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The effects of short-term rainfall variability on leaf isotopic traits of desert plants in sand-binding ecosystems

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ABSTRACT

Sand-binding vegetation is effective in stabilizing sand dunes and reducing soil erosion, thus helps minimize the detrimental effects of desertification. The aim of this study is to better understand the relationships between water and nutrient usage of sand-binding species, and the effects of succession and rainfall variability on plants' water–nutrient interactions. We examined the effects of long-term succession (50 years), inter-annual rainfall variability (from 65% of the mean annual precipitation in 2004 to 42% in 2005) and seasonality on water–nutrient interactions of three major sand-binding species (*Artemisia ordosica*, *Hedysarum scoparium* and *Caragana korshinskii*) by measuring foliar $\delta^{13}C$, $\delta^{15}N$ and [N]. Long-term succession in general did not significantly alter $\delta^{13}C$, $\delta^{15}N$ and [N] of the three species. Short-term rainfall variability, however, significantly increased foliar $\delta^{13}C$ levels of all three species by 1.0–1.8‰ during the severely dry year. No significant seasonal patterns were found in foliar $\delta^{13}C$ and $\delta^{15}N$ values of the three species, whereas foliar [N] varied by season. For the two leguminous shrubs, the correlations between $\delta^{13}C$ and $\delta^{15}N$ were positive in both sampling years, and the positive correlation between [N] and $\delta^{13}C$ was only found in the severely dry year. The results indicate that these sand-binding plants have developed into a relatively stable stage and they are able to regulate their nitrogen and water use in responding to environmental conditions, which reinforces the effectiveness of plantation of native shrubs without irrigation in degraded areas. However, the results also indicate that short-term climate variability could have severe impact on the vegetation functions.

1. Introduction

Desertification is one of the major environmental problems worldwide (Reynolds et al., 2007) and it occurs in almost every habitable region such as North America (e.g., Schlesinger et al., 1990; Li et al., 2008; Ravi et al., 2009), Africa (e.g., Thomas et al., 2008; Wang et al., 2010a) and northern China (e.g., Chen et al., 1996; Mitchell et al., 1998; Liu et al., 2012). The deserts in northern China are expanding at an estimated rate of 2100 km^2 $year^{-1}$ (Chen et al., 1996; Mitchell et al., 1998).

Revegetation of native shrubs, a massive ecological engineering project (Mitsch et al., 1993), has been one of the most effective methods to reduce desertification. Large areas of China's desert regions have been reclaimed through planting of native plants since the 1950s (Shapotou Desert Research and Experiment Station, 1986). For example, the 1000-km long Baotou-Lanzhou railway that passes through Shapotou region has been protected by sand-binding shrubs that were planted in 1956, 1964, 1981 and 1987, respectively (Shapotou Desert Research and Experiment Station, 1986). The success of these efforts suggests that it is an effective approach to control desertification and to restore the ecological environment along transportation corridors in the desert regions of China (Xiao et al., 2003a; Li et al., 2006). Many revegetated

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species, such as *Caragana intermedia*, *Calligonum arborescens* and *Tamarix ramosissima*, disappeared over the years, whereas some native species such as *Artemisia ordosica*, *Hedysarum scoparium* and *Caragana korshinskii* survived during succession and have become the dominant shrubs (Ma et al., 2002). As a result of long-term succession, the planted vegetation ecosystem is expected to develop into a stable system (Xiao et al., 2003b). The effects of long-term succession and short-term climate variability (e.g., rainfall) on the function of these successful sand-binding species (e.g., *A. ordosica*, *H. scoparium*, and *C. korshinskii*) are not yet fully understood, which hinders our ability to predict future successional pathways of such planted ecosystems under the circumstances of potential warming and drought in this region (Solomon et al., 2007).

In this study, we measured dual isotope (^{13}C and ^{15}N) compositions and nitrogen concentrations ([N]) of three dominant species, i.e., *A. ordosica*, *H. scoparium*, and *C. korshinskii*, and analyzed their interactions to investigate the effects of long-term succession (50 years) and short-term drought (2 years) on plant uptake of water and nitrogen at a desert stabilized by sand-binding plants in northern China. Besides providing valuable isotopic information of these sand-binding species, this study will have both theoretical and applied importance in the restoration of degraded ecosystems and in improving our ability to predict the response of planted sand-binding vegetation to climate change.

