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Spatial configuration drives complementary capture of light of the understory cotton in young jujube plantations

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ABSTRACT

In intercropping systems (growing > 1 species in a field), interactions between species affect the performance of plants and the overall yield. These interactions lead to plastic responses in plant traits due to the specific environmental conditions typical for intercrops, especially in agroforestry in which the understory crop is strongly shaded by the trees. To quantify the extent to how physiological plasticity is driven by inter-specific competition, field experiments with mixtures of cotton and jujube trees grown in strips were conducted in 2012 and 2013 in Hetian, Xinjiang, China. Cotton was grown at three levels of inter-specific competition, represented by the distance between the adjacent cotton and tree rows without change in plant density. The highest cotton yield was attained farthest away from the trees, i.e. at the lowest level of inter-specific competition, with a higher proportion of fiber in the bolls as well as a higher boll density compared to plants grown at higher inter-specific competition. Low inter-specific competition also increased maximum leaf area index (LAI), total light interception and dry matter accumulation. However, light-use efficiency was higher at high levels of inter-specific competition especially in the rows close to the tree line, associated with a higher fraction of diffuse radiation. These results aid in the optimization of the spatial pattern of crops in agroforestry system.

1. Introduction

Intercropping including two or more crop species grown together is an ancient farming practice. Intercropping is practiced globally, such as in Africa, Asia, Europe and America (Yu et al., 2016). Increasing species richness can improve crop yields and ecosystem performance (Li et al., 2013, 2016). Overyielding, the phenomenon that mixtures of species achieve higher yields than the monocultures of these same species, is commonly attributed to complementarity in resource use and less niche overlap between species (Vandermeer, 1990; Li et al., 2013; Zhang et al., 2017). However, when plants need the same resource during the same time and in the same space, competition occurs. Competition, a struggle to preempt resources above- and below-ground such as light, water and nutrients, is an important determinant of plant growth. Therefore, overyielding of mixtures largely depends on the balance between inter- and intra-specific competitions. This balance can be influenced through choice of species, cultivars and crop management (e.g. planting distance). Complementarity occurs when plants use different resources or use the same resource separated in time or space (Franco et al., 2015; Venjakob et al., 2016). Selection of crop species and optimizing row configuration and sowing windows of intercropping are often practiced to maximize this complementarity and thus to minimize competition (Smith and Francis, 1986; Davis and Woolley, 1993; Yu et al., 2015).

Agroforestry combines agricultural sustainability, biodiversity conservation (Pretty et al., 2006; Mbow et al., 2014) and other ecosystem services such as reducing erosion (Lenka et al., 2012) and enhancing microbial communities in soil (Banerjee et al., 2016). Integrating trees into the agricultural landscape increases both above- and below ground productivity by sequestering carbon, and potentially addresses social concerns of climate change (Brandle et al., 1992; Kort and Turnock, 1999). In light of the high potential of agroforestry for food security, climate change adaptation and mitigation, tree-based agricultural systems are currently being promoted in many regions (Garrity et al., 2010; Sendzimir et al., 2011).

Plant functional traits, i.e. measurable features at the individual

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plant level, influence whole plant fitness directly or indirectly (Lavorel et al., 1997; Albert et al., 2010), and are increasingly used to quantify the plant responses to the environment and genotype (Woodward and Diament, 1991; Lavorel et al., 1997; de Bello et al., 2009). Plant traits can vary both genetically (e.g. between species or cultivars of a given species) or plastically within one genotype (Bradshaw, 1965). The latter entails plants modifying physiological traits in response to factors such as light, water and nutrients, as well as directly to neighboring individuals (Alpert and Simms, 2002; Givnish, 2002; Abakumova et al., 2016). These responses can be adaptive to these environments. Plasticity affects plant resource capture, survival and eventually the structure and growth dynamics of vegetation (Violle et al., 2007). Interactions with neighboring species impose selection on plasticity, and determine species coexistence and community structure (Abakumova et al., 2016). Understanding the plasticity of physiological traits responding to environmental gradients and levels of inter- and intra-specific competitions has been seen as a central issue in community ecology (McGill et al., 2006).

Inter-specific interaction affects plant performance (Zhang et al., 2012) and thus resource capture and yield (Trinder et al., 2012, 2013; Zhang et al., 2017). Increasing plant density could be applied to compensate the negative effects of trees on crop in the agroforestry (Wang et al., 2016). However it is unclear to what extent the intercropped plants would perform better when the inter-specific competition is reduced by adapting row distances within the agroforestry system. There is limited knowledge on how plant performance is affected by trees through plasticity in plant physiological traits in different spatial configuration, especially on (i) how spatial configuration affects the plasticity of physiological traits of understory crop in agroforestry; and (ii) how much these changes affect light capture, when the inter-specific competition levels are modified by agronomic practices.

In this study, we chose a commonly used jujube/cotton agroforestry system in arid Xinjiang, China, to quantify the physiological traits (e.g. photosynthesis, transpiration, growth parameters and fruits setting) and light capture of understory plant in relation to the gradients of inter-specific competition obtained from different distances between adjacent tree line and border crop row. The objective of this work was thus to assess the effect of inter-specific competition in agroforestry on plant growth, light capture, light use efficiency and yield in relation to the plasticity in physiological traits in intercropping.

