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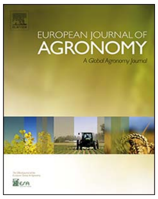

Agroforestry enables high efficiency of light capture, photosynthesis and dry matter production in a semi-arid climate

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ABSTRACT

Agroforestry systems, which combine annual crops with trees, are used widely in semi-arid regions to reduce wind erosion and improve resource (e.g. water) use efficiency. Limited knowledge is available on optimizing such systems by the choice of crop species with specific physiological traits (i.e. C3 vs C4, N-fixing vs non-N-fixing). In this study we quantified the light interception and utilization efficiency of trees and crops in agroforestry systems comprising apricot trees and a C3 species (sweet potato), a C4 species (millet) or an N-fixing legume species (peanut), and used measurements in the sole stands as a reference. A significant delay in leaf growth was found in millet. Maximum LAI of millet was 17% higher in agroforestry then expected from sole crop LAI, taking into account the relative density of 2/3, while a 25% decrease in maximum LAI compared to expected was observed in peanut and sweet potato. The total light interception in agroforestry was 54% higher than in sole tree stands and 23% higher than in sole crops. The millet intercepted more light and produced more biomass in agroforestry than peanut and sweet potato. The LUE values of the crops in the mixed systems were higher than those of the sole crops, as was the photosynthetic efficiency of individual leaves, especially in plants in the border rows of the crop strips. High light capture in agroforestry made a greater contribution to productivity of understory crops than the increases in light use efficiency. We conclude that agroforestry systems with apricot trees and annual crops, especially millet, can improve light utilization in semi-arid climates and contribute to regional sustainability and adaptation to climate change.

1. Introduction

Agroforestry (AF) has many benefits, including food production, biodiversity conservation (George et al., 2013), soil enrichment (Udawatta et al., 2008), carbon sequestration (Nair et al., 2009) and efficient resource use (Munz et al., 2014). It also plays an important role for a multifunctional and sustainable agriculture landscape (Schroth and da Mota, 2013) by offering ecological services and environmental benefits by reducing soil wind erosion and desertification (Branca et al., 2013). For these reasons, apricot-based agroforestry has been widely practiced in the Khorchin region in Northeast of China. The yield and water use efficiency of apricot agroforestry with annual crops millet, peanut and sweet potato were higher than sole stands, especially when a legume crop (peanut) or a C4 crop (millet) was used (Bai et al., 2016).

The overyielding of intercropping might be the result of an increase in light interception (Marshall and Willey, 1983; Du et al., 2015; Wang et al., 2015), light use efficiency (Gao et al., 2010) or a combination of both (Ceotto et al., 2013). Light interception (LI) is mainly determined by leaf area index and light extinction coefficient and might be affected by intercropping due to spatial configuration and changes in morphological traits of species (Zhang et al., 2014; Wang et al., 2016). Light interception of cotton in a jujube/cotton agroforestry decreased but light use efficiency increased (Zhang et al., 2014) due to the shading by the trees in agroforestry, which depends on the distance between the crop rows and the trees.

The light use efficiency (LUE) is defined as the efficiency of conversion of light into biomass, and is obtained from the slope of the linear relation between biomass and cumulative intercepted

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photosynthetic active radiation (PAR) (Monteith, 1977; Sinclair and Muchow, 1999). LUE differs between C3 and C4 species and is affected by environmental and management factors such as the proportion of diffuse radiation (Dengel et al., 2015), temperature (Garcia et al., 1988), vapor pressure deficit (Gonias et al., 2012), nitrogen status (Garcia et al., 1988), water stress (Collino et al., 2001) and use of plant growth regulator (Mao et al., 2014). Crop LUE is higher in diffuse radiation than in direct light (Alton et al., 2007; Sinclair and Muchow, 1999). Water stress in crops reduces stomatal conductance, leading to a decline of internal CO_2 availability and thereby reduced photosynthesis and LUE (Zhou et al., 2016). LUE is determined mainly by crop net photosynthesis and is related closely to the leaf N concentration (Lawlor and Young, 1989). In agroforestry, trees remove a large fraction of the available light for the crops, and there is competition for water and nitrogen between trees and crops. Therefore, LI and LUE of crops in agroforestry likely depend on species traits such as C3 vs C4, and the ability to fix N: C4 plants can keep a higher carbon assimilation rate when in high light intensity or temperature, and N-fixing legumes in crop mixture systems can improve nitrogen uptake. However, important system characteristics remain unknown: does a C4 crop species show higher light use efficiency in agroforestry than C3? Does a legume in agroforestry improve LUE due to improved N-uptake?

An agroforestry canopy is temporally and spatially heterogeneous. To determine LI and LUE of shaded crops, it is essential but difficult to calculate the proportionsof radiation intercepted by the understory crop on a daily basis (Yang et al., 2014; Munz et al., 2014). A simple row structured crop model for light interception in strip intercropping (Pronk et al., 2003; Zhang et al., 2008; Wang et al., 2015) was successfully applied in agroforestry by Zhang et al. (2014). In this paper, we applied row-structured light-interception model to quantify overall LUE during the crop growth season of each crop at field level, and supported this with the measurements of radiation conversion efficiency (photosynthetic efficiency).

The objectives of this study were therefore to: (1) quantify light interception and use efficiency of crops in an apricot-based agroforestry system in relation to crop traits (C4/C3 and N-fixation/none); (2) to compare the overall light use efficiency at field level with photosynthetic efficiency at individual organ level to better understand the shading effect on light utilization in crop/tree mixtures.