Stable isotopes are used in the investigation because they provide integrated information on plant water and nutrient use and serve as powerful tracers in ecosystem studies. The stable carbon isotope ratio (δ^{13}C) of plant tissues reflects the relations between plant carbon and soil water. The effect of water availability on carbon isotope discrimination during photosynthesis of C_3 plant is relatively well understood (e.g., Farquhar et al., 1982). For example, photosynthesis depends on water availability, and low water availability can decrease the assimilation of carbon, thereby reducing plant productivity and the corresponding nitrogen requirements or assimilation rates, leading to different patterns of δ^{13}C and δ^{15}N variation (Yoneyama et al., 2001). Foliar δ^{13}C typically increases when water availability is low, as a result of stomatal closure and reduced transpiration (Peuke et al., 2006). And foliar δ^{13}C is higher in the water-limited treatment relative to the well-watered treatment (Grant et al., 2012). Analyses of δ^{13}C have greatly increased our understanding of the relationships between water and carbon use by desert plants (Ehleringer, 1993). Nitrogen isotope ratio (δ^{15}N) provides information on ecosystem nitrogen cycling (Högberg et al., 1995; Roggy et al., 1999; Ometto et al., 2006; Bai et al., 2009) and plant nitrogen isotope discrimination is related to the availability of nutrients and water (Högberg, 1997; Swap et al., 2004; Aranibar et al., 2008; Wang et al., 2010b). Previous studies showed that succession affected N cycling and it was reflected in foliar δ^{15}N (Davidson et al., 2007; Wang et al., 2007), and foliar δ^{15}N signatures decreased as successional age increased at both the plant community and species levels (Wang et al., 2007).

Plant δ^{13}C and δ^{15}N signatures are often regulated by two or more factors (BassiriRad et al., 2003; Murphy and Bowman, 2009). For example, Schulze et al. (1991) point out that the significant correlation between δ^{15}N and δ^{13}C values of nitrogen-fixing African trees is caused by decreased water use efficiency, compared with that of the non-nitrogen-fixers. The decreased water use efficiency in nitrogen fixer usually is a result of the extra cost of carbohydrate supply to the nitrogen-fixing diazotroph (Farquhar and Richards, 1984).

Previous research also shows that photosynthetic capacity is strongly correlated with C_3 plant foliar [N] because photosynthetic enzymes, such as RuBP carboxylase, contain large amounts of nitrogen (Reich et al., 1998; Tognetti and Penuelas, 2003). It is also found that higher photosynthetic activity leads to enriched foliar δ^{13}C values (O'Leary, 1981). Because of these two reasons, positive correlations between foliar δ^{13}C and [N] have been found in many cases (e.g., Sparks and Ehleringer, 1997; Wang et al., 2008). Such relationships together with the positive correlation between foliar δ^{15}N and [N] in non-nitrogen-fixing plants (Hobbie et al., 2000; Wang et al., 2007) suggest that foliar δ^{13}C, δ^{15}N, and [N] levels are closely linked.

This study is to investigate the interactions of plant nitrogen and water use in planted sand-binding vegetation after long-term succession and to test whether there are functional group (potential nitrogen-fixer and non nitrogen-fixer) dependent adaptation strategies to water and nitrogen variations in the harsh environments. Specifically, the objectives of this study are to investigate (1) the long-term effect (up to 50 years) of successional age on the isotopic signatures (δ^{13}C and δ^{15}N) and [N] of three dominant shrubs in planted sand-binding vegetation communities; (2) the effects of seasonality and short-term drought on variations in isotopic signatures and [N] of each species; and (3) the relationships between δ^{13}C, δ^{15}N, and [N] of the three shrub species. The results will provide important implications on how plant species adapt to harsh environments in terms of water use efficiency and nutrient use during succession and how plant species respond to environmental changes.

2. Materials and methods

2.1. Study area

Shapotou region is located at the southeastern border of the Tengger Desert in China (Fig. 1). The region receives high solar radiation and is low in relative humidity. Average annual precipitation is 180.2 mm, with 80% of the rainfall occurring from May to September. The mean annual temperature is 10.0 °C, with a mean January temperature of −6.9 °C and a mean July temperature of 24.3 °C. The water table is more than 80 m below ground, thus rainfall is usually the only source of water for plants.

The planting of sand-fixing vegetation in the mobile dunes of the Shapotou region began in 1956 and subsequent revegetation occurred in 1964, 1981 and 1987, respectively. There was no irrigation or fertilization for these plantings. We calculated the successional age as of the year 2005 (the final year of the sampling), and the four sites selected were 50 year-old, 42 year-old, 25 year-old and 19 year-old for 1956, 1964, 1981 and 1987 planting, respectively. As a result of long-term succession, the mobile dunes were already stabilized at the time of the experiment. Local ecosystems have changed into a grass dominated semi-desert landscape with increasing rates of biological processes and an accumulation of soil organic matter despite the extreme environment (Table 1) (Xiao et al., 2003b). In all planted zones, the three dominant species survived long-term succession were *A. ordosica*, *H. scoparium* and *C. korshinskii*. *A. ordosica* is a succulent, non-nitrogen-fixing semi-shrub xerophyte, and is found in desert and semi-desert biomes. *H. scoparium* and *C. korshinskii* are leguminous xerophytic shrubs and have been reported to have nitrogen fixing activities (Tan et al., 1996; Ma, 2003). The soil physical and chemical properties also improved after revegetation (Table 1) though levels of variation remained high. The vegetated soil profile in the area were composed of a surface biological crust (up to 13.0 mm thick), a transitional layer (up to 50 mm thick) and an original layer of shifting sand (Duan et al., 2003). The biological crust may supply most of the fixed nitrogen to desert plant and soil communities. It may also reduce the loss of nutrient-rich fine soil particles to erosion by binding soil particles together, promoting the formation and increasing the size of soil aggregates.