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Impacts of regulated deficit irrigation on yield, quality and water use efficiency of Arabica coffee under different shading levels in dry and hot regions of southwest China

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ABSTRACT

The yield and quality of Arabica coffee (*Coffea arabica*) cannot be guaranteed due to irrational irrigation and light management in dry and hot regions of southwest China. The objective of this study was to obtain rational irrigation and shading mode for efficient light and water use, suitable yield and high nutritional quality of Arabica coffee. Taking full irrigation (FI) as the control, the effects of deficit irrigation (DI) (DI75 and DI50, 75 and 50% of full irrigation amount, respectively) on photosynthesis, yield, nutritional quality and water use efficiency (WUE) were investigated under four shading levels (Sh0 no shading, Sh30, Sh45 and Sh60, 30, 45 and 60% shading, respectively) using the field experiments, and a comprehensive benefit assessment model of yield, nutritional quality and WUE was established under different irrigation and shading treatments. Results indicated that DI75 increased leaf apparent radiation use efficiency and the contents of crude fat and chlorogenic acid in dry bean if compared to FI. In comparison with Sh0, Sh30 enhanced dry bean yield, WUE and the contents of total sugar and chlorogenic acid in dry bean. Compared with FISh0 (CK), DI75Sh30 raised dry bean yield, WUE, and the contents of total sugar, protein, crude fat and chlorogenic acid, but reduced the caffeine content. Principal component analysis showed that DI75Sh30 had optimal comprehensive nutritional quality, and TOPSIS method indicated that DI75Sh30 had the optimal comprehensive benefit, showing that our results can provide scientific basis for rational irrigation and light management of Arabica coffee in dry and hot regions.

1. Introduction

China mainly cultivates Arabica coffee (*Coffea arabica*) in Yunnan province, and the planting area and yield of Arabica coffee in this province were about 1.18×10^5 ha and 1.39×10^5 t in 2016 (Hao et al., 2017). In dry and hot regions of southwest China, there is abundant sunshine, low rainfall, large evaporation and long duration of dry season, and no irrigation or flood irrigation in local planting restricts high-efficient production of Arabica coffee (Cai et al., 2007).

Regulated deficit irrigation (RDI) can save much irrigation water, maintain or increase crop yield, and improve quality (Marsal et al., 2016; Kang et al., 2000; Patanè et al., 2011; Santesteban et al., 2011). Compared with full irrigation (FI), mild deficit irrigation (80% of full irrigation amount) decreases the yield of Arabica coffee only by 6.4%, while it enhances the contents of protein, crude fat and chlorogenic acid in dry bean, and improves raw and cup quality of coffee bean and water use efficiency (WUE) (Liu et al., 2014; Tesfaye et al., 2013; Shimber et al., 2013). Medium and severe deficit irrigation treatments (60 and 40% of full irrigation amount, respectively) reduce dry bean yield and WUE significantly, but raise the contents of caffeine and crude fiber in dry bean (Liu et al., 2016a). Currently, it is unclear if it is possible to achieve sufficient yield, high quality and WUE of Arabica coffee in dry and hot regions.

Due to the shading habit of Arabica coffee growth, shading cultivation can create a suitable microclimate environment, reduce leaf surface temperature (Steiman et al., 2011; Boreux et al., 2016; Nesper et al., 2017), change leaf photosynthetic characteristics (Araujo et al., 2008; Liu et al., 2016b), control pests and diseases, balance vegetative and reproductive growth (Damatta, 2004), decrease biannial bearing (Vaast et al., 2006), increase bean size and improve the quality of drinks (aroma, taste and acidity) (Bote and Struik, 2011; Vaast et al., 2006). However, the effect of shading on the yield was not consistent (Bosselmann et al., 2009; Haggar et al., 2011; Ricci et al., 2011; Van Asten et al., 2011). Previous studies found that the contents of chlorogenic acid and total sugar (fructose, glucose and sucrose) in dry bean are the highest at 40% shading (Somporn et al., 2012). Other

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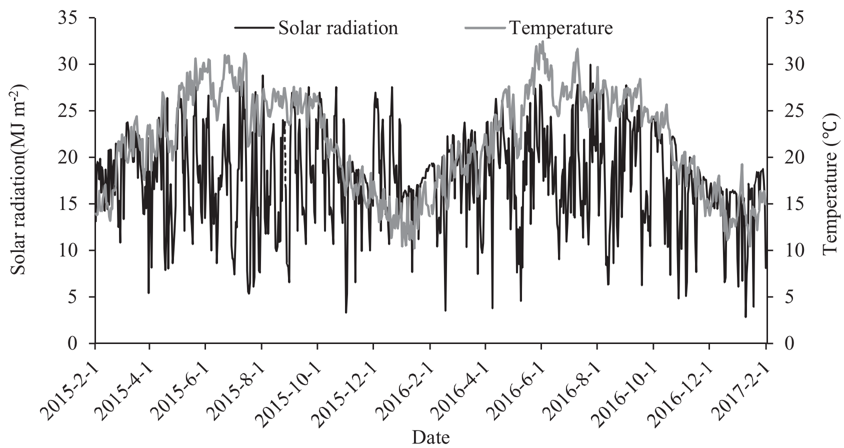

Fig. 1. Changes of daily average solar radiation and temperature during the experimental period.

studies have found that high shading level raises leaf area, quality and particle size of coffee bean, but declines coffee yield (Jaramillobotero et al., 2010; Somporn et al., 2012). Hence, suitable shading for improving the yield, quality and WUE of Arabica coffee in hot and dry regions needs further investigation.

