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Tree mortality in response to climate change induced drought across Beijing, China

Xiongqing Zhang · Yuancai Lei · Yong Pang · Xianzhao Liu · Jinzeng Wang

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Abstract Tree mortality in response to climate change induced drought has emerged as a global concern. Small changes of tree mortality rates can profoundly affect forest structure, composition, dynamics and ecosystem services such as carbon sequestration. Our analyses of longitudinal data from natural stands (82 plots) in Beijing showed that tree mortality rates have increased significantly over the two decades from 1986 to 2006. In contrast, recruitment rates decreased significantly over this period. The increase in overall mortality rates resulted from an increase in tree deaths dominantly attributed to changes in temperature and precipitation resulting in drier conditions across latitudes, elevations, tree species, and tree sizes. In addition, the results showed that mortality rates of Chinese pine (*Pinus tabuliformis*) (β_1=0.0874) as a result of climate change induce drought were much smaller than oak (*Quercus*) (β_1=0.1583).

1 Introduction

Global climate change is predicted to yield increases in frequency and severity of drought under warming climate (Hoerling and Kumar 2003; Yeh et al. 2009). The drought has led to terrestrial ecosystems changes, including changes in carbon balances (Arnone et al. 2008; Ma et al. 2012), net primary productivity (Zhao and Running 2010; Chen et al. 2013), forest biodiversity (Clark et al. 2011), plant phenology (Khanduri et al. 2008; Wolkovich et al. 2012), tree species distribution (Bourque and Hassan 2008), and forest growth (Barber et al. 2000;

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X. Zhang
State Key Laboratory of Tree Genetics and Breeding, Key Laboratory of Tree Breeding and Cultivation of the State Forestry Administration, Research Institute of Forestry, Chinese Academy of Forestry, Beijing 100091, People's Republic of China
e-mail: xqzhang85@yahoo.com

X. Zhang · Y. Lei (✉) · Y. Pang · X. Liu
Research Institute of Forest Resource Information Techniques, Chinese Academy of Forestry, Beijing 100091, People's Republic of China
e-mail: yclei@caf.ac.cn

J. Wang
Beijing Forestry Survey and Design Institute, Beijing 100029, People's Republic of China

Feeley et al. 2007). These changes have also been accompanied by increasing forest dieback and mortality (Breshears et al. 2005; van Mantgem and Stephenson 2007; Carnicer et al. 2011). Understanding and predicting the consequences of global climate change on forest ecosystem is emerging as one of the grand challenges for forest scientists (Bonan 2008).

Tree mortality, one of the main components of forest succession, is a complex process affected by environmental, pathological, and physiological factors, as well as random events (Franklin et al. 1987a, b; Yang et al. 2003). Model results indicate that small changes of tree mortality rates can profoundly affect forest structure, composition, dynamics and ecosystem services such as carbon sequestration (e.g. Pacala et al. 1996; Wyckoff and Clark 2002). Tree mortality not only affects carbon fluxes but also alters water and energy fluxes between the atmosphere and land surface (Breshears and Allen 2002; Chapin et al. 2008).

Recently, several studies (Breshears et al. 2005; Adams et al. 2009) have indicated that tree mortality caused by warmer temperatures and climate change induced drought have unexpectedly increased around the global scale during the past decade. This has emerged as a global concern for forests under the warming climate and widespread increases in aridity in the coming decades (Seager et al. 2007). Across large areas of temperate forests of the western United States, van Mantgem et al. (2009) showed that regional warming and consequent increases in water stress are likely contributors to the widespread increases of tree mortality rates. Phillips et al. (2009, 2010) reported that tropical forests would suffer catastrophic tree mortality in response to moisture stress. In southern Europe, tree mortality amplified with increased climate change induced drought (Carnicer et al. 2011). Across the boreal forest of Canada, tree mortality has increased pervasively in response to the impacts of climatic warming and drought (Michaelian et al. 2011; Peng et al. 2011). Several droughts have been also associated with increased mortality among many tree species in Africa (Lwanga 2003), in Australia (Fensham and Fairfax 2007). Allen et al. (2010) reviewed the research about drought induced tree mortality and revealed emerging climate change risks for forests in the world.

