Dendrochronologia 40 (2016) 1–11

Contents lists available at ScienceDirect

Dendrochronologia

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

Original article

# Tree-ring-based reconstruction of drought variability (1792–2011) in the middle reaches of the Fen River, North China

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ARTICLE INFO

*Article history:*
Received 6 May 2015
Received in revised form 5 May 2016
Accepted 12 May 2016
Available online 20 May 2016

*Keywords:*
Dendrochronology
PDSI
North China
East asian monsoon

ABSTRACT

We developed a tree-ring chronology based on 52 ring-width series from 25 *Pinus tabulaeformis* trees at Tianlong Mountain (TLM) using the *signal-free* method. TLM is located in the middle reaches of the Fen River, North China, and is influenced by the East Asian monsoon system. Tree growth was highly correlated (0.789) with the Palmer Drought Severity Index (PDSI) from May to July and indicated a drought-stress growth pattern. Therefore, we developed a robust May-July PDSI reconstruction for 1792–2011 that explained 62.3% of the instrumental variance for 1951–2005. Severe drought years determined by the reconstruction are consistent with conditions reported in historical documents. The TLM PDSI reconstruction was consistent with other tree-ring-based hydroclimate reconstructions in North China; thus, it may accurately represent dry/wet changes that occur over a large area. Cyclical spectral peaks at 2–8 years in the reconstructed PDSI may indicate ENSO activity, as suggested by the positive correlation with the western Pacific sea-surface temperatures (SSTs) and the negative correlation with the eastern Pacific SSTs on the inter-annual scale.



## 1. Introduction

Increasing temperatures and decreasing precipitation have caused water shortages and drought in North China, particularly in arid and semi-arid regions such as Shanxi province, the region considered in the present paper (Sun et al., 2013). These more frequently occurring droughts in recent decades have caused great concern among the public (Meng, 2003; Wang et al., 2006; Chen et al., 2014, 2015a). The Fen River is the longest river and contains the largest basin in Shanxi Province. It is the second largest tributary of the Yellow River (Sun et al., 2013). A prominent feature within the Fen River Basin, drought causes critical water and grain shortages and seriously restricts sustainable agricultural development (Yin, 2002). For example, extreme droughts in the 1920s–1930s in northern China reduced food production so severely that at least four million people starved to death (Liang et al., 2006). Therefore, a historical record of drought variability would significantly help our understanding of droughts with regard to their severity and could provide a means of estimating their frequency. Unfortunately, instrumental records are only available for 60 years in this area, too short a time to gain a thorough understanding of the long-term regional variability of drought events and their underlying mechanisms. On the other hand, using natural proxies to perform paleoclimatic reconstructions may enable such long-term understanding.

Tree rings have been widely used for drought reconstructions because of their annual resolution, wide spatial distribution, and sensitivity to climate change (Li et al., 2006a; Cook et al., 2010; Chen et al., 2013, 2016). The Palmer Drought Severity Index (PDSI) was developed in 1965 to measure moisture conditions by incorporating the supplies and demands of antecedent precipitation, temperature, and soil moisture into a primitive hydrological accounting system (Palmer, 1965; Li et al., 2007). Following the methodology of Palmer (1965) and utilizing a $2.5^\circ \times 2.5^\circ$ grid system, Dai et al. (2004) developed a worldwide PDSI dataset. This PDSI dataset has been applied globally for drought reconstructions

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http://dx.doi.org/10.1016/j.dendro.2016.05.001
1125-7865/

(Cook et al., 2004, 2010). In China, PDSI reconstructions have been generated based on tree rings. For example, Li et al. (2008) reconstructed the drought history across China and Mongolia over the past four centuries and inferred the history of moisture variability during summer monsoons. Fang et al. (2010, 2012a) reconstructed the drought history of Kongtong Mountain in northern China and Guiqing Mountain in northwestern China. In addition, Liang et al. (2007) reconstructed the drought history of the Ortindag Sand Land in eastern Inner Mongolia. Further, Kang et al. (2012) reconstructed the drought history of north-central China, which indicated that recently observed reductions in tree growth were caused by a weak monsoon in combination with variability in atmospheric circulation. Although some temperature and precipitation reconstructions have been generated for the upper reaches of the Fen River and surrounding areas (Li et al., 2006a, 2013b; Yi et al., 2006; Cai et al., 2010; Sun et al., 2013), the PDSI has not been reconstructed using tree rings in the Fen River Basin.

Cook et al. (2010) reconstructed drought variability over the Asian monsoon area and produced the Monsoon Asia Drought Atlas (MADA). However, the MADA does not contain any chronologies for the study region considered herein, and the local hydroclimate pattern was reconstructed using remote tree-ring chronologies based on a 1000-km search radius (Cook et al., 2010), such that local information may be lacking. Thus, reconstruction of local drought variability via tree-ring samples from the region remains to be needed over the last several centuries for this TLM area.

