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Stable isotope analysis reveals prolonged drought stress in poplar plantation mortality of the Three-North Shelter Forest in Northern China

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ABSTRACT

The Three-North Shelter Forest (TNSF) is an important ecological barrier in northern China. However, in the last decade, poplar tree degradation has occurred in ~80% of TNSF stands in Zhangbei County (Hebei Province), with about one-third of trees either dead or dying. Using isotopic techniques, we investigated the corrected $\delta^{13}C$ value of tree-ring ($\delta^{13}C_{cor}$) and intrinsic water-use efficiency (iWUE) differences between non-dieback and dieback trees of the same age to understand the cause of poplar dieback death associated with the TNSF. We found that the diameter of poplar trees within the same age group decreased as degradation progressed. From 1997, inter-group differences of $\delta^{13}C_{cor}$ and iWUE occurred but were not statistically significant. The differences became significant from 2002. Comparisons suggest that the continuous occurrence of positive ΔiWUE ($iWUE_{dieback} - iWUE_{non\text{-}dieback}$) may be the threshold for subsequent divergence of the two groups. Stepwise regression revealed that the impact of groundwater depth on iWUE was stronger than that of other environmental factors (e.g., temperature and evapotranspiration) and was the leading cause of poplar degradation. IsoSource model analyses indicated that non-dieback trees took water mainly from soil 30–80 cm below the ground surface, and that dieback trees did it mainly from 0–30 cm below the surface. Non-dieback trees used more water from the 80–150 cm soil layer and groundwater than did dieback trees. Groundwater depth, which increased in the experimental area and so aggravated local droughts, was strongly related to cumulative water consumption but not to evapotranspiration (ET_0), indicating that increasing groundwater depth was primarily caused by the change in land use. Therefore, poplar dieback in the TNSF in Zhangbei County was attributed to groundwater overuse associated with changed land use, which enhanced the duration and intensity of water stress on the trees.

1. Introduction

Traditionally, the Beijing–Tianjin–Hebei (BTH) region of China is frequently affected by sandstorms. The TNSF Program was initiated to build a “Green Great Wall” for northern China (Zhang et al., 2017). After four decades of development, the TNSF of Zhangbei County (Zhangjiakou City, Hebei Province) now has an essential role in protecting the BTH region from sandstorms (Wang et al., 2010). In its early stage, the program primarily selected poplar trees (*Populus simonii* Carr) because of their survival ability and fast growth. In the last decade, however, extensive degradation and mortality of poplar trees have been occurring in the shelterbelt plantations. A recent survey of TNSF shelterbelts (102 × 10^3 hectares) in Zhangbei County found that ~80% of the forest stands were degraded, and die-off or near die-off trees accounted for one-third of the total area. One reason for this high mortality could be aging of these trees (> 30 years) and decline of physiological functions as a natural result of aging. Another reason, however, may be related to external factors such as widespread and rapid drought (Adams et al., 2010; Clifford et al., 2013), drought-induced pathogen and insect outbreaks (McDowell et al., 2011). The exact cause of poplar degradation can be determined only by analyzing their ecological and physiological histories.

With the global warming and the change of precipitation pattern, droughts are becoming increasingly frequent (Hartmann et al., 2015; Ryan, 2011). In recent years, tree mortality and forest decline are frequently reported, which are commonly related to droughts at regional

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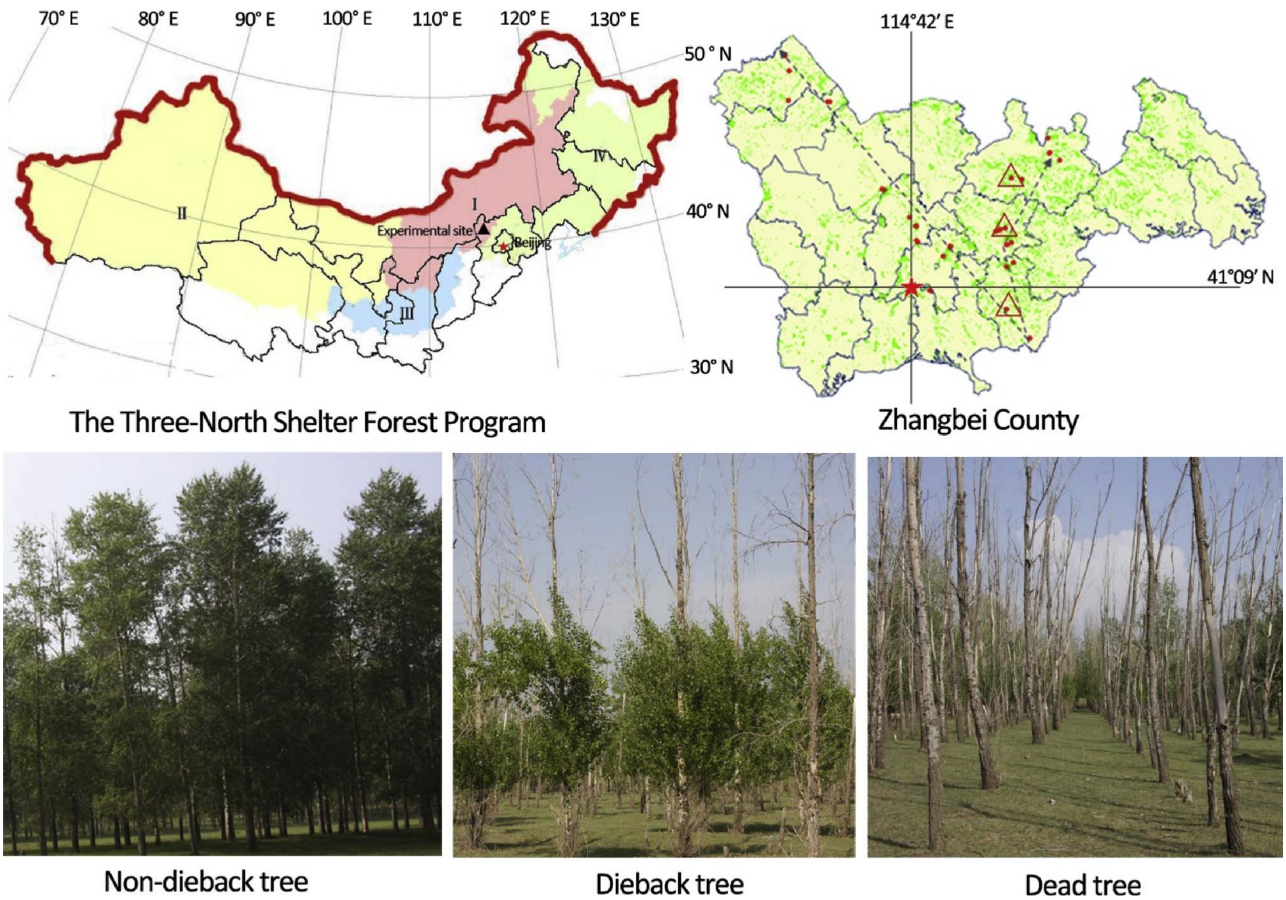

