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Extreme natural drought enhances interspecific facilitation in semiarid agroforestry systems

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ABSTRACT

Agroforestry is a widely advocated adaptation strategy for enhancing agricultural resilience to extreme climates. However, it is somewhat controversial and there is limited evidence regarding its efficacy in semiarid regions. Here we describe studies on jujube agroforestry regimes using two different cash crops: the annual fodder species rape (*Brassica napus*) and the perennial daylily (*Hemerocallis fulva*). The jujube agroforestry systems were characterized with respect to their interspecific water interactions and their responses to extreme natural drought using stable isotopic techniques and in situ soil water observations in China's semiarid Loess Plateau region. We found that agroforestry altered the jujube trees' water sources but its impact depended on soil wetness: compared to monocultures, jujube trees in agroforestry systems generally shifted to deeper water under dry conditions but to shallower water under wet conditions. Complementary water use between jujube trees and crops was observed on most sampling dates, but there was clear evidence of water competition in the shallow layer under relatively wet conditions. Furthermore, a simple index, Relative Difference in Soil Water content (RDSW), was developed to indicate interspecific water interactions under various wetness conditions. It was found that facilitative interspecific interactions were clearly enhanced in both agroforestry systems during extreme drought. In addition, jujube yields in agroforestry systems were clearly higher than in monoculture. These findings demonstrate that agroforestry is a climate-smart agricultural system and can increase the resilience of semiarid jujube plantations to extreme real-world drought.

1. Introduction

Global crop yields are projected to start decreasing in the 2030s due to unprecedented climatic changes, e.g., extreme drought (IPCC, 2014), and these losses will be borne primarily by smallholder farmers in developing countries (Lasco et al., 2014). This potential decline in agricultural production, together with the expected growth of human populations necessitates the development of agricultural systems with higher response capacities than those currently in use (Tscharntke et al., 2011). However, agricultural intensification via monoculture, which is widely practiced by smallholder farmers, reduces the ecological resilience of land and makes it more vulnerable to climate extremes (Lott et al., 2009). Agroforestry is an alternative agricultural strategy based on the cultivation of trees and shrubs alongside crops. It is often recommended by agro-ecologists as a strategy for increasing agricultural resilience to climate change (e.g., Mbow et al., 2014; Lasco et al., 2014).

A fundamental hypothesis of agroforestry is that the species involved have complementary water use patterns and therefore avoid undue competition (Fernández et al., 2007), which has been well known in natural ecosystems (Ong and Leakey, 1999). This hypothesis is generally valid in water-rich regions such as humid tropical areas (Schwandenmann et al., 2010; Lin, 2010). However, in water-limited regions (e.g., semiarid and sub-humid areas), water competition is a major concern in agroforestry (Livesley et al., 2004; Ling et al., 2017). The benefits of shade trees in ameliorating microclimates can be negated by low soil water availability due to interception loss and canopy transpiration (Ong et al., 1991; Ong and Leakey, 1999). Intense competition for soil water due to the presence of inappropriate shade tree species has been reported to reduce crop yield during drought periods (Rao et al., 1997; Jose et al., 2004; Sudmeyer and Hall, 2015). These negative effects cause farmer to remove shade trees or inter-row

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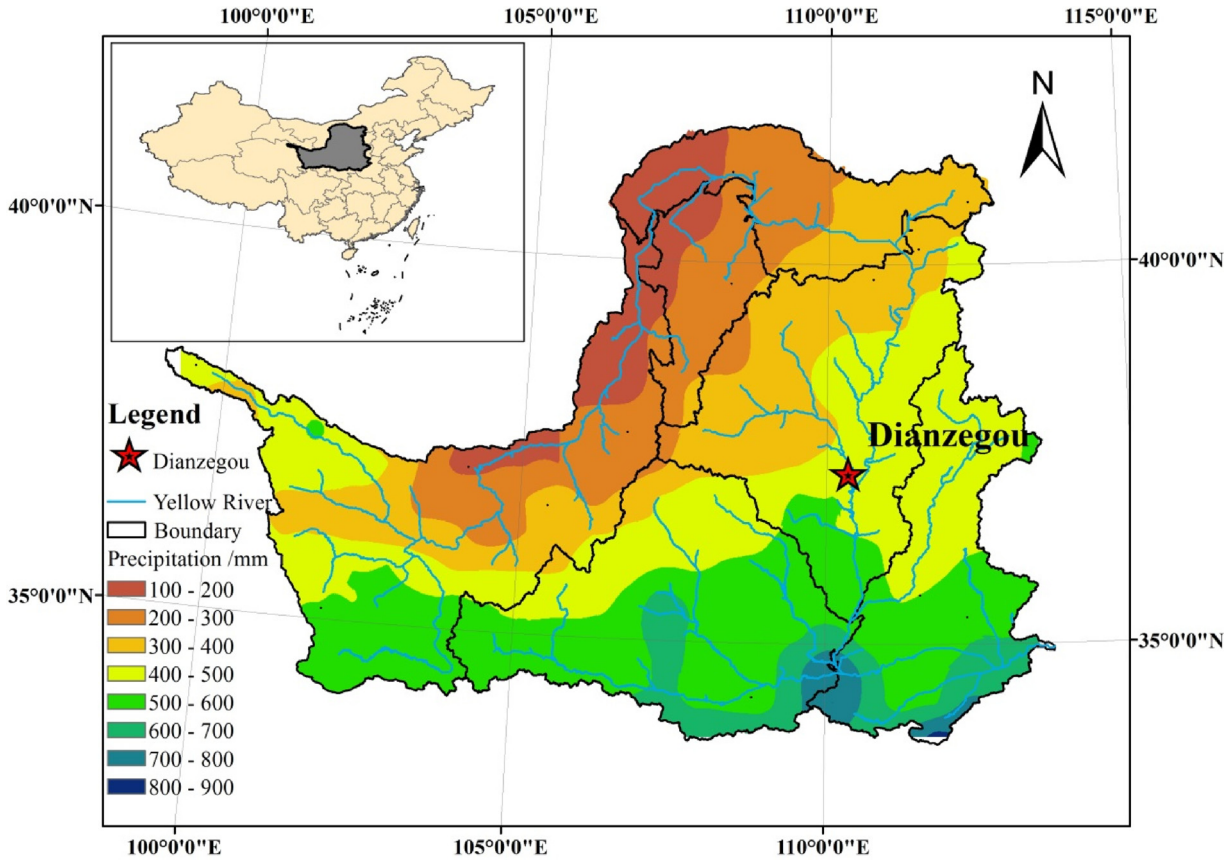

