: $\mathrm{kg \cdot C/m^2}$). Compared with the MOD17A3, the MOD17A3H updates the Biome Property Look Up Tables, uses the meteorological data of the updated Global Modeling and Assimilation Office, and improves the spatial resolution from 1 km to 500 m (Running *et al.*, 2015). The data passed the test conducted by the eddy covariance flux towers distributed in different climate zones and biozones (Malone *et al.*, 2016; Turner *et al.*, 2006; Cracknell *et al.*, 2015). Therefore, this study no longer verified the accuracy of the MOD17A3H data product.

3.3 scPDSI data

This study selected the global monthly scPDSI data product to analyze the drought-wet changes of the study area and their influence on ecosystems during 2002 to 2013. The data is available from the rainfall and drought data set (http://www.cru.uea.ac.uk/) edited by the Climatic Research Unit in the University of East Anglia (UEA). Its spatial resolution is 50 km, and the data is dimensionless. The value range is [−5.0, 5.0]. Compared with the early PDSI, the scPDSI is more suitable for diverse climatic types, and has a greater advantage in detecting extremely dry or wet conditions (Wells *et al.*, 2004). With reference to the scPDSI-based drought–wet grading criteria specified by Wang Zhaoli (2016), this study combined the drought–wet grades as needed and specified the following drought–wet grades: drought (scPDSI < -1), normal ($-1.0 \leqslant$ scPDSI < 1.0), and wet ($1.0 \leqslant$ scPDSI).

3.4 WUE

The WUE is an index used to reflect the water absorption and utilization efficiency of plants. It is also an important variable that connects the carbon cycle and the water cycle of the vegetation ecosystem (Niu *et al.*, 2011). This study used the model proposed by Rosenberg *et al.* (1983) to calculate the WUE, thereby measuring the amount of organic carbon that can be sequestrated by evapotranspiring 1 kg water on a plant per unit area ($\mathrm{gC/kg^{-1}H_2O}$). The WUE can be expressed as follows:

$$\mathrm{WUE} = \mathrm{NPP}/\mathrm{ET}$$

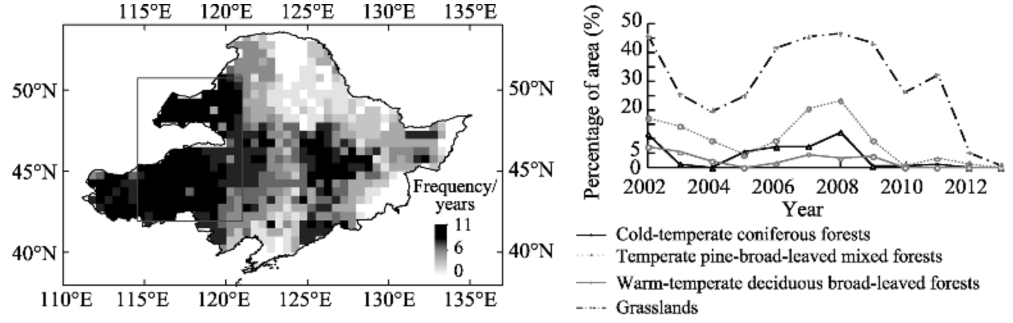
where NPP refers to the net primary productivity, and ET refers to evapotranspiration.

4 Result analysis

4.1 scPDSI distribution characteristics of Northeast China

Figure 2a shows that drought frequently occurs in the regions stretching from 114.55°E to 120.90°E (i.e., at least nine times) (regions inside the red frame). In contrast, drought seldom occurs in the mountainous regions in the north and east and coastal regions in the south (i.e., zero to 3 years). According to Figure 2a combined with Figure 1, the regions with a high drought frequency are mostly grasslands, whereas those with a low drought frequency are mainly forests.

Figure 2b presents the percentage of the droughty forest/grassland areas to the total area of forests/grasslands. The changing trend in the percentage of the area of drought forests to the total area of forests was basically consistent with that in the percentage of the area of drought grasslands to the total area of grasslands. The droughty forest/grassland area of was very large in 2002 and 2008, but very small in 2004 and 2013. This finding was consistent with the analysis results of Figure 4a. Specifically, the droughty forest area of accounted for a small proportion, whereas the area of drought grasslands accounted for a large proportion during these years.



