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Mixing trees and crops increases land and water use efficiencies in a semi-arid area

Wei Bai[a,b], Zhanxiang Sun[b,*], Jiaming Zheng[b], Guijuan Du[b], Liangshan Feng[b], Qian Cai[b], Ning Yang[b], Chen Feng[b], Zhe Zhang[b], Jochem B. Evers[d], Wopke van der Werf[d], Lizhen Zhang[c,*]

[a] College of Land and Environment, Shenyang agricultural University, Shenyang 110161 Liaoning, China
[b] Tillage and Cultivation Research Institute, Liaoning Academy of Agricultural Sciences, Shenyang110161 Liaoning, China
[c] College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China
[d] Wageningen University, Centre for Crop Systems Analysis (CSA), Droevendaalsesteeg 1, 6708 PB, Wageningen, The Netherlands

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ABSTRACT

Sustainable increases in food production in semi-arid regions require efficient use of land and water resources. Agroforestry is the practice of combining tree and crop cultivation on a land parcel and may increase both land productivity and water use efficiency. We conducted two years of field experiments in the semi-arid Khorchin region in Liaoning, China, to determine to which extent land and water use efficiencies were affected by mixing apricot (*Prunus armeniaca*) trees with annual crops: peanut (*Arachis hypogaea*), millet (*Pennisetum italica*) or sweet potato (*Ipomoea batatas*). Apricot yields were not significantly affected in the agroforestry, compared to the sole stand, but yields of the annual crops were lower when grown under trees than as sole crops, with relative crop yields of 0.46 for millet and 0.35 for both peanut and sweet potato in the agroforestry. Crop rows near tree rows had lower yields than crop rows further away from trees. Land equivalent ratios (LER) were 1.34, 1.44 and 1.33 in mixed systems with peanut, millet and sweet potato, respectively. Mixing crops and trees did not increase water extraction from the top 100 (2012) or 200 cm (2013) soil profile comparing to sole tree. Thus, with increased crop output and similar apricot yield, the water use efficiency was improved in the mixed system. Water use efficiency of the mixed system was characterized with the water equivalent ratio (WER). This index, analogous to LER, expresses the relative yield total per unit of water in the mixed system compared to the sole crops. WERs were 1.39, 1.51, and 1.34 in agroforestry systems with peanut, millet and sweet potato, respectively. We conclude that apricot-based agroforestry improves the productivity and water use efficiency of rain-fed agriculture in this semi-arid area, especially when a drought adapted crop such as millet is used.

1. Introduction

Crop production in semi-arid areas is very sensitive to variation in rainfall and to soil erosion by wind (Feng et al., 2010). Especially in regions such as the Khorchin region in north-east China, a typical semi-arid area with fragile natural and agricultural systems at the transition of agriculture and natural grassland, agriculture suffers from drought during crop growth in summer due to limited total rainfall and from frequent sand storms in spring (Bai et al., 2014). Through agroforestry farmers aim to increase resource use efficiency (e.g., for light or water), reduce wind erosion (Zhu et al., 2000) and mitigate risks related to climate change (Smith et al., 2012). Apricot-based agroforestry is a newly emerging crop production system in Khorchin, where apricot production represents more than 90% of total Liaoning apricot production (Zhang and Li, 2004). Farmers usually grow apricot trees at a wide row spacing because the frequent seasonal drought and deep underground water table (below 200 m) do not allow sustained tree production at high densities after approx. six years. Sometimes crops are grown between tree rows because the row spacing is wide enough, but often the space is left unused. Local farmers found that they could obtain additional output and revenue by growing understory crops such as peanut, millet, sweet potato, pumpkin or vegetables under-

* Corresponding authors.
E-mail addresses: sunzhanxiang@sohu.com (Z. Sun), zhang.lizhen@hotmail.com, Zhanglizhen@cau.edu.cn (L. Zhang).

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neath the apricot trees. These understory crops also reduced wind erosion. According to local farmers, the income generated in apricot agroforestry is approximately 25% higher than in sole apricot and almost double that in sole peanut or millet. However, no scientific studies have been made to substantiate these claims and elucidate underlying mechanisms.

Agroforestry may increase land productivity, as measured by a land equivalent ratio (LER) of 1.19 in pear agroforestry (Meng and Zhang, 2004), and of 1.24–1.45 in a jujube agroforestry system (Zhang et al., 2013). A LER above 1.0 indicates high land use efficiency compared to monocultures (Willey, 1990; Zhang et al., 2007). The LER in agroforestry systems may be up to 2.0 (Smith et al., 2012). The increase of land productivity in agroforestry (Ghosh, 2004; Unger et al., 2013; Craig et al., 2013; Sun et al., 2014) can be due to various factors, including increased radiation capture (van der Werf et al., 2007), higher radiation use efficiency (Zhang et al., 2014), a reduction of soil evaporation (Lin, 2010), greater soil fertility (Rivest et al., 2003), and better soil properties (Risch, 1983).

Wallace (2000) stresses the importance of water use efficiency in agriculture to meet future food demands. Contrary to the wealth of information on land use efficiency (Yu et al., 2015), comparatively little information is available about water use efficiency in mixed plant production systems. Water use efficiency (WUE) may be greater in mixed systems than in monocultures (Morris and Garrity, 1993). Wallace et al. (1999) reported that soil evaporation was reduced by canopy shade in a *Grevillea robusta* agroforestry system in Kenya. Higher WUE in intercropping was due to increased root density in the upper layers, thus decreasing water loss by evaporation e.g. in maize and cowpea (Ghanbari et al., 2010).