The capital of China, Beijing belongs to the North of China, where is sub-humid and semi-arid climate zone. Ren et al. (2005) reported that annual precipitation decreased significantly and annual mean temperature increased significantly in northern China including Beijing over the past half century. Recent climate changes in this region may have had substantial impacts on the forests as a result of widespread drought-induced tree mortality. Long-term forest permanent sampling plots (PSPs) could provide direct estimates of tree mortality rate and possible insights into the future role of forests in the global carbon cycle under a changing climate. The possibility of increasing tree mortality induced by climate change induced drought in Beijing is a particular concern in China as well as in the world. The forests in Beijing provided fundamental services for human such as primary products, water supply, hydrological regulation, environmental purification, soil formation and conservation, wind protection and sand fixation, biodiversity conservation, increasing employment, recreation, science and education (Xie et al. 2010), and play a critical role in Beijing's carbon budget. Investigating tree mortality of Beijing forests due to climate change induced drought provides helpful insights into exploring forest resilience carbon cycle in Beijing, as well as in sub-humid and semi-arid climate zone of China under a changing climate. However, to our knowledge, no study has used long-term forest observation plots to directly investigate tree mortality and mortality rates of different tree species as a result of recent climate change in Beijing, as well as in sub-humid and semi-arid climate zone of China.

Here, we provide a first detailed analysis of long-term, annual-resolution tree mortality and recruitment across Beijing temperate forest, China. We seek to explore whether systematic changes in tree mortality and recruitment have occurred in the forests of Beijing, and, if any changes have occurred, whether they could be attributed to changes in climatic variables or in other potential contributing factors.

2 Methods

2.1 Study sites and data selection

Beijing is located in north latitude 39°26′ to 41°03′, and longitude 115°25′ to 117°30′, the north-west edge of Huabei plain in China (Fig. 1), occupying an area of 16,410.54 km^2. This study was conducted using data from permanent plots between 1986 and 2006, 0.067 ha each, across Beijing, China, which were aggregated over 2×2 km grid. Diameter of each tree was measured after its height reached 1.3 m. Measurements was carried out every 5 years. For our analysis, we limited analyses to forest plots based on the following criteria: (1) All plots were in natural forest stands, which we defined as stands that developed naturally rather than after forest management, such as thinning, harvesting, or other silvicultural treatments. (2) To avoid changes in tree mortality caused by other disturbance, only plots with no evidence of fire, flood, storm, or insect disturbance were chosen. (3) To compare changes in tree recruitment (a threshold size of diameter at breast height for tree recruitment in China is DBH=5 cm) and mortality rates, all plots were at least measured for three times (Table S1). (4) Complete tree mortality and recruitment records were required in the study. In addition, the tree diameter measurements in all of the plots were conducted after the tree height reached 1.3 m during the first census. (5) The individual trees must have been clearly tagged, identified to species and repeatedly measured. (6) To obtain climatic data for each plot, the spatial location of all plots was required.

To find data meeting these criteria above, we selected and thoroughly reviewed data from permanent sample plots (PSPs) across Beijing. Although there were many PSPs across Beijing, most of the plots did not meet our criteria. Finally, there were 82 long-term plots which met our criteria for analysis. Table S1 summarizes the key characteristic of the 82 plots, and their locations are shown in Fig. 1.

2.2 Climate variables

Commonly mean annual temperature and annual precipitation were used for analyzing climate-tree mortality functions. To obtain the two variables associated with the individual plots, the daily 4-km raster gridded climate dataset (Chen et al. 2011) for Beijing from 1986 to 2006 was used. In addition, according to Wang et al. (2006) we used the annual heat-moisture index (*AHM*) to indicate the annual climatic water deficit, because it integrates mean annual temperature (*MAT*) and annual precipitation (*AP*) into one single parameter: $AHM=(MAT+10)/(AP/1000)$ which better reflects evapotranspiration and soil moisture content than precipitation and temperature alone. The larger the value of *AHM* is, the greater the probability of drought (Kapeller et al. 2012).