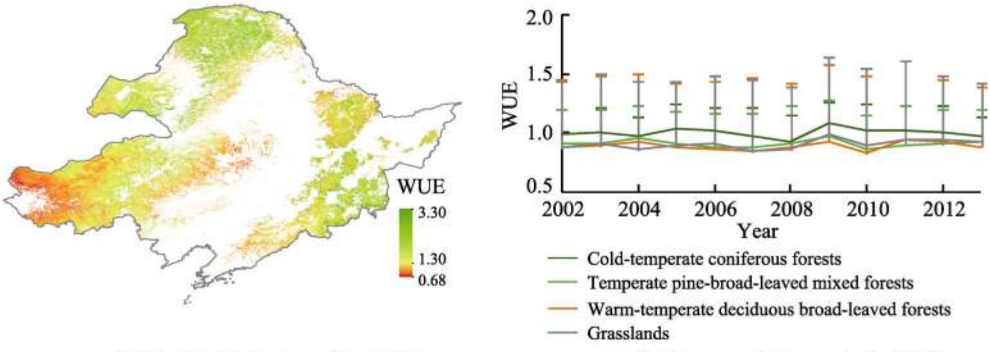
(a) Spatial distribution of drought frequency (b) Interannual changes in percentage of drought regions

Figure 2 Spatial distribution of drought frequency (a) and the annual change in the percentage of drought regions (b) in Northeast China from 2002 to 2013

The droughty forest/grassland areas accounted for the largest proportion in 2008. Taking 2008 as an example, this study discussed the response of the WUE of forests and grasslands to drought in Northeast China.

4.2 Spatio-temporal characteristics of the WUE of natural vegetation

A great spatial variation was observed in the annual average WUE (in the range of 0.68 to 3.30, Figure 3a) of the natural vegetation in Northeast China. The annual average WUE was very high in the north of the Greater Khingan Mountains and east of the Changbai Mountains, where the main vegetation types were cold-temperate coniferous forests and temperate pine-broad-leaved mixed forests. The annual average WUE was very low in the central and western parts of Northeast China, where the main vegetation type is grasslands. Figure 3b shows the temporal characteristics of the annual average WUE. The interannual difference in the annual average WUE of the forests or grasslands was very small. The annual average WUE of the cold-temperate coniferous forests was in the range of 0.93 to 1.08, which was slightly higher than that of the temperate pine-broad-leaved mixed forests (0.85 to 0.97), warm-temperate deciduous broad-leaved forests (0.82 to 0.94), and grasslands (0.84 to 0.99). The standard deviation of the WUE of the cold-temperate coniferous or temperate pine-broad-leaved mixed forests was in the range of 0.17 to 0.33, which was smaller than that of the warm-temperate deciduous broad-leaved forests or grasslands (i.e., in the 0.36 to 0.67 range). The WUE of the cold-temperate coniferous forests was higher than that of the grasslands and other types of forests. Moreover, a small regional difference in their WUE was observed. The WUE of the temperate pine-broad-leaved mixed forests was a little lower than that of the cold-temperate coniferous forests. A small regional difference in their WUE was also observed. The WUE of the warm-temperate deciduous broad-leaved forests or grasslands was very low, and a large regional difference in their WUE was found.



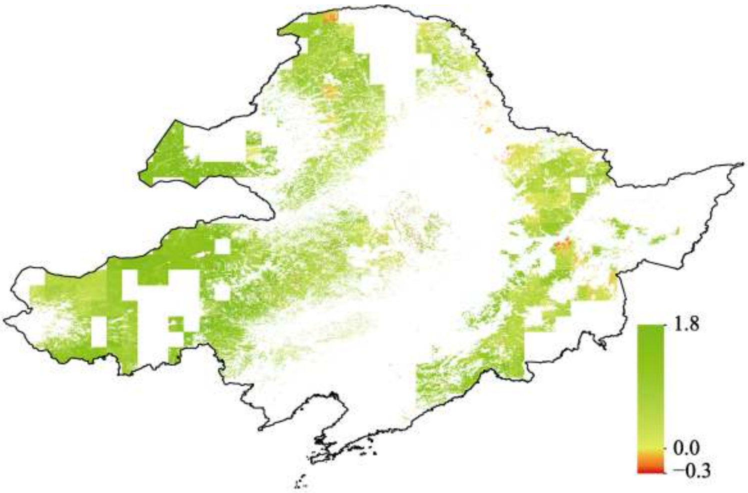
(a) Spatial distribution of the WUE (b) Interannual changes in the WUE

Figure 3 Spatial distribution (a) and interannual changes (b) of the WUE of the natural vegetation in Northeast China from 2002 to 2013

