Agricultural and Forest Meteorology 180 (2013) 164–172

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Response of chestnut phenology in China to climate variation and change

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ARTICLE INFO

Article history:
Received 7 February 2013
Received in revised form 2 May 2013
Accepted 10 June 2013

Keywords:
Chestnut
Climate change
First flowering
Growing season length
Leaf coloring
Partial Least Squares regression

ABSTRACT

Climate change has affected the phenology of plants and animals throughout the world, but few studies have evaluated climate responses of fruit trees in East Asia. In particular, the response of tree phenology to warming during different parts of the year has not been explored. We evaluated long-term records (1963–2008) of chestnut (*Castanea mollissima* Blume) first flowering, leaf coloring and length of the growing season from Beijing, China. Phenological dates were related with daily temperatures (subjected to an 11-day running mean) for the 12 months leading up to the respective events, using Partial Least Squares (PLS) regression. For each phenological indicator, regression results identified two relevant phases, during which temperatures were correlated with event timing or growing season length.

First flowering dates in Beijing advanced by 1.6 days per decade over the length of the record, whereas leaf coloring showed no significant trend. The growing season expanded by 4.3 days per decade. First flowering was advanced by high temperatures between January and June, but delayed by warm conditions during the chill accumulation phase (late October through early January). Leaf coloring was advanced by warm conditions during most of the growing season, but delayed by high temperatures in fall. Variation in the length of the growing season was strongly correlated to variation in spring phenology.

All phenological indicators of chestnut appeared to respond to high temperatures during certain parts of the growing season in a way that ran counter to currently dominant effects. For instance, warming during the period of chill accumulation delayed rather than advanced spring phenology. These secondary temperature responses may explain responses of certain plants and ecosystems that are not in line with general trends of advanced spring and delayed fall phases. It seems possible that the importance of these effects may increase as warming continues.

1. Introduction

Climate change has affected the timing of life events of plants and animals in recent decades. A number of methods have been used to examine these responses, including species-level ground observation, satellite remote sensing and direct warming experiments (Badeck et al., 2004; Cleland et al., 2007; Wolkovich et al., 2012). Most studies have indicated that spring phenological events (e.g. leaf unfolding and first flowering) and fall phenological events (e.g. leaf coloring and fall) have been advanced and delayed, respectively, resulting in longer growing seasons (Matsumoto et al., 2003; Menzel and Fabian, 1999). However, some exceptions to these general observations have been detected at high latitudes and high altitudes (e.g. Iceland, Kola Peninsula of Russia, and the Tibetan Plateau of China), where delayed spring events, advanced fall phenology or shortened growing seasons appeared (Frich et al., 2002; Kozlov and Berlina, 2002; Yu et al., 2010).

The majority of published studies have focused on phenological changes in natural vegetation. Relatively few reports are available on the response of fruit trees to climate change despite the high economic and agricultural values of these crops (Chmielewski et al., 2004). In Germany, first flowering dates of apple and sweet cherry advanced by about 2.1 days per decade from 1961 to 2000. Bloom dates there were significantly correlated with mean temperatures between February and April, with tree phenology advancing by about 5 days per 1 °C increase during this period (Chmielewski

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http://dx.doi.org/10.1016/j.agrformet.2013.06.004

et al., 2004). In France and Switzerland, advanced flowering has also been observed in apple and pear trees over the last 40 years (Guédon and Legave, 2008). In the northeastern United States, flowering of apple and grape was advanced by 2.0 and 1.5 days per decade, respectively, from 1965 to 2001 (Wolfe et al., 2005). In South Africa, full bloom dates of apple and pear have advanced on average by 1.6 days per decade from 1973 to 2009, and by 3.6 days per 1 °C rise in mean spring temperature (Grab and Craparo, 2011). Relevant reports from Asia are scarce. In Japan, the combined effect of advanced budding and delayed leaf fall for ginkgo extended the growing season by 12 days between 1953 and 2000 (Matsumoto et al., 2003). In China, researchers at the Institute of Geographic Sciences and Natural Resources Research at the Chinese Academy of Sciences (IGSNRR-CAS) investigated the response of woody plants to climatic change in Beijing, North China, as well as in the entire country, mentioning phenological changes of certain fruit trees (Bai et al., 2011; Ge et al., 2011; Xu et al., 2005; Zheng et al., 2006, 2003; Zhong et al., 2010).