2. Materials and methods

2.1. Experiment design

Field experiments were conducted in 2012 (Experiment 1) and 2013 (Experiment 2) at Hetian city (37°9′N, 79°53′E), in southern Xinjiang, China. The area has a cold desert climate, characterized as very low rainfall (37.1 mm per year averaged over 30 years), cold winters, and hot summers, as BWk in the Köppen-Geiger classification (Peel et al., 2007). The maximum air temperature, minimum air temperature and precipitation in two growing seasons are shown in Fig. 1. The weather data was obtained from the weather station of Hetian Meteorological Bureau. The soil is arenosol with a bulk density of 1.4 g cm^{-3}. Total N content in the top 30 cm soil layer was 5.8 g kg^{-1}, Olsen P 21.2 mg kg^{-1} and NH_4OAc- extractable K 51.3 mg kg^{-1}.

Experiments were in a randomized block design with four replicates. Plot area was 45 m^2 (15 m in length × 3 m in width) in Experiment 1 and 30 m^2 (15 m length × 2 m width) in Experiment 2. An early maturing cotton variety (*Gossypium hirsutum*) XLZ46 was used. Jujube cultivar (*Zizyphus jujuba* Mill.) was Junzao 1. Three patterns of jujube/cotton intercropping with different row configurations were tested (Fig. 2). Spacing between tree rows was 3.0 m in Experiment 1 and 2.0 m in Experiment 2, and therefore our definitions of low, middle and high inter-specific competition differed between experiments. In low inter-specific competition (LIC) the distance from border cotton row to the adjacent tree line was 1.1 m in Experiment 1 and 0.6 m in Experiment 2; cotton row spacing was 40 cm in both cases. In middle inter-specific competition (MIC): the distance from border cotton row to tree line was 1.0 m in Experiment 1 and 0.5 m in Experiment 2; cotton row spacing was 50 cm. Finally, in high inter-specific competition (HIC) distance from border cotton row to tree line was 0.9 m in Experiment 1 and 0.4 m in Experiment 2; cotton row spacing was 60 cm. In total three cotton rows were sown between tree lines. Cotton plant distance in a row for all treatments was the same (8.9 cm). Thus, cotton plant density for unit total ground area in the agroforestry (homogeneous density) for three treatments was the same, 11.2 plants m^{-2} in Experiment 1 and 16.8 plants m^{-2} in Experiment 2. Distance between trees within a row was 1.25 ± 0.25 m for all treatments. In Experiment 1, the row orientation was south-north, the jujube trees were 7 years old and approx. 2.7 m high. In Experiment 2, the row orientation was east-west, the jujube trees were 5 years old and approx. 2.4 m high. Overall, the inter-specific competition in Experiment 2 was stronger than in Experiment 1 due to the narrower tree row spacing.

Cotton was sown on 23 April (Experiment 1) and 21 April (Experiment 2). The final harvests were made on 15 and 13 October, respectively. Jujube trees leafed out at the beginning of May and were harvested on October 25 in both experiments. Flood irrigation was applied ten times with an amount of 50 mm each at an interval of ~15 days during the crop growing season, according to farmers' practice. Fertilizer was applied at a rate of 300 kg ha^{-1} N and 150 kg ha^{-1} P in both experiments. Plastic film was applied only for cotton rows to increase soil temperature and reduce evaporation (Zribi et al., 2015; Wang et al., 2009). The plant growth regulator mepiquat chloride (MC) was applied four times at a rate of 300 g ha^{-1} per season to control the excessive vegetative growth of cotton. The main stem of the cotton plants was topped on 15 July to arrest further branch production, and branches were topped two weeks later.

2.2. Measurements

2.2.1. Dry matter and leaf area

To determine dry matter and leaf area index, three plants in each row in a sub-sampling area per plot were randomly harvested per month. A sub-sampling area of 1.0 m in length and 3.0 m in width in Experiment 1 and 1.0 m in length and 2.0 m in width in Experiment 2 were selected for each sampling. Each sub-sampling area was at least 1.0 away from previous samplings to avoid the density effect due to the samplings. The plant samples were taken on 14 June, 12 July, 13 August, and 23 September in Experiment 1, and on 24 June, 23 July, 20 August and 23 September in Experiment 2. Plant height, number of leaves, branches and fruits were measured first. Subsequently, the leaves, stems and fruits (squares, flowers and bolls) were separated to measure leaf area and dry matter. Leaf area of all individual leaves was measured by multiplying the leaf length, width and a shape factor of 0.82 (Zhang et al., 2008; Zhang et al., 2014). Dry matter was measured after drying samples in an oven at 80 °C for 48 h until a constant weight was reached.

2.2.2. Cotton yield and yield components

All plants in a sampling area of 5 m^2 were harvested per row to measure final yield. The seed cotton was sun dried to a water content of 13%. To determine yield components, boll numbers (only open bolls) per plant in the sampling area were counted to assess boll density, bolls per unit ground area (bolls m^{-2}). Fifty bolls in the sampling area was randomly harvested per row to determine single boll weight and lint (fiber) proportion.

2.2.3. Light intensity within the cotton canopy

In Experiment 2, the intensity of photosynthetic active radiation (PAR) within the canopy was measured by a line sensor (LI-191SA, LI-COR, USA) to quantify the spatial distribution of PAR with the canopy.