The present paper reports the first tree-ring chronology (1792 CE–2011) for the Tianlong Mountain area using signal-free regional curve standardization (RCS) methodologies and reconstructs the PDSI variability that has occurred over the last two centuries along the middle reaches of the Fen River. The objectives of the study were as follows: (1) to explore the potential use of the tree-ring width proxy to infer the hydroclimate history of this region; (2) to investigate the regional representativeness of this reconstructed hydroclimate variability; and (3) to investigate the relationship between hydroclimate variability and SSTs.

## 2. Materials and methods

### 2.1. Study area

Our research area, the Tianlong Mountain Natural Reserve (TLM, 37°44′N, 112°22′E), is located 36 km from the center of Taiyuan in the middle reaches of the Fen River, North China, at an elevation of 1255–1402 m (Fig. 1). The TLM has a warm temperate continental monsoon climate (Wang et al., 2012) with an annual average temperature and total annual precipitation of 9.9 °C and 442 mm, respectively, based on data obtained from the nearest meteorological station (Taiyuan Station, 37°28′N, 112°20′E, 778.3 m elevation) (Fig. 2) for the 1951–2011 time period. Highest monthly mean temperatures occur in June (22.0 °C), July (23.7 °C), and August (22.0 °C), and summer precipitation from June to September accounts for 73% of total annual precipitation.

### 2.2. Tree-ring data and methods

Fifty-two tree-ring samples were collected from 25 old-growth Chinese pine trees (*Pinus tabulaeformis*). Most of the sampled trees were located at the edge of the forest, although some trees were located on a steep hillside with thin soil and rocky conditions (Fig. 3). Two or three samples were collected from single trees using increment borers at different orientations. Each sampled tree was photographed so that detailed site-specific features could be recorded to aid in the selection of appropriate tree-ring-sample candidates.

The samples were air-dried, finely sanded and cross-dated using standard dendrochronological techniques (Stokes and Smiley, 1968). The exact calendar years pertaining to each growth ring were assigned based on visual cross dating (Fritts, 1976). Such visually cross-dated tree rings were then measured and verified using the COFECHA program for quality control (Holmes, 1983). Age-related growth trends were removed using the RCSigFree program (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). All raw measurements were conservatively detrended by fitting negative exponential curves, linear regression curves, and Friedman super-smoother curves for the samples that showed anomalous growth or suppression (Cook, 1985). The detrended tree-ring series were averaged to generate the original standard (STD) chronology through biweight robust-mean estimations (Cook, 1985). Because it is difficult to distinguish "medium-frequency" (e.g., interdecadal variations) growth trends from common external forcing signals (e.g., climate variations) in data-adaptive fitted curves obtained for a tree-ring series, fitting growth curves often incorporate common forcing signals; this phenomenon is commonly referred to as the "trend distortion" problem (Melvin and Briffa, 2008). For example, a warming trend may cause the tree-ring width to increase in recent periods, which can artificially raise the fitted growth curve (e.g., negative exponential growth curve) and thereby result in underestimation of the warming trend (Fang et al., 2012b). The *signal-free* method was introduced to mitigate this problem by extracting the common external forcing signal from the conservative fitted curves and then adding them back to the STD chronology by a series of iterations.

Accordingly, the *signal-free* method was used to generate fitted curves without the incorporation of common external forcing signals. First, each signal-free measurement made for tree-ring standardization was calculated as the ratio of the raw measurement to the corresponding early version chronology (the original STD chronology in the first iteration). These signal-free measurements included the trees' growth trends and the common external forcing signals incorporated into the conservative fitted curves. Second, the signal-free measurements were detrended using conservative fitting curves to separate the common external forcing signals from the growth trends, thereby enabling us to obtain fitted curves for the signal-free measurements (growth trends of trees) and the *signal-free* chronology (i.e., the common external forcing signals). Third, the raw tree-ring measurements were detrended using the fitted curves of the *signal-free* measurements (growth trends of trees), and the first iteration STD chronology was generated. These steps were repeated until the final two STD chronology indices became very similar (Melvin and Briffa, 2008; Briffa and Melvin, 2009). Under ideal conditions, the final *signal-free* chronology indices should be close to 1 and should not contain the common external forcing signals. Because the final detrending curves of the raw tree-ring measurements lacked the common external forcing signals, the trend distortion problem was mitigated. The tree-ring chronology calculations obtained using the *signal-free* method were strictly based on the procedures introduced by Melvin and Briffa (2008).

Four iterations were conducted in this study. A comparison of the chronology indices with and without *signal-free* iterations since 1900 is shown in Fig. 4. A larger marginal fluctuation was observed in the first *signal-free* chronology iteration, indicating that it contained the common external forcing signals. After four iterations, the final *signal-free* chronology was relatively steady, flat, and close to 1, indicating that it contained the common external forcing signals to a much lesser extent (Fig. 4a). There is little distinction between the third and the fourth iteration STD, at which point the iteration ended. There were differences between the final STD chronology and the original STD chronology, particularly for the 1950s–1980s and 2000s data, indicating that additional common