2.3 Statistical models

We used the same statistical models of van Mantgem et al. (2009) and Peng et al. (2011), which are simple, appropriate to the data, and capable of detecting directional changes in mortality and recruitment rates. Accounting for differences among the plots, we used generalized nonlinear mixed models (GNMMs) to regress mortality and recruitment rates. Therefore, we added a normal random effect to the linear function based on plot identity. To estimate

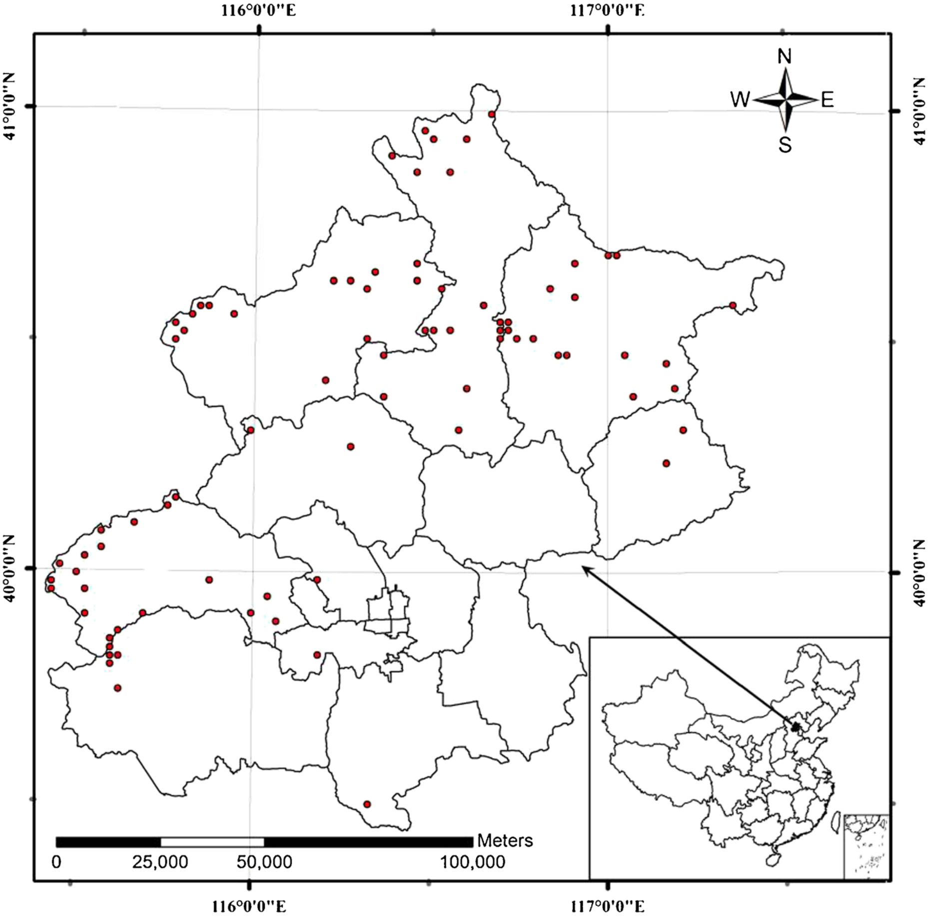

Fig. 1 Locations of the 82 forest plots across Beijing, China

changes in annual mortality rates we modeled the rate(s) as a logistic function $\exp(\beta_0+\beta_1 t_j+\gamma_i)/(1+\exp(\beta_0+\beta_1 t_j+\gamma_i))$, where i represents plot number, t_j represents the year of jth census, β_0 and β_1, are regression parameters, and γ_i is the random effect parameter among the multiple plots. We applied a statistical model to our data where n_{ij} was the number of trees alive at the previous census for the ith plot and the jth census, and m_{ij} represents the corresponding count of mortality rates:

$$m_{ij}|\gamma_i \sim \text{negative binomial with mean } n_{ij}p_{ij} \text{ and variance } \quad n_{ij}p_{ij}\left(\frac{n_{ij}p_{ij}+a^{-1}}{a^{-1}}\right) \tag{1}$$

$$p_{ij} = 1-(1+\exp(\beta_0+\beta_1 x+\gamma_i))^{-c_j} \quad \gamma_i \sim N\left(0,\sigma_\gamma^2\right) \tag{2}$$

where p_{ij} represents the probability of mortality over the census interval, x the explanatory variables (measurement year or climate variables), and c the census interval length in years.

The random intercept parameter γ_i follows a normal distribution. The negative binomial distribution is an extension of the Poisson distribution with $\alpha>0$ representing overdispersion (Affleck 2006).

We modeled annual recruitment rates as $\exp(\beta_0+\beta_1 t_j+\gamma_i)$ and applied a similar statistical model in which r_{ij} is the number of recruits:

$$r_{ij}|\gamma_i \sim \text{negative binomial with mean } n_{ij}p_{ij} \text{ and variance } \quad n_{ij}p_{ij}\left(\frac{n_{ij}p_{ij}+a^{-1}}{a^{-1}}\right) \tag{3}$$

$$p_{ij} = (1+\exp(\beta_0+\beta_1 x+\gamma_i))^{c_j}-1 \quad \gamma_i \sim N\left(0,\sigma_\gamma^2\right) \tag{4}$$

where p_{ij} is the rate of recruitment between the two consecutive censuses.

Parameters were estimated using maximum likelihood method with the plot effect modeled as random intercepts. Parameters estimates (β_1) of annual trends were converted to annual fractional changes in percentage using the formula $\alpha(\%)=(\exp(\beta_1)-1)*100$ (van Mantgem and Stephenson 2007; van Mantgem et al. 2009). Trends in forest density, forest age, and climatic variables were estimated using linear mixed models (LMM).

3 Results

3.1 Changes in mortality and recruitment rates

Over the two decades of census, mortality rates increased significantly for all plots combined and both the south and the north regions (<40.1°N, and 40.1°N, respectively) ($P<0.05$, Table 1, Fig. 2). Mortality rates also increased for small and large trees (<10 cm, and >10 cm) ($P<0.05$, Table 1, Fig. 2) and at low, middle, and high elevations (<501 m, 501 to 1,000 m, >1,000 m, respectively) ($P<0.05$, Table 1, Fig. 2). The four most abundant tree species in all plots (comprising 80.5 % of plots) were oak (*Quercus*), Chinese pine (*Pinus tabuliformis*), birch (*Betula*), TuanLinden (*Tilia tuan*). All four showed increasing mortality rates in (Fig. 2 and Table 1), as did all the remaining species (19.5 % of all plots).

In contrast to mortality rates, recruitment rates decreased significantly for all plots and in both south and north regions (Table 2). Recruitment rates also increased significantly for middle, and high elevations, but not significantly for low elevation ($P=0.0992$, GNMMs, Table 2).

3.2 Relationships between mortality rates and climatic variables

At our study sites, annual precipitation showed a significant decrease over the study period (decreasing from 525.59 mm in 1986 to 482.78 mm in 2006) ($\beta_{\text{year}}=-4.7298$, *S.E.*=0.6801, $P<0.0001$, linear mixed model (LMM); Fig. 3), and mean annual temperature increased significantly (increasing from 7.32 °C in 1986 to 8.51 °C in 2006) ($\beta_{\text{year}}=0.0674$, *S.E.*= 0.0022, $P<0.0001$, LMM; Fig. 3). The combination of the two variables resulted in a significant increase in the annual heat-moisture index (*AHM*) ($\beta_{\text{year}}=0.5193$, *S.E.*=0.0516, $P<0.0001$, LMM; Fig. 3).