Fig. 1. Location of the Three-North Shelter Forest Program and experimental sites in Zhangbei County, Hebei Province, China. Dots show sampling of tree growth. Triangles show sampling of tree rings and water source.

scale (Pasho et al., 2011; Rowland et al., 2015). Three hypotheses have been proposed to explain drought-related tree mortality, such as hydraulic failure (Pangle et al., 2015; Plaut et al., 2012), carbon starvation (Dickman et al., 2015; McDowell, 2011; Sevanto et al., 2014) and biological attacks (McDowell et al., 2008; Speckman et al., 2015). In natural condition, the drought-induced tree mortality and forest decline are a long process of development, thus, it is required to continuously monitor drought-related physiological indicators (e.g., photosynthesis, evapotranspiration and stomatal conductance) over a long period. However, it is hard to be conducted and remains a challenging task.

Cellulose in tree rings offers a stable carbon isotope composition ($\delta^{13}C$) record of past climatic and environmental conditions during their growth (Loader et al., 2003; Schleser et al., 2015). The $\delta^{13}C$ in tree rings are valuable tools for retrospectively understanding ecophysiological response of trees to CO_2 elevation and climate change over annual to decadal scales. Under drought stress, a plant reduces stomatal conductance to avoid hydraulic failure, inevitably lowering the rate of photosynthesis and carbon assimilation (Lévesque et al., 2014; Mitchell et al., 2013). As a result, $\delta^{13}C$ also increases. The $\delta^{13}C$ ratio is directly related to water balance and iWUE. Studies have found that iWUE not only increases with increasing atmospheric CO_2 but also escalates significantly during droughts (Linares & Camarero, 2012; Nock et al., 2011; Wang et al., 2012), and so offers an important indicator of plant adaptation to such stresses (Battipaglia et al., 2014; Lévesque et al., 2014). By analyzing differences in iWUE of tree rings between non-dieback and dieback trees, we can evaluate the difference in intensity of drought stress on such trees. Several recent studies have investigated relationships between iWUE and factors such as plant growth (Urrutia-Jalabert et al., 2015; Wang et al., 2012), water stress (Battipaglia et al., 2014; Linares & Camarero, 2012), climate change (Fernández-de-Uña et al., 2016) and drought-induced tree mortality (Hartmann et al., 2015; Hereş et al., 2014; Pellizzari et al., 2016). However, the association between iWUE and environmental changes (e.g., temperature, ET_0-P, water table and land use) affected by human activities during tree dieback death were still poorly understood.

Water is an important resource for plant growth (Inzé, 2010). In recent years, irrational use of natural resources has aggravated global climate change and inequality in water resource distribution, leading to severe regional water shortages and plant mortality (Barbeta et al., 2015; Zhang et al., 2008). Several important questions related to extensive poplar dieback death in the TNSF remain unanswered, and clarification of these questions may provide important clues to understanding these events and developing potential solutions. These questions are as follows: (1) why, even in the co-located shelterbelt, do some poplar trees die back while others do not? (2) When did the dieback trees begin to show growth decline? (3) Which factor induced the degradation, climate change or land use? (4) Are dieback trees different in their water source and water use from non-dieback trees? There are difficulties in analyzing these questions because detailed records of poplar growth, degradation and death over the past 40 years were not kept. Stable hydrogen, oxygen and carbon isotopic techniques, however, provide effective tools for unraveling these questions.

In this study, we analyzed the dieback of poplar trees in the TNSF of Zhangbei County and the underlying factors, using isotopic techniques characterizing tree-ring stable carbon isotope, iWUE and water sources. Our objectives were to: (1) quantitatively evaluate poplar growth and dieback; (2) characterize differences in $\delta^{13}C_{cor}$, iWUE and basal area increment (BAI) between dieback and non-dieback trees; (3) ascertain whether non-dieback and dieback trees are different in their sources of water; and (4) identify major factors responsible for poplar degradation