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# Progresses and prospects in the coupling effects of water-saving irrigation and shade cultivation on Arabica Coffee at Dry-hot Valley in Southwest China

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## ABSTRACT

China is one of coffee-producing areas in Asia and the yield of coffee in Yunnan province occupies 98% of China. Arabica coffee in Yunnan has special quality character of mellow but not bitter, fragrant but not strong and slight fruit acid taste. Shade cultivation and water-saving irrigation are two important factors affecting the growth of coffee, while there are randomness and blindness in the shade cultivation and irrigation of Arabica coffee in dry-hot valley of Yunnan Province. In this paper, the research progresses in the effects of water-saving irrigation and shade cultivation on the physiology ecology, yield and quality of Arabica coffee are discussed. Finally, several scientific problems need to be urgently studied: the physiological and ecological response mechanism, the quantitative relationship between physiology ecology and canopy micro environment, water consumption law, efficient use of water and quality and high yield mechanism as well as the coupling models of irrigation and shade cultivation of Arabica coffee under different irrigation and shade cultivation strategies.

**Keywords:** Arabica Coffee, Water-Saving Irrigation, Shade Cultivation, Coupling Effects.

## 1. INTRODUCTION

Coffee is the second raw material products in the world (the oil is the first), which consumption is three and four times of cocoa and tea [1]. China is one of the main coffee-producing countries in Asia, and the main producing area is Yunnan province. The Arabica coffee in Yunnan is famous for “mellow but not bitter, fragrant but not strong and slight fruit acid taste”. Coffee was listed as the main developmental industry by Outline of Development Plan of Biological Industry in Yunnan (2006-2020), and 12th Five-Year plan of Yunnan province proposed to increase the planting areas to 66600 $hm^2$ and it had reached to 29300$hm^2$ [2].

The dry-hot valley is one of the regions with the greatest potential for agricultural development in the southwest mountainous areas, including the northern and southern subtropical climate valleys along the middle and lower reaches of the rivers such as the Jinsha River, the Nu River and the Lancang River. The average rainfall in this area is 600~800 mm, 90% of the precipitation is concentrated in about 91 days, and the soil drought stress is serious especially from March to May. In dry season, the atmospheric evaporation is more than 1300 mm, which belongs to the extremely arid area. The drought has seriously restricted the land production potential in dry-hot valley, which productivity of cultivated land was only 60~70% of the light and temperature potential productivity [3]. Dry-hot valley is suitable for cultivation of Arabica coffee with sufficient light and heat, high temperature in winter, short frost period or no frost, rich land resources and warm winter climate characteristics [3]. Fig 1 shows Yunnan’s height above sea level temperature climate, and general geographical situation make the growing conditions comparable with both Colombia and Indonesia. Fig 2 shows the coffee-planting area was $12.2\times10^4$ $hm^2$ in 2014, which was 3 times of the planting area ($4.3\times10^4$ $hm^2$) in 2010; the yield was $11.8\times10^4$t in 2014, which was more than 2 times of the yield ($4.9\times10^4$t) in 2010. Lujiangba Baoshan city in Yunnan which has the typical dry-hot valley climate has become the whole country and even the world's largest coffee production base and fine breed base in Fig 3. Arabica coffee-planting area has reached 2406 $hm^2$ at Lujiangba until 2008 [3]. The yield and quality of Arabica coffee cannot be guaranteed due to seasonal drought frequent concurrent, heat-water contradiction, foehn effect in dry-hot valley [4]. Severe drought occurred in 2009~2010 for 60 years which leaded the province's coffee crops failure up to 60 thousand acres and the death rate of newly planted coffee seedlings was as high as 40%. The drought led the production decreased, the particles were too small, the proportion of immature beans increased of Arabica coffee and caused economic losses of coffee-planting nearly 600 million yuan [5]. Therefore, to ensure the quality and high yield of Arabica coffee in dry-hot valley, the crux and the key to solve the problem was water-saving irrigation to change the current status of local traditional field irrigation or unscientific irrigation.