We suggested that regional climate change induced drought would be the dominant contributor to the increasing tree mortality rates. In the study, annual mean temperature and

Table 1 Fixed effects in the generalized nonlinear mixed models (Eq. 2) describing annual mortality rate, *n* is the number of forest plots used in the model

Model	Data	β_1	*S.E.*	*P*	*n*
Mortality trends	All plots	0.1514	0.0189	<0.0001	82
Mortality trends by latitude	<40.1°N	0.1070	0.0233	0.0001	24
	>40.1°N	0.1921	0.0291	<0.0001	58
Mortality trends by elevation	<501 m	0.1109	0.0396	0.0123	18
	501 to 1,000 m	0.1630	0.0355	<0.0001	30
	>1,000 m	0.1592	0.0273	<0.0001	34
Mortality trends by species	Oak	0.1583	0.0340	<0.0001	120
	Chinese pine	0.0874	0.0376	0.0346	53
	Birch	0.1066	0.0355	0.0239	26
	TuanLinden	0.1602	0.0705	0.0724	20
	Others	0.1855	0.0372	<0.0001	57
Mortality trends by diameter class	<10 cm	0.1149	0.0276	0.0001	101
	>10 cm	0.1754	0.0294	<0.0001	175

AHM were both significantly positively correlated with tree mortality rates for all plots (P= 0.0239, P<0.0001, respectively, GNMMs, Table 3), and annual precipitation was significantly negatively correlated with tree mortality rates (P<0.0001, GNMMs, Table 3).

We also found that both the competition index (i.e. forest density) and stand age were not significant correlated with tree mortality (Fig. 4), which suggests that increasing tree mortality was not caused by competition index and age.

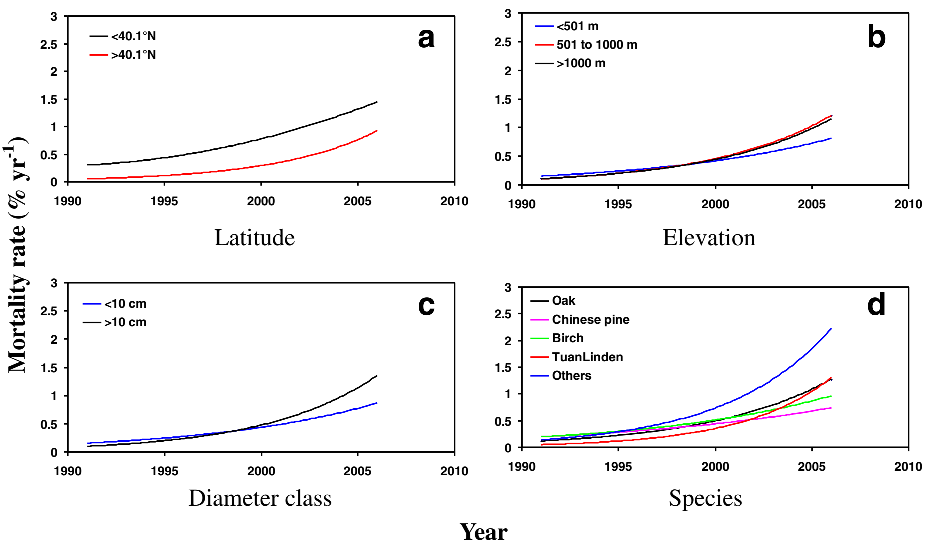

Fig. 2 Modeled trends in mortality rates for latitude, elevation, diameter class and species

Table 2 Fixed effects in the generalized nonlinear mixed models (Eq. 4) describing annual recruitment rate, n is the number of forest plots used in the model

Model	Data	β_1	S.E.	P	n
Recruitment trend	All plots	−0.0806	0.0195	<0.0001	82
Recruitment trend by latitude	<40.1°N	−0.0798	0.0321	0.0204	24
	>40.1°N	−0.0531	0.0253	0.0402	58
Recruitment trend by elevation	<501 m	−0.0679	0.0389	0.0992	18
	501 to 1,000 m	−0.0910	0.0413	0.0356	30
	>1,000 m	−0.0682	0.0265	0.0150	34