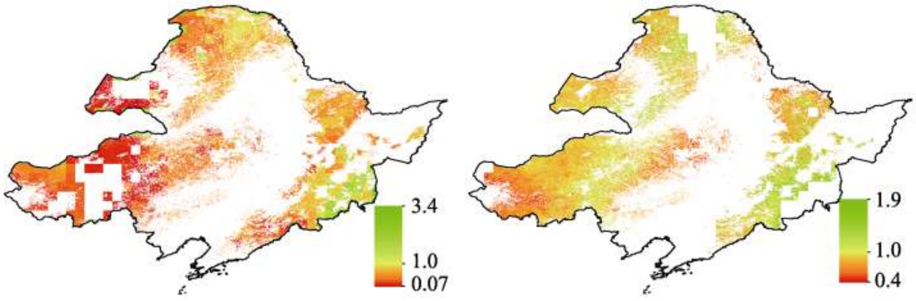
4.3 Response of the WUE of the natural vegetation to drought

4.3.1 Changes in the WUE of the natural vegetation in drought conditions

This study provides a comparison between the average WUE in the drought areas in 2008 (1.08 for the cold-temperate coniferous forests, 0.95 for the temperate pine-broad-leaved mixed forests, 0.97 for the warm-temperate deciduous broad-leaved forests, and 1.10 for grasslands) and that in normal conditions in other years (the baseline value of the WUE is denoted as $\text{WUE}_{\text{Baseline}}$; 0.99 for the cold-temperate coniferous forests; 0.86 for the temperate pine-broad-leaved mixed forests; 0.87 for the warm-temperate deciduous broad-leaved forests; and 0.86 for grasslands) (Figure 4 and Table 1). The regions with $\Delta\text{WUE} > 0$ accounted for 86.11% of the total area of the natural vegetation. The warm-temperate deciduous broad-leaved forests with $\Delta\text{WUE} > 0$ accounted for 97.16% of their total area. Meanwhile, the grasslands with $\Delta\text{WUE} > 0$ accounted for 94.25% of their total area. The proportion of the grasslands with $\Delta\text{WUE} > 0$ in the regions stretching from 114°E to 119° was higher than that in other regions. The cold-temperate coniferous forests with $\Delta\text{WUE} > 0$ were mainly distributed in the north of the Greater Khingan Mountains. In contrast, the temperate pine-broad-leaved mixed forests with $\Delta\text{WUE} > 0$ were very scattered and alternately distributed with the temperate pine-broad-leaved mixed forests with $\Delta\text{WUE} < 0$ and $\Delta\text{WUE} = 0$. Drought will evidently result in a little increase in the WUE of the natural vegetation in most parts of Northeast China.



(a) Difference between the WUE in drought regions in 2008 and annual WUE over years in normal water conditions (baseline value)



(b) Distribution of the average WUE in normal conditions over years (baseline WUE)

(c) Distribution of the WUE in drought regions in 2008

Figure 4 Comparison of the average WUE between drought conditions and normal water conditions in 2008

This study extracted the baseline WUE values ($\text{WUE}_{\text{Baseline}}$) at the interval of 0.1° longitude and 0.1° latitude, the scPDSI values in drought conditions in 2008 (scPDSI_2008), the WUE values in drought conditions in 2008 ($\text{WUE}_{\text{Drought}}$), and the differences between WUE and $\mathrm{WUE}_{\mathrm{Baseline}}$ (ΔWUE) according to Figures 4a and 4c. This study analyzed the correlation between different variables (Figure 5: "1", "2", "3", and "4" stand for the cold-temperate coniferous forests, temperate pine-broad-leaved mixed forests, warm-temperate deciduous broad-leaved forests, and grasslands, respectively).

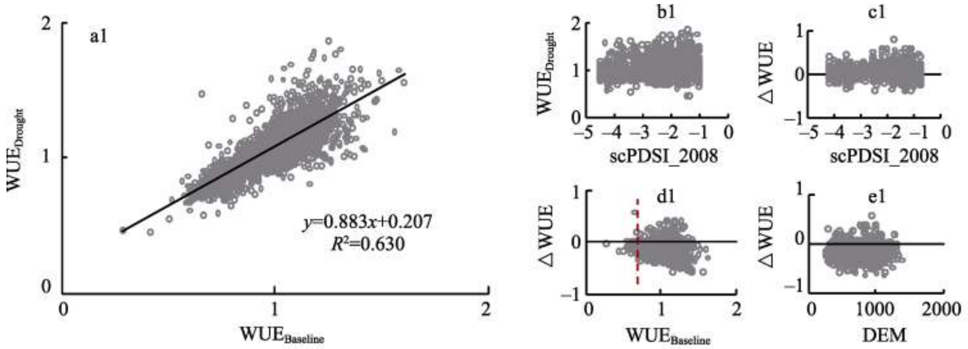
Table 1 Changes in the WUE of the natural vegetation in drought conditions in Northeast China in 2008