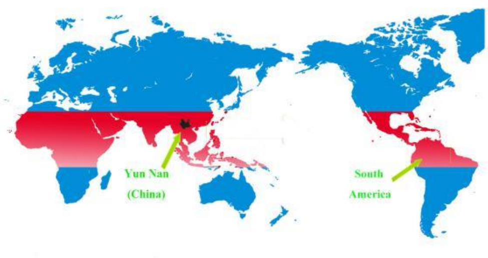
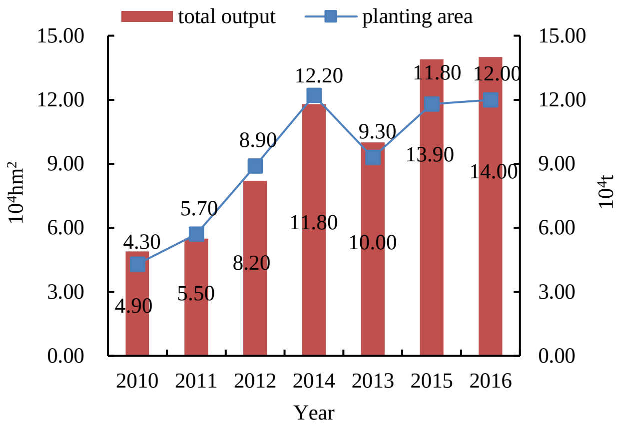



**Figure 1.** The location of Yunnan relative to the world coffee growing area




Data source: Office of the Ministry of agriculture for the development of South Subtropical Crops

**Figure 2.** The status quo of coffee production in China in recent years

**Figure 3.** Coffee planting areas in Lujiangba

Arabica coffee was native to the lower levels of tropical rain forest in Africa Ethiopia and formed the growth habits of loving warm, moist and shade during the phylogeny development [6]. The studies indicated that appropriate shade cultivation can improve the microclimate environment, enhance the drought resistance and cold resistance of coffee tree , avoid excessive coffee beans and premature senility, and also can prevent the pests and diseases (such as brown spot, anthracnose, longicorn and root mealybug pests) and soil erosion, improve soil fertility and the land utilization rate, reduce the cost of production management with improved coffee quality and production performance [6-8]. Dehong launched a rubber-based three-dimensional agricultural research, screening out the efficient planting mode under rubber intercropping coffee, and coffee and measured the yield of coffee and rubber in Tab 1 [9]. Appropriate shade cultivation of coffee can also promote the nutritional absorption of coffee, but if the shade crops and shade selections is not reasonable, it will compete for water, nutrients and light, and inhibit the normal growth and development of coffee. However, there are randomness and blindness about the cultivation of Arabica coffee in dry-hot valley and the basic research on the response mechanism of physiology ecology and water use efficiency under different shade conditions are still weak. Quality and high yield mechanism and other scientific issues are not clear, so it needs for systematic in-depth study.

**Table 1.** The yield of compound cultivation between coffee and rubber tree in Dehong Tropical Crop Science Institute

| Year | The yield of coffee(kg/hm$^2$) | The yield of rubber(kg/hm$^2$) | Shade intensity(%) |
|---|---|---|---|
| 1994 | 88.5 | 136.5 | 25 |
| 1995 | 2475.0 | 283.5 | 30 |
| 1996 | 5133.0 | 445.5 | 40 |
| 1997 | 3544.5 | 598.5 | 45 |
| 1998 | 4095.0 | 876.0 | 50 |
| 1999 | 2839.5 | 922.5 | 55 |
| 2000 | 3243.0 | 1057.5 | 60 |

## 2. RESEARCH PROGRESS AT HOME AND ABROAD

### 2.1 Effects of irrigation on the physiological ecology of Arabica coffee

There are many studies on the physiological characteristics of coffee under water deficit, but less in China. Water deficit decreased the stomatal conductance and photosynthetic rate, and stomatal conductance decreased most, but the effects on chlorophyll fluorescence parameters were not significant [4,10]; Mild water stress decreased coffee photosynthetic rate and transpiration rate, soluble protein, chlorophyll, carotenoid, stomatal opening rate and water potential, while increased the activity of peroxidase, proline, MDA content and cell membrane permeability [11,12]. Irrigation at high temperature in dry season could increase the photosynthetic rate, the number of flowering and fruits, and made the flowering time in advance [13], while frequent irrigation inhibited bud opening [14]. Re-watering after continuous water deficit could stimulate the flower buds to open synchronously and shortened the harvest period. It has also been shown that the mild water deficit (-0.3~-0.5MPa) would promote the flowering of coffee in the white bud stage, and the buds showed the nature of the secondary xylem only in this stage [14]. Water stress could significantly increase the activity of superoxide dismutase, peroxide and ascorbate peroxidase of coffee, and reduced the cell damage, so then water stress increases the drought resistance of coffee. In addition, there are many studies on the gene expression [17] of water physiology [15], drought resistance [12,16] and water stress of different varieties coffee. Most of the above studies are carried out under the condition of pot simulation, mechanism of physiological and ecological responses of the coffee under different irrigation systems in the field is still lacking, which is difficult to provide scientific basis for water-saving irrigation of Arabica coffee.