4 Discussion

For the 82 long-term forest PSPs across Beijing, China, tree mortality rates have increased significantly over the past two decades. In contrast, recruitment rates decreased significantly for these plots (Table 1). In the study, we considered that two classes of possible causes of the increasing tree mortality rates: endogenous processes and exogenous processes (climate). Among endogenous processes, perhaps forest density and stand age were the best-known causes of increasing tree mortality (Franklin et al. 1987a, b; van Mantgem et al. 2009). We found no significant relationship between tree mortality and forest density (Fig. 4) during the study period, which suggests that increasing tree mortality was not caused by forest density. This result is consistent with recent findings by van Mantgem et al. (2009) in the coniferous forests of the western United States. Regarding stand age, it seems logical that particularly when no treatments are carried out in a stand, tree mortality rate increases with stand age. If this is true in our case, we could expect to see no parallel increase in the mortality rates of small trees. However, the mortality rates of small trees have increased over the two decades (P= 0.0001, Fig. 2, Table 1). And our results also showed that the observed tree mortality increase does not appear to be attributable to stand age (Fig. 4). Peng et al. (2011) reported that the pervasive increase in tree mortality rates across Canada's boreal forest cannot be attributed to the age factor, which is consistent with the present results.

We also found that tree mortality rates increased in all major species rather than being limited to those dominated by a particular life history trait (such as shade intolerance). The result indicates that successional dynamics are unlikely to be primary drivers of the increasing mortality rates, which is consistent with the results of van Mantgem et al. (2009) for temperate forests in the western United States. Relationships between tree mortality and climate change are also influenced by tree species with drought tolerance (Gitlin et al. 2006). Li and Zhang (1993) identified the Chinese pine as drought-tolerant tree species with dehydration postponement at high tissue water potential, which had the strong abilities to hold water and maintain turgor (Zhang and Li 1995). In this study, we found that the β_1 value for Chinese pine was smaller than oak (Table 1), which was consistent with the previous study (Zhang et al. 1994) that the drought tolerance ability of the Chinese pine was stronger than that of the oak according to the water parameters of the forest. We also found that the β_1 value for the Chinese pine (conifer tree) was the smallest among these species (Table 1). In temperate forests, drought may be more likely to result in death of broadleaved tress than conifer trees because of their increased vulnerability to xylem cavitation (Maherali et al. 2004). In addition, mortality rates of small size trees were smaller than that of large trees in this study (Table 1), which was consistent with previous researches (Mueller et al. 2005; Nepstad et al. 2008) reported that larger trees often appear more prone to drought induced mortality.