Vegetation type	ΔWUE < 0	ΔWUE > 0	ΔWUE = 0
Cold-temperate coniferous forests (%)	4.56	80.00	15.44
Temperate pine-broad-leaved mixed forests (%)	6.13	73.95	19.93
Warm-temperate deciduous broad-leaved forests (%)	0.78	97.16	2.06
Grasslands (%)	1.09	94.25	4.66
Total (%)	3.10	86.11	10.79

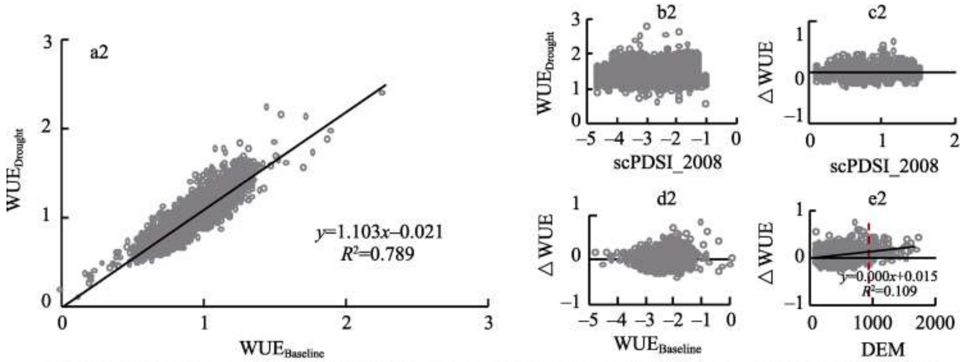
Regarding the four vegetation types, a significant linear positive correlation was always found between $\mathrm{WUE}_{\mathrm{Drought}}$ and $\mathrm{WUE}_{\mathrm{Baseline}}$ (sig < 0.001) (Figures 5a2 to 5a4), but no significant correlation between $\mathrm{WUE}_{\mathrm{Drought}}$ and scPDSI_2008 (Figures 5b1 to 5b4) and between ΔWUE and scPDSI_2008 (Figures 5c1 to 5c4). This study analyzed the correlation between ΔWUE and $\mathrm{WUE}_{\mathrm{Baseline}}$ and found the following phenomena: 1) a rise in the WUE of all cold-temperate coniferous forests with $\mathrm{WUE}_{\mathrm{Baseline}} < 0.69$ was found in drought conditions (Figure 5d1); 2) a rise in the WUE of most of the cold-temperate coniferous forests with $\mathrm{WUE}_{\mathrm{Baseline}} \geqslant 0.69$ and a decrease in the WUE of only a few of the cold-temperate coniferous forests with $\mathrm{WUE}_{\mathrm{Baseline}} \geqslant 0.69$ were observed; and 3) no obvious linear correlation existed between ΔWUE and $\mathrm{WUE}_{\mathrm{Baseline}}$ and between ΔWUE and DEM (Figure 5e1). Drought will result in an increase in the WUE of some of the temperate pine-broad-leaved mixed forests and warm-temperate deciduous broad-leaved forests. No obvious boundary line or changing trend was found (Figures 5d2 and 5d3). However, a significant positive correlation between the altitudes and the ΔWUE of the temperate pine-broad-leaved mixed forests was observed. A rise in the WUE of all temperate pine-broad-leaved mixed forests with DEM $\geqslant$ 964 can be seen in drought conditions (Figure 5e2). Meanwhile, the grasslands exhibited a significant linear negative correlation (sig < 0.001) between ΔWUE and $\mathrm{WUE}_{\mathrm{Baseline}}$. In drought conditions, a rise in the WUE of all the grasslands with $\mathrm{WUE}_{\mathrm{Baseline}} < 0.61$, an increase in the WUE of most of the grasslands with $\mathrm{WUE}_{\mathrm{Baseline}} \geqslant 0.61$, and a decline in the WUE of a few of grasslands were observed. A significant positive correlation was also found between the altitudes and the ΔWUE of grasslands. Furthermore, an increase in the WUE of all grasslands with DEM $\geqslant$ 1440 existed (Figure 5e4).