### 2.2 Effects of irrigation on water consumption, yield and quality of Arabica coffee

There are studies on water consumption law of coffee mostly used the estimation method, but the rarely reported in China. Soil evaporation coefficient and basal crop coefficient were 0.24 and 0.76 of 5 years coffee under drip irrigation, respectively, using the method of stem flow and Bowen ratio [18]. Using the double crop coefficient method, the soil evaporation coefficient and basal crop coefficient of Brazilian coffee were 0.35 and 0.65 [19]. The basal crop coefficient of the coffee were 1.27, 0.87 and 0.60, when the reference crop evapotranspiration was <2, 2~4 and >4 mm/d, respectively. The basal crop coefficient of sprinkler irrigation and drip irrigation were 0.52~0.82 and 0.50~0.65, and changed with the evapotranspiration of the reference crop [20]. There were fewer study results on coffee water-saving irrigation, although coffee has a large water consumption in the growth period [21].

Soil drought is one of the most important environmental factors limiting the growth and yield of coffee. There were fewer reports on the yield and quality of Arabica coffee under water-saving irrigation. There were studies indicated that sufficient irrigation could significantly increase the soil water content, leaf relative water content, stomatal conductance and yield, partial root zone irrigation and deficit irrigation could improve the quality of coffee beans, and partial root zone irrigation could save 50% irrigation water and significantly improved water use efficiency [22]. The study of coffee quality in 3 production areas in Brazil indicated that the chemical composition of coffee bean was affected by the planting environment, and the effect of irrigation was not significant [23]. The studies focused on the comparison of different regions about the research of coffee quality in China, and the studies indicated that coffee beans were better in Baoshan, Pu'er and Dehong, reaching the international standards and industry standards [24], and established a correlation between altitude and the quality of Arabica coffee [25].

### 2.3 Effects of shade cultivation on the physiological ecology of Arabica coffee

Shade cultivation will affect the light intensity, which has a significant impact on the photosynthetic characteristics of coffee. There were studies indicated that shade cultivation reduced the photosynthetic rate, transpiration rate, stomatal density and dry wet ratio, while increased the stomatal conductance and leaf water potential in China. Diurnal variation of photosynthetic rate was asymmetric double-peak curve under no shade and a small degree of shade, while it was a single peak curve when the shade degree was larger [26]. It also indicated that the photosynthetic characteristics of the leaves under different shade levels were basically the same; compared with the physiological characteristics of the leaves, the plasticity of the morphological anatomy of the leaves was higher [27]. The studies found that the photosynthetic rate of coffee was low, generally less than 2.5μmolm$^{-2}$s$^{-1}$. Shade cultivation could increase chlorophyll content, apparent quantum efficiency, decrease ascorbic acid accumulation and leaf phenotypic plasticity, but no significant effect on the main anti-oxidative enzymes and malondialdehyde [28]. Shade cultivation also could reduce the leaf surface temperature, increase the surface area, without affecting the growth of lateral node [29]. The studies also indicated that, the inhibition of stomatal conductance on net photosynthetic rate decreased gradually with the increased of shade degree, while the effects of photon flux density on net photosynthetic rate was not significant [30]. It can be seen that the current physiological and ecological studies of coffee shade cultivation focus on chlorophyll, photosynthesis and stomatal conductance, while the research on photosynthetic adaptability, canopy structure, light compensation point and light saturation point that reflecting light tolerance and the fluorescence parameters that explaining the change of photosynthetic rate is insufficient.

### 2.4 Effects of shade cultivation on water consumption, yield and quality of Arabica coffee

The scientific and reasonable shade cultivation can create a suitable environment for the growth of coffee, so as to ensure high and stable yield [31]. Studies on coffee shade cultivation mostly focused on the economic benefits, while lacking of selections of shade cultivation index and mode in China. Now, there are lots of models of coffee stereo cultivation, including coffee and rubber, tea, macadamia nut, banana and longan, but the adaptability and output value of each model are different [6,32]. The model of coffee and banana intercropping in Hainan significantly shortened the payback period, and increased the output value and the benefit [33]. The appropriate shade cultivation of Arabica coffee could promote growth and dry bean yield, and increase chlorophyll content and leaf nutrient content [34]. Shade cultivation could significantly improve the cup quality of products (aroma, flavor and acidity), and increase the ratio of dry and fresh [35].