It is impossible to separately determine water uptake (WU) and water use efficiency (WUE) for each component species in intercropping, because the root systems of intercropped crops explore overlapping soil volumes to compete water and nutrients (Li et al., 2013). However, we can measure water use of the intercrop as a whole. To determine overall WU and WUE of intercrops, parameters of ΔWU (Morris and Garrity, 1993) for relative water uptake and water equivalent ratio (WER) for relative water use efficiency (Mao et al., 2012) were developed to compare the advantage of water use between intercrops and sole crops. Here we study the productivity and water use of apricot agroforestry systems in Khorchin as a case study in the sustainable intensification of agricultural productivity under semi-arid conditions.

The objectives of this study were to (a) quantify land productivity and water use efficiency in three common types of apricot agroforestry, i.e. apricot/peanut, apricot/millet, and apricot/sweet potato; (b) quantify the growth of the understory crops and the spatial distribution of soil moisture in the soil in relation to water competition between crops and trees.

2. Materials and methods

2.1. Field experiments

Field experiments were conducted in Zhanggutai (42°43′N, 122°22′E), Liaoning province, northeast China, in 2012 and 2013. The experimental site is at 227 m above sea level. Annual potential evaporation measured by evaporation pan is 1700–1800 mm. The annual mean air temperature is 7.2 °C. The average length of the frost-free period is 156 days. Average relative humidity is 59%. Annual wind speed is 3.7–4.6 m s^{-1}. The climate is classified as cold with a dry winter and hot summer (Dwa) in the Köppen-Geiger classification (Peel et al., 2007). The site has an Aeolian sandy soil with a bulk density of 1.45 g cm^{-3}, a soil moisture content at field capacity in the top 200 cm of 30.1%, a pH of 6.21, an organic matter of 6.58 g kg^{-1}, a total soil nitrogen content of 0.483 g kg^{-1}, a total phosphorus content of 0.281 g kg^{-1}, and a total potassium content of 2.7 g kg^{-1}. Total rainfall was 756 mm in 2012 and 590 mm in 2013, while rainfall during the crop growing season from May to September was 526 mm in 2012 and 456 mm in 2013. The annual mean air temperature was 7.3 °C in 2012 and 7.8 °C in 2013, while the mean air temperature during the crop growing season was 21.2 °C in 2012 and 21.3 °C in 2013 (Fig. 1).

Seven cropping systems were compared: sole millet (*Setaria italica*), sole peanut (*Arachis hypogaea*), sole sweet potato (*Ipomoea batatas*), sole apricot tree (*Prunus armeniaca*), and three agroforestry systems, each consisting of one of the annual crops additively intercropped between the apricot rows. The sole apricot and agroforestry treatments were included in a randomized complete block designed with 3 replicates in both years. Plots of sole crops were grown in a separate field, randomly assigned to a block 150 m away from the agroforestry plots to avoid above-and below ground interactions between trees and sole crops. Every plot covered an area of 67.5 m^2 (15 m length × 4.5 m width). The rows were oriented north-south. The distance between apricot tree lines was 4.5 m with 2 m distance between trees in the row. Crops were sown in strips of six rows at 0.5 m distance, with 1 m distance between the outer rows of the crop strip and the tree line (Fig. 2). Row spacing and plant densities and row distances in the sole crop systems were the same as in the agroforestry plots, the only difference being the continuity of crop rows, without interruptions by any tree lines. Therefore, the agroforestry plots had 33% fewer rows per unit of total area than the sole crop plots. Crops were sown on May 21, both in 2012 and 2013. Crops were harvested on September 25 in

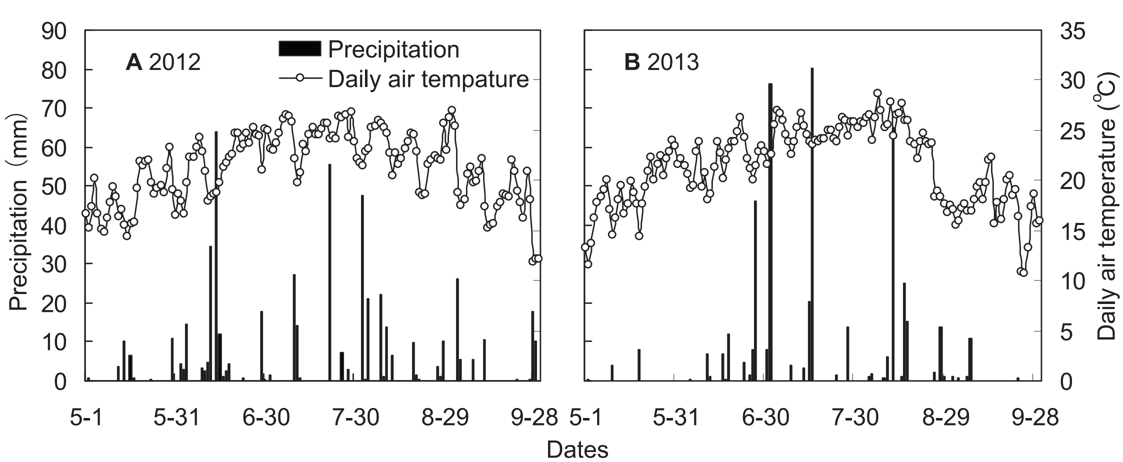

Fig. 1. Daily air temperature and precipitation during crop growing season at Zhanggutai, Liaoning, China in 2012 (A) and 2013 (B).