Drip irrigation can promote coffee growth, and enhance yield and economic income under shade cultivation (Perdoná and Soratto, 2015a,b, 2016). However, how to effectively combine deficit irrigation and shading to maintain yield and improve quality and WUE of Arabica coffee is unsolved and needs further investigation. Therefore, the objective of this study was to investigate the effects of deficit irrigation on photosynthesis, yield, nutritional quality and WUE of Arabica coffee under different shading levels by comparing with full irrigation, and then establish a comprehensive benefit evaluation model of coffee yield, nutritional quality and WUE using improved TOPSIS (Technique for order preference by similarity to an ideal solution) method to seek for optimal irrigation and shading mode, so as to provide the scientific basis for rational irrigation and light management of Arabica coffee in dry and hot regions of southwest China.

2. Materials and methods

2.1. Experimental site and materials

The field experiments were conducted from 2015 to 2017 in Lujiangba, Baoshan, Yunnan, southwest China (latitude 21°59′ N, longitude 98°53′ E, altitude 750 m a.s.l.). The experimental site is in dry and hot regions, with average annual sunshine hours of 2328 h, annual rainfall of 755.4 mm (80% of total rainfall from June to October), annual evaporation of 2101.9 mm, annual temperature of 21.3 °C and relative humidity of 71%.

The soil at the experimental field was a reddish brown sandy loam, and the contents of organic matter, total N, total P, available N, available P and available K in the topsoil (0–20 cm) were 12.5 g kg^{-1}, 1.0 g kg^{-1}, 1.2 g kg^{-1}, 90 mg kg^{-1}, 13 mg kg^{-1} and 125 mg kg^{-1}, respectively. Experimental trees were five-year-old Arabica coffee trees (Catimor CIFC7963) with planting spacing of 1.5 m and row spacing of 2.0 m.

2.2. Experimental method

Three irrigation levels and four shading levels were included in the experiments. This experimental plan yielded 12 treatments (i.e. 3 × 4), and each treatment was replicated with three plots, totally 36 plots. Each plot had the area of 45 m^2 (9 m × 5 m) and 15 trees. Guard rows around the plots were used to eliminate any edge effects. Three irrigation levels included full irrigation (FI) and two deficit irrigation (DI) levels (DI75 and DI50, 75 and 50% of full irrigation amount, respectively). Irrigation frequency was seven days and irrigation date was postponed with 1–2 d when a rainfall event occurred. Four shading levels with black shading nets of different light-transmitting capabilities included no shading (natural light intensity, Sh0), and three shading levels (Sh30, Sh45 and Sh60, 30, 45 and 60% of shading natural light intensity, respectively). The treatment of FI and Sh0 (FISh0) was took as the control (CK). The unmovable scaffold covered with the shading net did not affect rainfall entry and sampling observation. The shading net above the coffee canopy was 1.5 m.

Irrigation quota in FI was determined by monthly water consumption of local Arabica coffee (Chen et al., 1995) and effective rainfall in this area as Eq. (1),

$$I_i = (ET_{ci} \times n) - Pr_i \tag{1}$$

where I_i is irrigation quota of FI at the i^{th} period (mm), ET_{ci} is averaged optimal water consumption at the i^{th} period (mm d^{-1}), n is the period (d), and Pr_i is effective rainfall at the i^{th} period (mm).

Surface drip irrigation system was worked under the pressure of 0.1 MPa. The both sides of each coffee tree respectively had a pressure compensating emitter with the flow rate of 2.5 L h^{-1}. The compound fertilizer (N-P_2O_5-K_2O, 15-15-15) of 500 g plant^{-1} was applied in mid-May and late-August according to local recommended rates. Fertilizers were uniformly applied into a 20-cm deep circular ditch at 40 cm away from tree truck. Weeding was done monthly, pest and insect was controlled in early May, and there was no pruning of coffee tree. Figs. 1–3 showed daily averaged solar radiation and temperatures, cumulative effective rainfall and irrigation amount and soil water budget during the experimental period, respectively.

2.3. Plant sampling and measurements

Photosynthetic characteristics of functional leaves were determined every two hours using a portable photosynthesis system (LI-6400XT, USA) from 10:00 to 16:00 in a typical irrigation period (May 14, 15, 17, 18 and 20, 2015, i.e. at 1, 2, 4, 5 and 7 d after irrigation).

Leaf water use efficiency was counted from Eq. (2),

$$WUE_L = Pn/Tr \tag{2}$$

where WUE_L is leaf water use efficiency (mmol mol^{-1}), Pn is net photosynthetic rate (μmol m^{-2} s^{-1}), and Tr is transpiration rate (mmol m^{-2} s^{-1}).

Leaf apparent radiation use efficiency was calculated from Eq. (3),

$$ARUE_L = Pn/PAR \tag{3}$$

where $ARUE_L$ is leaf apparent radiation use efficiency (mmol mol^{-1}), Pn is net photosynthetic rate (μmol m^{-2} s^{-1}), PAR is photosynthetic