Generally, most of the above studies conduct regression analyses between monthly or annual mean temperatures and phenological events to estimate the response of phenology to climate change. However, climate data at a monthly or annual scale might not be detailed enough for considering specific temperature effects on phenology that are restricted to particular parts of the year (Matsumoto et al., 2003). For example, there is evidence that only temperature increases during certain periods advance spring events, while warming during some stages of winter dormancy might have a phenology-delaying effect (Luedeling et al., 2012). For flowering and leaf emergence, temperate fruit and nut trees require the fulfillment of a chilling requirement (Campoy et al., 2011; Luedeling, 2012). Particularly in warm growing regions, but possibly also in colder places, warming during the chill accumulation phase should cause a delay in the fulfillment of chilling requirements, which could precipitate into a delaying effect on spring phases. The abundance of reports on advanced bloom and leaf emergence (Fitter and Fitter, 2002; Menzel et al., 2006; Parmesan, 2007) indicates that the effect of winter warming has thus far been small compared to the impact of rising temperatures in spring. Yet theory dictates that the winter warming effect exists and could become important, as temperatures increase further. Severe future losses in winter chill have been projected for many places, indicating future problems for several important fruit producing regions (Darbyshire et al., 2013; Luedeling et al., 2011a, 2009c). Commonly reported linear models of advancing phenology are not normally capable of accounting for such effects. It is noteworthy in this context that many studies of spring phenology trends that considered large numbers of species, while showing advancing phenology for most, have often included a sizeable number of 'diverging species' (Cook et al., 2012), which have either shown no change in phenology or even displayed delays. Cook et al. (2012) recently linked these diverging responses to winter warming. While less information is available on fall events, it also seems likely that the timing of leaf coloring or leaf fall is driven by temperature responses during certain periods only (Menzel, 2003).

Our analysis was based on an observational record of chestnut phenology from Beijing, China, where bloom, leaf unfolding and leaf coloring have been recorded since 1963. A novel method (Partial Least Squares regression) was used to correlate the phenology dates to temperature variation at daily resolution. The objective of the present study is to identify the relevant periods influencing chestnut phenological stages and to comprehensively evaluate the responses of spring event (first flowering), fall event (leaf coloring) and the length of the growing season to temperature variation during the relevant periods.

2. Materials and methods

2.1. Study area

Located on the North China Plain, Beijing has the longest and most abundant records of phenology in China (Zhang et al., 2005). Compared to American and European zones at similar latitude, climatic variation in Beijing is substantially greater, leading to greater variation in the timing of phenological events and providing valuable information for elucidating climate responses of species (Lu et al., 2006).

In Beijing, species-level phenological observations of plants were conducted in Beihai Park and Summer Palace. Both parks are former royal gardens with a long history of more than 150 years. The former is located in the city center, and the latter is in the suburbs. To reduce the influence of the urban heat island effect, we chose the Summer Palace (40°01′ N, 116°20′ E, 50 m a.s.l.) as the research site.

2.2. Phenology data

Phenological data of chestnut (*Castanea mollissima* Blume) at Beijing Summer Palace during 1963–2008 were acquired from the Chinese Phenological Observation Network (CPON) – a nationwide system of monitoring stations that has conducted standardized, systematic and comprehensive phenological observations of plants and animals across China since 1963. Details of the phenological observation method have been described by Wan and Liu (1979) and Lu et al. (2006). All observations were carried out daily during the growth period on the southern side of the trees. For analysis of the relationship between chestnut phenology and climatic variation during the whole year, we chose first flowering as indicator of spring phenology, and leaf coloring as indicator of fall events. First flowering was registered when 10% of flowers were open, corresponding to stage 61 on the BBCH ('Biologische Bundesanstalt Bundessortenamt und Chemische Industrie') scale for pome and stone fruits (Meier et al., 1994; applied here, because we are not aware of a scale for chestnuts). Leaf coloring dates (BBCH stage 95) were recorded when 50% of leaves had changed color (Chen et al., 2005). For calculating the length of the growing season, we interpreted first leaf unfolding (stage 11 on the BBCH scale) and leaf coloring as signs of start and end of the growing season (Chen et al., 2005; Dai et al., 2012).

2.3. Climatic data

Daily minimum and maximum temperatures in Beijing during 1963–2008 were obtained from the Beijing Meteorological Station which is only 2.5 km from the Summer Palace, so that temperatures recorded there should closely mirror conditions at the observation site. Mean daily temperatures were computed as the arithmetic mean between minimum and maximum temperatures (Luedeling et al., 2012). To ensure the emergence of recognizable temperature response patterns of phenological stages in subsequent statistical analyses, we subjected daily temperatures to an 11-day running mean (Luedeling and Gassner, 2012; Luedeling et al., 2012).

2.4. Identification of relevant periods influencing chestnut phenology

Partial Least Squares (PLS) regression was used to analyze the response of chestnut phenology (first flowering, leaf coloring, and length of growing season) to variation in mean daily temperatures during all 365 days of the year, based on data for 1963–2008. PLS regression, a procedure commonly used in chemometrics (Wold et al., 2001) and hyperspectral remote sensing (Luedeling et al.,