There were studies indicated that shade cultivation had a significant effect on sensory indexes, size, defects or broken beans proportion of coffee, and the yield and the shade degree was negative linear correlation [29]. The study on the quality of Colombian coffee indicated that the highland cultivation was not conducive to the sensory characteristics of coffee (aroma, acidity, sweetness and bitterness), and the effect on the appearance characteristics was not significant. The effect of shade cultivation on sensory characteristics was not significant at low altitude, and the number of small beans significantly reduced [36]. The intercropping could reach the purpose of coffee shade cultivation, and obtain higher economic incomes. The intercropping effect of coffee and banana in Uganda was investigated by investigation and experimental observation and the results showed that banana had no significant effect on the yield of coffee. The average annual yield of fresh Arabica coffee were 1230 kg/hm$^2$ and 1180 kg/hm$^2$ under no shade and banana as a shade, medium coffee were 1250 kg/hm$^2$ and 1090 kg/hm$^2$, respectively. Banana and coffee intercropping improved the marginal effect of Arabica coffee and medium grain coffee 9.1 and 2.1 times [37]. The studies indicated that shade cultivation could delay the maturation of coffee, and increase the number of leaves, lower branches, and leaf area, and reduce shoots growth point and blight. The coffee yield of shade cultivation was slightly higher than no shade, but the difference was not significant [38]. However, the study on water consumption law, yield and quality of Arabica coffee in dry-hot valley at different shade cultivation is still lacking and needs further study.

### 2.5 The coupling effects of irrigation and shade cultivation on the physiology ecology, water consumption, yield and quality of Arabica coffee

There are many studies about the effects of single factor of water or shade cultivation on the physiology and ecology, and the coupling effect of water and light needs systematic and in-depth research. The adaptability of coffee to water and light was studied by means of weighing water control and artificial shading. The results indicated that the coupling effect of water and light on the morphological and physiological characteristics of coffee was not significant. The photosynthetic rate was inhibited by the stomatal limitation of the coffee under the condition of shade cultivation and water deficit, and the water use efficiency was improved by leaves osmotic adjustment and reducing tissue elasticity. Compared with water, coffee showed higher plasticity to light. The photosynthetic rate was closely related to the biochemical index of the leaves under shade cultivation and the shade cultivation could not alleviate the adverse effects of drought on coffee [39].

The coupling effects of irrigation and shade cultivation on the water consumption, yield and quality of coffee were rarely reported, while the coupling effects of nutrient and shade cultivation were reported in part. The studies on growth and yield of coffee under different shade and fertilization levels indicated that the node number and yield of coffee decreased with the increased of shade, and the effect of fertilization on the growth and yield of coffee was not significant. The effects of the first 3 years on the nutrition and reproductive growth of coffee was not significant and then 3 years had a significant effect on the number of nodes, leaf area and yield. Shade treatment could increase the leaf area of coffee and reduce the number of nodes, but the impact on the average production for many years was not obvious [40]. In addition, it was found that the leaf area and specific leaf area of coffee increased with the increased of shade, while the yield and the number of fresh beans decreased with the increased of shade. Shade cultivation could improve the fresh weight of coffee beans, delay and shorten the maturity period. The leaf area and leaf thickness of coffee were larger and the length of the branches were shorter. There was no significant effect of fertilization on the leaf area, specific leaf area and fresh fruit yield of coffee [41].

## 3. EXPECTION

In conclusion, there were many studies on the effect of single factor of water or shade cultivation on the physiological and ecological characteristics of coffee, but there were fewer studies about the effect of the coupling on the physiological and ecological of coffee; the studies on canopy micro climate environment and the response mechanism and correlation of physiological ecology was insufficient; the law of water consumption of coffee was mostly based on the estimation method; the water consumption law, the efficient use of water and the mechanism of improving the yield and quality of Arabica coffee under the condition of water-saving irrigation and shade cultivation were not clear, especially the suitable irrigation and shade cultivation indicators and coupling patterns were rarely reported.

In order to explore the mechanism of quality and high yield, water-saving effect and an efficient way to achieve of Arabica coffee under different irrigation and shade cultivation strategies, combined with the climate characteristics of dry-hot valley, it is necessary to further study the response mechanism of physiology ecology of Arabica coffee, the quantitative relation between physiology ecology and canopy micro environment, water consumption law, the mechanism of efficient use of water, quality and high yield and the coupling model of irrigation and shade cultivation.

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