4.3.2 Influence of drought on ET, NPP, and LAI

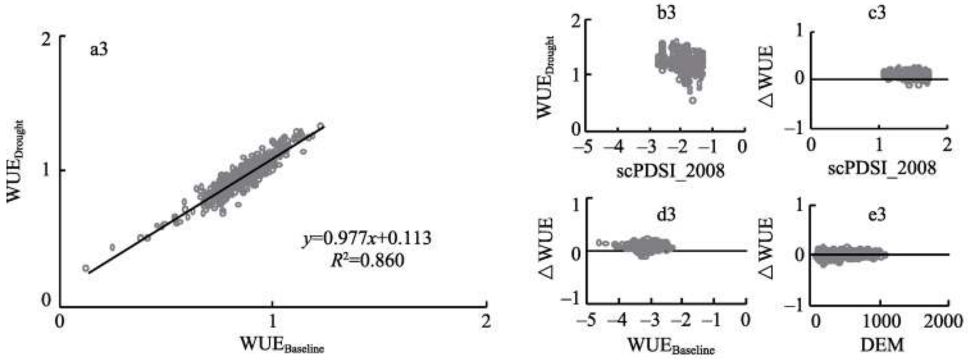
This study analyzed the distribution of ET, NPP, and LAI in normal water conditions with regard to the vegetation with a rise or decline in the WUE in drought conditions in 2008 (Figure 4a) to further explore the reasons for the changes in the WUE (Figure 6 and Table 2). The average ET of the pixels of the cold-temperate coniferous forests with ΔWUE > 0 was 482.21. Their peak of the distribution frequency (percentage) was approximately at 460. Meanwhile, the average ET of the pixels of the cold-temperate coniferous forests with ΔWUE < 0 was 440.20, and their peak of distribution frequency (percentage) was approximately at 400. No significant difference was found in the average values between the two



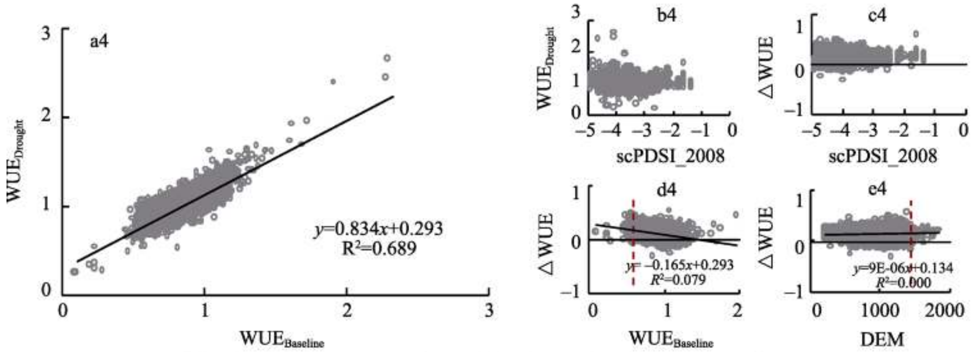
(a) Relationship between $WUE_{Drought}$ and $WUE_{Baseline}$ (a1), $WUE_{Drought}$ and scPDSI_2008 (b1), ΔWUE and scPDSI_2008 (c1), ΔWUE and $WUE_{Baseline}$ (d1), and ΔWUE and DEM(e1) in cold-temperate coniferous forests in the dry area in 2008



(b) Relationship between various variables in temperate pine-broad-leaved mixed forests in the dry area in 2008



(c) Relationship between various variables in warm-temperate deciduous broad-leaved forests in the dry area in 2008



(d) Relationship between various variables in grasslands in the dry area in 2008

Figure 5 Changes in the WUE of the natural vegetation in drought conditions in 2008 groups of data (sig < 0.001). The average NPP of the pixels of the cold-temperate coniferous forests with ΔWUE > 0 was 454.23, and their peak of distribution frequency (percentage) was approximately at 500. In addition, the average NPP of the pixels of the cold-temperate coniferous forests with ΔWUE < 0 was 520, and their peak of distribution frequency (percentage) was approximately at 420. A significant difference was found in the average values between the two groups of data (sig < 0.001). The average LAI of the pixels for the cold-temperate coniferous forests with ΔWUE > 0 was 1.47, and their peak of distribution frequency (percentage) was approximately at 1.5. Meanwhile, the average LAI of the pixels of the cold-temperate coniferous forests with ΔWUE < 0 was 1.51, and their peak of distribution frequency (percentage) was approximately at 1.65. No difference was found in the average values between the two groups of data (sig = 0.001). Evidently, the WUE for the vegetation with high ET and low NPP was more likely to rise in drought conditions, while the LAI had no significant influence on the WUE.

The WUE for the temperate pine-broad-leaved mixed forests with high ET and NPP was more likely to rise in drought conditions, while the LAI had no significant influence on the WUE. The WUE for the grasslands with low ET, NPP, and LAI was more likely to rise in drought conditions. Meanwhile, the ET, NPP, and LAI had no significant influence on the WUE in drought conditions of the warm-temperate deciduous broad-leaved forests. The reason for changes in the WUE was yet to be further explored.