Fig. 1. The location of the study site and the spatial distribution of annual mean precipitation of the Loess Plateau.

grasses/crops to avoid competition with main species (Bisseleua et al., 2009; Steffan-Dewenter et al., 2007). However, the benefits of agroforestry are expected to be significant in the long term because it promotes the development of more complex agroecosystems (Ong and Leakey, 1999; Tscharntke et al., 2011).

There is an intense debate about the resilience of agroforestry systems towards extreme droughts, which is a crucial aspect of the sustainability of agroforestry in general (Ong and Kho, 2015). The stress-gradient hypothesis (SGH) states that in natural ecosystems, increasing levels of abiotic stress promote facilitative interspecific interactions, or at least do not increase competition (He et al., 2013). However, the validity of the SGH in man-made ecosystems (e.g. agroforestry systems) is rarely tested. In a cacao agroforestry plantation in a tropical humid region (mean annual precipitation, MAP, > 2000 mm), Schwendenmann et al. (2010) found that shade trees used more soil water from deeper layers and cacao continued to abstract shallow water when precipitation was reduced to 20% of the ambient amount using an artificial understory roof. These complementary water use strategies increased interspecific facilitation and only mildly reduced sap flux density and cacao yield in the drought treatments. However, this artificial drought did not accurately mimic real-world droughts which are typically accompanied by elevated air temperatures. In a cocoa agroforestry system in a less humid climate (MAP < 1200 mm), Abdulai et al. (2018) found that extreme natural drought caused extensive cocoa mortality due to strong competition for soil water. However, to our knowledge, the response of interspecific water interactions in agroforestry has been not reported to extreme droughts in semiarid regions of MAP < 600 mm.

China alone possesses almost half the world's small farms (Cui et al., 2018). A range of agroforestry forms have been practiced for thousands of years on these small farms, many of which continue to thrive today (Hong et al., 2017). The Loess Plateau is a particularly important region of China because it was the cradle of Chinese civilization and because it is subject to severe soil erosion that threatens the viability of its agroecosystems (Gao et al., 2014). Consequently, it has been a hotspot for research on ecological rehabilitation in recent years (Chen et al., 2015; Wang et al., 2015; Feng et al., 2016; Gao et al., 2018), and has become China's most successful ecological restoration zone thanks to the implementation of the Grain for Green Project (Fu et al., 2016). Among the tree species suitable for revegetation, tree cash crops such as jujube (*Ziziphus jujuba*) stand out because they are effective at controlling soil erosion and increasing farmers' incomes (Li et al., 2018). In practice, jujube farmers prefer monoculture and generally clear all vegetation between jujube rows to avoid interspecific water competition. Although suitable intercropping has been shown to beneficially affect soil water storage (Ling et al., 2017), little is known about how the water use strategy of tree cash crops is affected by intercropping and how interspecific water interactions respond to extreme real-world drought.

The primary objectives of this study were (i) to investigate the impacts of intercropping on water use by jujube trees and differences between annual and perennial crops; (ii) to examine seasonal variations in interspecific water interactions under various soil wetness situations; and (iii) to probe the response of interspecific water interactions to extreme real-world drought. Our hypotheses were that (i) intercropping would cause jujube trees to draw water from deeper soil layers compared to monoculture jujube trees to avoid undue competition for water; that (ii) the deeper roots of perennials compared to annuals would give rise to greater interspecific water competition with jujube trees under low soil water conditions; and that (iii) prolonged and extreme drought would result in severe interspecific water competition, reducing jujube yields. These hypotheses were tested by measuring stable isotope levels in xylem and soil water samples, *in situ* soil water content, and fine-root distributions in a rainfed jujube agroforestry

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