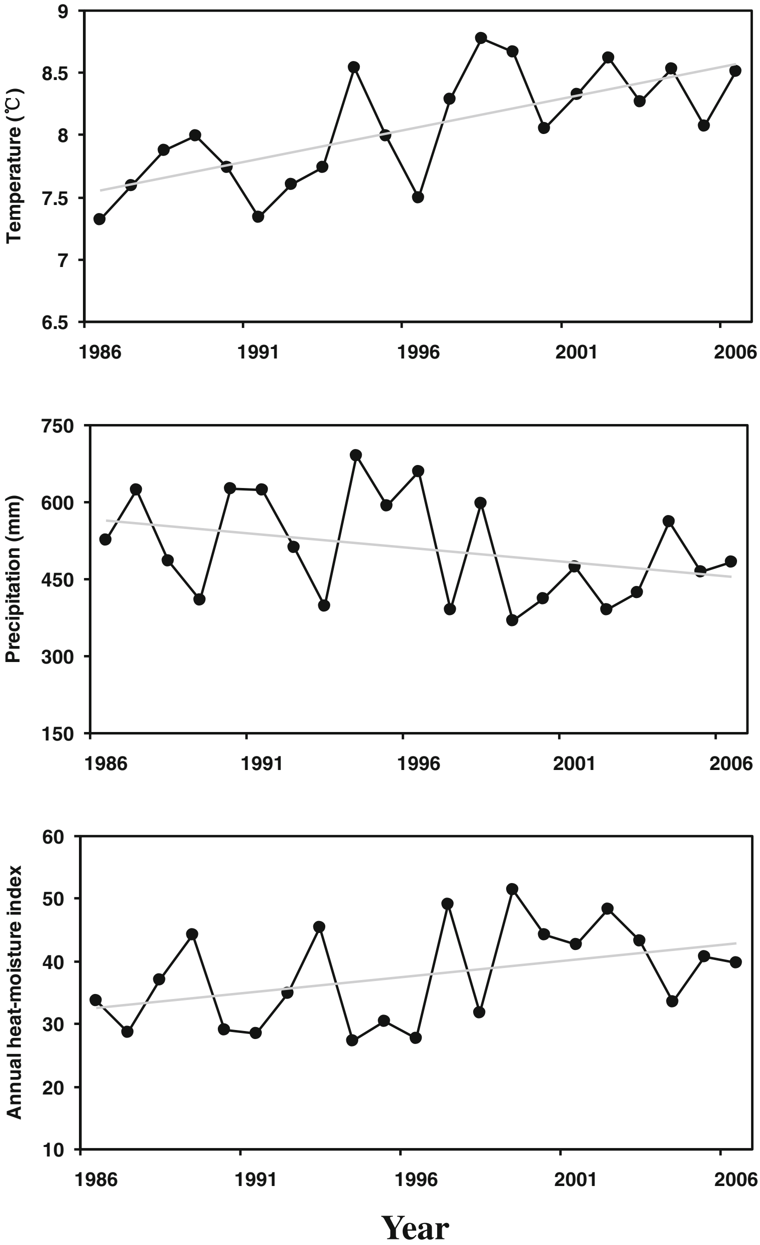

Fig. 3 The average annual temperature (°C), annual precipitation (mm), and annual heat-moisture index (*AHM*) for study locations

Across our study sites, annual precipitation decreased significantly from 1986 to 2006, in contrast, annual mean temperature and annual heat-moisture index (*AHM*) increased significantly during this period (Fig. 3). Zheng et al. (2012) reported that the annual mean temperature of Beijing from 1960 to 2008 increased at a rate of 0.39 °C decade^{-1}. This warming

Table 3 Fixed effects in the generalized nonlinear mixed models for annual changes in annual tree mortality rates as predicted by climatic variables

Data	β_1	*S.E.*	*P*
Annual mean temperature (AMT)	0.1817	0.0789	0.0239
Annual precipitation (AP)	−0.0038	0.0008	<0.0001
Annual heat-moisture index (AHM)	0.0457	0.0104	<0.0001

climate has contributed to declining fraction of precipitation. From 1961 to 2004, annual precipitation decreased at a rate of 1.722 mm year^{-1} (Xu et al. 2006). Climate change is expected to produce warmer temperatures and lower precipitations in Beijing (Wang et al. 2009). Water crisis is also expected as a consequence of climate change (Arnell 2004).

To understand the response of tree mortality to a warming climate, we examined three variables that govern forest growth and mortality: temperature, precipitation and a heat-moisture index. At our study sites, we found that tree mortality rates decreased significantly with increasing precipitation, and in contrast, increased significantly with warmer temperature and higher heat-moisture index (Table 3). The response of tree mortality rates to climate change induced drought could be caused by three factors: (i) carbon starvation (stopping most photosynthesis, thus failing in supporting the metabolic costs of maintaining tissue) (Adams et al. 2009); (ii) hydraulic failure (increasing water deficits and thus increasing the water stress) (Mcdowell et al. 2008; van Mantgem et al. 2009); or (iii) outbreaks of biotic agents (such as the growth and reproduction of insects and pathogens that attack trees) (Peng et al. 2011). Liu