Table 2 Indices of the natural vegetation in Northeast China in normal water conditions

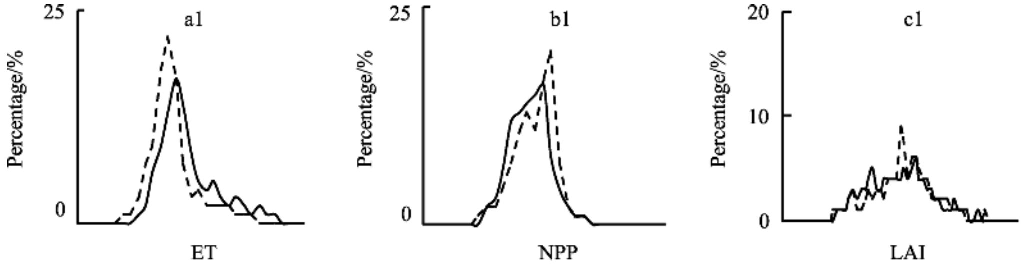
Vegetation type	ΔWUE	ET (mm/year)		NPP (kgC/m^2)		LAI	
		Mean	Comparison of the means	Mean	Comparison of the means	Mean	Comparison of the means
Cold-temperate coniferous forests	ΔWUE > 0	482.21	sig < 0.001	454.23	sig < 0.001	1.47	sig = 0.101
	ΔWUE < 0	440.20		520.00		1.51	
Temperate pine-broad-leaved mixed forests	ΔWUE > 0	526.99	sig < 0.001	468.76	sig < 0.001	1.40	sig = 0.131
	ΔWUE < 0	508.27		438.31		1.43	
Warm-temperate deciduous broad-leaved forests	ΔWUE > 0	419.41	sig = 0.253	360.45	sig = 0.061	0.63	sig = 0.726
	ΔWUE < 0	394.14		353.08		0.62	
Grasslands	ΔWUE > 0	329.19	sig = 0.032	280.30	sig < 0.001	0.81	sig < 0.001
	ΔWUE < 0	318.84		299.40		0.80	

Note: An independent-sample T test was used to compare the average values.

5 Discussion

5.1 Overall WUE of Northeast China at below-average level

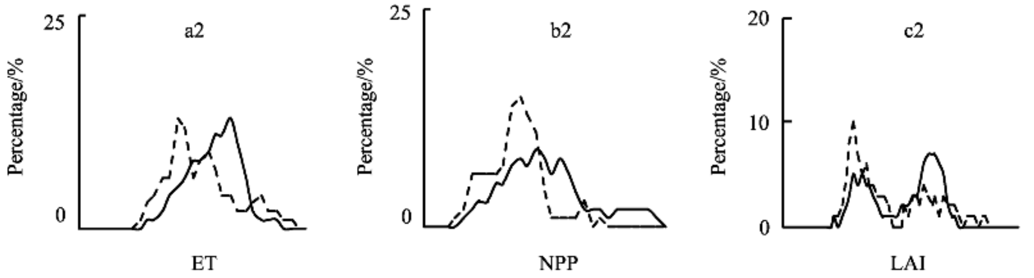
The photosynthesis capability varies among different types of vegetation; hence, a certain difference can be found in the WUE and the carbon use efficiency between them (Stella *et al.*, 2009; Jin *et al.*, 2017). The findings herein support the above-mentioned conclusion. The average WUE of the forests in Northeast China in normal water conditions was in the range of 0.82 to 1.08 gC/kg^{-1}H_2O, which was higher than that of the grasslands in the range of 0.84 to 0.99 gC/kg^{-1}H_2O. Table 3 describes the value range of the WUE and the CUE of the forests in other studies across the world. The WUE of the forests in Northeast China was at a relatively low level, while the WUE of the grasslands in Northeast China was at a medium