2. Materials and methods

2.1. Field experiments

The field experiments were conducted in 2012 and 2013 at Zhanggutai (42°43′N, 122°22′E), Liaoning, China. The altitude is 226.5 m. The 30 years averaged annual air temperature is 7.2 °C, relative humidity is 59% and wind speed is 3.7–4.6 m s^{-1}. The soil is an aeolian sandy soil with a bulk density of 1.45 g cm^{-3}, measured by cutting-ring method, pH of 6.21, organic matter of 6.58 g kg^{-1}, total soil nitrogen content of 0.48 g kg^{-1}, total phosphorus of 0.28 g kg^{-1}, and total potassium of 26.95 g kg^{-1}. The total rainfall during the crop growing season was 526 mm in 2012 and 456 mm in 2013. The daily maximum and minimum air temperatures precipitation and radiation estimated by measured sunshine hours (Zhou et al., 2005) during the crop growing season are given in Fig. 1.

The experiments comprised seven cropping systems, which were three intercropping systems: (1) apricot (*Prunus armeniaca*) and millet (*Setaria italica*); (2) apricot and peanut (*Arachis hypogaea* Linn); (3) apricot and sweet potato (*Ipomoea batatas*); and 4 monocultures (4) sole apricot; (5) sole millet; (6) sole peanut; and (7) sole sweet potato. The experimental plots for all agroforestry treatments were laid out as a randomized block design with 3 replicates, and all plots for sole crops were laid out as a randomized block designed with 3 replicates in another field which was 150 m away from the agroforestry plots. Every plot covered an area of 67.5 m^2 (15 in length × 4.5 in width).

The apricot trees were 12-year-old in 2012 and 13-year-old in 2013. Distance between two adjacent tree rows was 4.5 m, and trees distance in a row was 2 m. The apricot had an average had an average plant height of 3.3 m at the time of the experiments. Apricots were harvested on July 19 in 2012 and July 23 in 2013. After apricot harvest, the leaves of trees stay green until the time of first frost. Six rows of crops (peanut, millet or sweet potato) were planted between tree rows at a row spacing of 50 cm (Fig. 2). The distance between a tree row and the adjacent crop row was 1.0 m. The plant density was 45 plants m^{-2} for millet, 25 plants m^{-2} for peanut and 6 plants m^{-2} for sweet potato in sole crops. The homogenous plant densities of mixing crops over whole intercropping area were 0.67 times the densities in sole crops, because only 67% of land was used to grow understory crops in the agroforestry. All crops were sown on May 21 in 2012 and 2013. All crops were harvested on September 25 in 2012 and September 20 in 2013.

Cultivars were Longwangmao for Apricot, LG2008-31 for millet, Baisha-1016 for peanut and Mingshui-1 for sweet potato. All crop cultivars were supplied by the Liaoning Academy of Agricultural Sciences. All plots received 375 kg ha^{-1} compound fertilizer (containing N 15%, P_2O_5 15% and K_2O 15%) before sowing. No further fertilizers were applied in 2012 whilst 225 kg ha^{-1} of ureophil (N 46%) was applied on July 30, 2013. No rhizobacteria were inoculated but nodulation of peanut was observed in the experimental plots after visual evaluation. No irrigation was given in both experimental years.

2.2. Dry matter and leaf area measurements

To determine LUE, dry matter and leaf area index (LAI) of the understory crops were measured five times on June 26, July 16, August 5, August 25 and September 14 in 2012; and on June 25, July 15, July 30, August 26 and September 20 in 2013. All plants in a sub-sampling area covering 1 m length in each crop row (6 rows) in each plot were separately harvested per row at each sampling time. Each sub-sampling area was at least 2 m apart from previous sampling areas to avoid border effects. The samples were separated into stems, leaves and reproductive organs. After weighting the fresh biomass, plant samples were oven-dried at 105 °C for 30 min to kill the tissues and then at 80 °C for approximately 2 days to achieve a constant weight.

The leaf length and width of all leaves of each of the sampled plants in each row and plot were measured using a ruler at the time of measuring fresh biomass. AThe individual leaf area was computed as the product of leaf length, width and an empirical leaf shape factor of 0.68 for millet (Oosterom et al., 2002; Payne et al., 1991) and 0.5 for peanut and sweet potato, as determined by the field observations. The leaf area index (LAI) was calculated as the product of plant density (per unit area of the whole agroforestry system) with plant leaf area. Specific leaf areas (SLA, m^{-2} kg^{-1}) was calculated as the ratio of measured LAI to leaf dry matter for each plot, separately for agroforestry and sole crop plots.

The LAI of apricot was estimated by a hemispherical image analysis using gap light analyzer software (Liu et al., 2013; Zhang et al., 2014). The images were taken at each sampling time for biomass by a fisheye camera (Nikon Co. Japan). The LAI of trees in each plot was averaged from three photos taken from the placements of tree row, 1 m from the tree line and the middle between the tree rows.

2.3. Simulation of leaf growth

The the beta growth function (Yin et al., 2003) was used to describe the dynamics of leaf area in different intercropping systems.

$$L = L_{max}(1 + \frac{t_e - t}{t_e - t_m})(\frac{t}{t_e})^{\frac{t_e}{t_e - t_m}} \tag{1}$$

$$C_m = \frac{2t_e - t_m}{t_e(t_e - t_m)}(\frac{t_m}{t_e})^{\frac{t_m}{t_e - t_m}} L_{max} \tag{2}$$