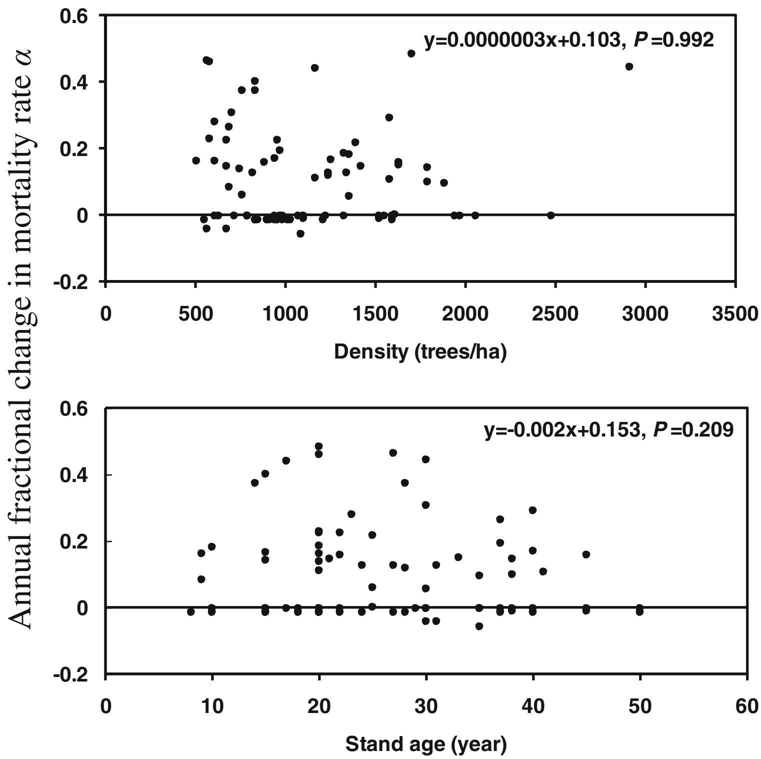

Fig. 4 Modeled annual fractional change in mortality rate *a* of individual plots relative to forest density and stand age

et al. (2013) found that rapid warming accelerates tree growth decline in semi-arid forests of inner Asia. Trees with slower growth rate were more susceptible to drought, and thus had higher mortality (Suarez et al. 2004). The contribution to tree mortality from climate change induced drought in the present study is consistent with both the apparent role of drought in episodes of recent tree mortality of subtropical monsoon evergreen broad-leaved forest in Southern China and the positive correlation between short-term variations in background mortality rates and climate change induced drought observed in temperate forests of the western United States (van Mantgem et al. 2009).

It should also be noted that other possible exogenous cause such as air pollution might affect tree mortality rates. Air pollution decreases tree vitality and accelerates death in a polluted environment. There are some studies on pollution caused changes of tree growth and the impact of tree defoliation on tree increment (Kramer 1986; Petras et al. 2004; Stravinskiene 2004). Ozone is the most pervasive of all air pollutants affecting forest health. Some researches (Isebrands et al. 2001; Percy et al. 2002; Karnosky et al. 2003) reported that O_3 reduced productivity gains in fast-growing species under enriched CO_2 atmospheres. Other air pollutants may also affect the forest health. N deposition may have subtle effects on forest health, thus exacerbating stand densification, susceptibility to insect, drought stress (Bytnerowicz et al. 2003). SO_2 gas is reported to causes direct red-brown discoloration and necrosis of foliage (Materna 2002) and reduced growth (Garsed and Rutter 1984). Beijing faces environmental problem of air pollution caused by rapid development economy and population and so on. If the air pollution factor had been used to analyze the effect of climate change induced drought on tree morality, the study would be improved and enhanced the results.

Overall, tree mortality rates have increased significantly over the past two decades across Beijing based on the PSPs data. The exogenous causes with regional warming and climate change induced drought were the dominant drivers of tree mortality, which was consistent with previous studies (Phillips et al. 2009; Peng et al. 2011). Under future global warming scenarios, droughts are likely to become more frequent in Beijing, and this trend is expected to continue in the future (Zhang et al. 2010), which would be a big threat to the Beijing environment.

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