Percentage distribution of ET frequency in cold temperate coniferous forests

Percentage distribution of NPP frequency in cold temperate coniferous forests

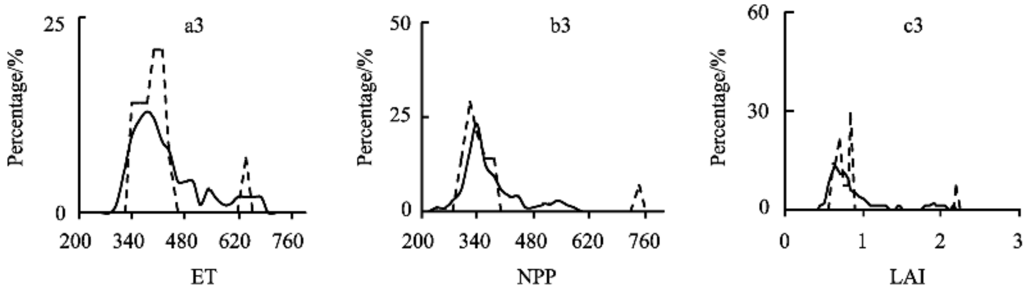
Percentage distribution of LAI frequency in cold temperate coniferous forests



Percentage distribution of ET frequency in temperate pine-broad-leaved forests

Percentage distribution of NPP frequency in temperate pine-broad-leaved forests

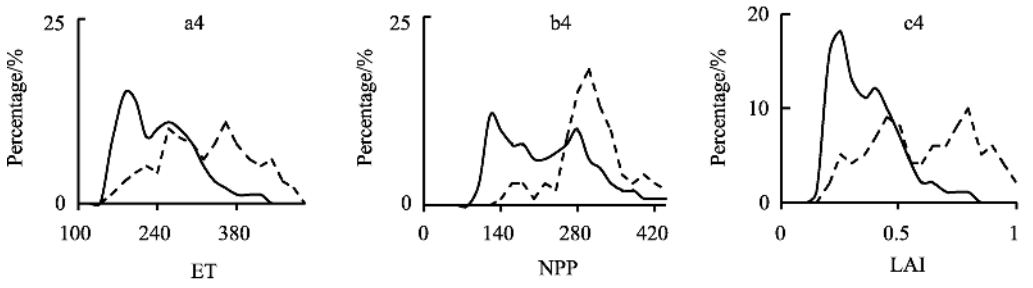
Percentage distribution of LAI frequency in temperate pine-broad-leaved forests



Percentage distribution of ET frequency in warm-temperate deciduous broad-leaved forests

Percentage distribution of NPP frequency in warm-temperate deciduous broad-leaved forests

Percentage distribution of LAI frequency in warm-temperate deciduous broad-leaved forests



Percentage distribution of ET frequency in grasslands

Percentage distribution of NPP frequency in grasslands

Percentage distribution of LAI frequency in grasslands

Figure 6 Distribution of ET, NPP, and LAI of natural vegetation in drought conditions. The solid line is the distribution curve of the frequency (percentage) of ET, NPP, and LAI in normal water conditions with regard to the pixels with ΔWUE $\geqslant$ 0 specified in Figure 5d. The dotted line is the distribution curve of the frequency (percentage) of the corresponding indices in normal conditions with regard to the pixels with ΔWUE < 0 specified in Figure 5d.

level. The difference in the WUE may be caused by the different climate conditions and vegetation types between the study areas.

Table 3 Comparison of the WUE data

Ecosystem class	Study area	Value ($gC/kg^{-1}H_2O$)	Data source
Forests	Yangtze River Delta, China	1.68–1.95	Wang *et al*. (2015)
	Changbaishan temperate broad-leaved Korean pine mixed forest, China	9.43	Yu *et al*. (2008)
	Qianyanzhou subtropical coniferous plantation, China	9.27	Yu *et al*. (2008)
	Dinghushan subtropical evergreen broad-leaved forest, China	6.90	Yu *et al*. (2008)
	Forest ecosystems, Europe	1.2–5.0	Kuglitsch *et al*. (2008)
	Urban-forest reserve, China	2.6 ± 0.2	Xie *et al*. (2016)
	Alpine area of Southwest China	0.83–1.46	Zhang *et al*. (2016)
	California, USA	1.33	Malone *et al*. (2016)
	Northeast China	0.82–1.08	This study
Grasslands	Yangtze River Delta, China	1.66	Wang *et al*. (2015)
	Xinjiang, China	0.26–0.69	Huang and Luo (2017)
	Qinghai-Tibet Plateau, China	0.62	Mi *et al*. (2015)
	Alpine area of Southwest China	0.84–1.14	Zhang *et al*. (2016)
	California, USA	1.73	Malone *et al*. (2016)
	Northeast China	0.84–0.99	This study

5.2 WUE as index for reflecting the responsiveness of plants to drought

The response to drought varies among different vegetation types (Reichstein *et al*., 2002; Lu *et al*., 2010). Some researchers contended that drought will result in a significant uptrend in the WUE of natural vegetation (Malone *et al*., 2016; Campos *et al*., 2013; Guillermo *et al*., 2013). Other researchers contended that drought will result in a decline in the WUE of most vegetation (Edwards *et al*., 2012; Gang *et al*., 2016) or ecosystems (Reichstein *et al*., 2002; Lu *et al*., 2010) possibly because their WUE has a remarkable internal variability and plasticity (Monclus *et al*., 2006; Ponton *et al*., 2002) caused by gene difference. This study supports the first view that drought will result in a little rise in the WUE of most forests and grasslands. The rise in the WUE means that plants acquire a high productivity under water stress (Guillermo *et al*., 2013), except that the rise is not linear (e.g., a decline in the WUE of very few plants is observed). Drought has evidently disrupted the ranking of the WUE of the forests and grasslands in Northeast China in normal water conditions. This result was also corroborated by the study on the relationship between the ΔWUE and the corresponding WUE in normal water conditions: 1) no significant linear correlation was found between ΔWUE and the corresponding WUE for the forests in normal water conditions and 2) a significant linear negative correlation between ΔWUE and the corresponding WUE was observed for the grasslands in normal water conditions. Drought will result in a little rise in the WUE of the plants with a low WUE in the normal water conditions, but in a linear downtrend in the WUE of the plants with a high WUE.

5.3 Deficiencies in the study

This study sensitively found the phenomenon that drought will result in a rise in the WUE of most vegetation in Northeast China, indicating that the forests and the grasslands in that area are resistant to drought. First, when this study used MODIS data products to study the natural vegetation status of the mountainous regions in the east of Northeast China, the spatial resolution (500 m) was indeed very low, thereby significantly affecting the accuracy. Second, the researchers had not accumulated sufficient historical data on ground-based verification and lacked sufficient experience in the ground-based verification of the MODIS data products. Third, this study did not definitely distinguish C3 plants from C4 plants (C4 plants have a great advantage over C3 plants in terms of high temperature resistance (Wilson *et al.*, 2007; Killi *et al.*, 2017)) and ignored the changes in the interior species of forests and grasslands. In addition, this study only considered the annual changes in the water conditions, and did not distinguish the occurrence time of drought. In the subsequent studies, the remote sensing data with a high spatial resolution must be selected, or a mode that allows the integration of high-resolution data and MODIS data products must be developed. Accumulating sufficient ground survey data and developing an effective data verification method are also necessary. The intent is to improve the spatial representativeness and accuracy of basic remote sensing data and make the research conclusions closer to the actual ones.

6 Conclusions

This work analyzed the spatio-temporal evolution law of productivity of natural vegetation in Northeast China based on the rainfall and scPDSI data from 2001 to 2013, land cover types, and the LAI, ET, and NPP data products specified by the MODIS. This work also studied the influence of drought events on the productivity of different vegetation types and their response to drought events. The research findings can be summarized as follows:

(1) In Northeast China, the regions with a high drought frequency are mostly grasslands, whereas the regions with a low drought frequency are mostly forests. Drought occurred on a large scale in 2002 and 2008, but on a small scale in 2004 and 2013.

(2) The annual average WUE of the natural vegetation ranged from 0.82 to 1.08 $C/kg^{-1}H_2O$. The WUE of the forests (0.82 to 1.08 $C/kg^{-1}H_2O$) was universally higher than that of the grasslands (0.84 to 0.99 $C/kg^{-1}H_2O$).

(3) In 2008, the regions with a rise in the WUE in drought conditions accounted for 86.11% of the study area. The warm-temperate deciduous broad-leaved forests with a rise in the WUE accounted for 97.16% of their total area. The grasslands with a rise in the WUE accounted for 94.25% of their total area.

(4) A significant linear positive correlation was found between the WUE in the drought conditions and the WUE in the normal water conditions. The degree of drought did not influence the WUE of the natural vegetation in an obviously linear manner. An increase in the WUE of all cold-temperate coniferous forests with $WUE < 0.69$ and all grasslands with $WUE < 0.61$ in the normal water conditions was observed in the drought conditions. An increase in the WUE of all temperate pine-broad-leaved mixed forests with $DEM \geqslant 964$ and all grasslands with $DEM \geqslant 1447$ was also observed in the drought conditions.

(5) The WUE of the cold-temperate coniferous forests and the temperate pine-broad-leaved mixed forests with a high ET or low NPP was more likely to rise in the drought conditions. The WUE for the grasslands with low ET, NPP, and LAI was also more likely to rise in

the drought conditions. Meanwhile, the ET, NPP, and LAI of the warm-temperate deciduous broad-leaved forests had no significant influence on the WUE in the drought conditions, and the main reason for the changes in the WUE has yet to be further explored.

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