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Dry-season deficit irrigation increases agricultural water use efficiency at the expense of yield and agronomic nutrient use efficiency of Sacha Inchi plants in a tropical humid monsoon area

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ABSTRACT

Application of deficit irrigation (DI) will be problematic in tropical humid monsoon areas, since high relative air humidity during growth there leads to stomata malfunctioning. A field split-plot experiment was used to evaluate the physiological features, growth and seed and oil yield of Sacha Inchi (*Plukenetia volubilis* Linneo) plants, a tropical promising woody oilseed crop, responded to DI and fertilization in southwest China. The field experiment consisted of a factorial combination of five irrigation levels applied in the dry season [rainfed; DI20, DI50, DI100 (i.e., with irrigation amount of 20, 50 and 100% crop evapotranspiration, respectively); and full irrigation (irrigation of water saturated soil)] combined with two levels of compound fertilizer (0 and 200 kg ha^{-1}) over two growing seasons, in a randomized complete block design with three replicates.

Results showed the growth and root to stem mass ratio had lower sensitivity responded to DI, probably owing to their extremely low root mass fraction and seasonal short-term effect of DI on leaf photosynthetic traits. Irrigation affected the seasonal variations in seed size, seed oil concentration and seed yield, depending on the harvest date; whereas, with constant mean seed size and mean seed oil concentration across irrigation and fertilization treatments, the total seed and seed oil yield over the growing seasons were largely determined by the seed numbers per unit area. The soluble sugar and nitrogen storages as the active process, are related to effective flower formation, fruit (seed) development and enhance productivity of Sacha Inchi plants, which was indicated by the positive relationships between total seed yield and total nitrogen pool in the vegetative tissues or sugar pool in stems across all treatments. Fertilization increased total seed and seed oil yield, but no interaction between irrigation and fertilization was found. Compared with DI100, DI50 and DI20 had significant lower total seed yield, especially under the fertilized condition, although having higher agronomic water use efficiency (WUEagr, yield divided by irrigated water applied) but lower agronomic nutrient use efficiency (NUEagr, increased yield divided by fertilization rate). As a water-demanding crop species, Sacha Inchi plants under DI100 with the similar values to full irrigation had the highest total seed yield and NUEagr, but at the expense of water use efficiency. The maximum seed yield and maximum WUEagr, or maximum WUEagr and maximum NUEagr of Sacha Inchi plants are not compatible because the negative relationships existed between each of them. The polynomial regression relationships between total seed or seed oil yield and relative evapotranspiration could help to develop appropriate water-saving techniques for Sacha Inchi plantation in the tropical humid monsoon region.

1. Introduction

Sacha Inchi (*Plukenetia volubilis* Linneo), a tropical woody vine, is a promising new oilseed crop species belonging to the family Euphorbiaceae. It is well known that Sacha Inchi seed contains a high concentration of polyunsaturated fatty acid, which is beneficial to human health (Noratto et al., 2012). As an evergreen, recurrent species, *P. volubilis* plants flower continuously throughout the growing season;

Abbreviations: DI, deficit irrigation; HI, harvest index; Gs, stomatal conductance; Pn, light-saturated photosynthetic rate; PNUE, photosynthetic nitrogen use efficiency; Tr, transpiration rate; SLA, specific leaf area; WUEi, instantaneous water use efficiency; WUEagr, agricultural water use efficiency; NUEagr, agricultural nutrient use efficiency

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the capsule fruits consist four-to-seven pods, with one seed per pod. The seed and oil yield of Sacha Inchi plants are highly variable and depend on environmental conditions and suitable agricultural management practices (Cai, 2011; Cai et al., 2012, 2013; Jiao et al., 2012; Yang et al., 2014). In the previous research, we found that natural drought conditions decreased plant growth rate, numbers of female flowers and fruit per plant, and fruit set of Sacha Inchi plants compared with the well-watered plants in the dry season (Jiao et al., 2012). Thus, irrigation in the dry season is helpful to optimize yield of the field-grown Sacha Inchi plants.

Defined as the application of irrigated water below full crop water requirement for evapotranspiration, deficit irrigation (DI) is a water-saving irrigation technique that theoretically allows the production of root-to-shoot signals that modify the physiology of the above-ground parts of the plant; specifically reducing stomatal conductance and improving water use efficiency (WUE) (Dodd et al., 2008). However, the physiological and biochemical responses are difficult to quantify; given that DI is usually applied to plants in accordance with both temporal and spatial droughts, depending on the quantification of crop's response to water limitations and total soil water availability (Dodd et al., 2008; Romero et al., 2012). Moreover, little is known about how long stomata remain partially closed with prolonged soil drying and what role re-watering may play in stimulating root growth under drying soils (Chai et al., 2016).

It has been identified that DI can save irrigated water and increase WUE greatly with a subtle or even positive impact on crop yield and quality simultaneously of some annual and woody crops, especially in arid and semiarid regions (Chai et al., 2016). But field trials have also reported reductions in crop yield under DI associated with lacks of the physiological responses (Tognetti et al., 2007; Trigo-Córdoba et al., 2015; Dbara et al., 2016; Gasque et al., 2016). The varied and inconsistent effects of DI have been found due to the multiple reasons: different soil types (Chai et al., 2016), environmental and experimental conditions (Marsal et al., 2008), different intensities and modulation of the chemical signal (Tardieu et al., 2015), different distribution of the soil water content (Dodd et al., 2008), different species/varieties adaptations to soil moisture heterogeneity (Martin-Vertedor and Dodd, 2011), root hydraulic redistribution (Bauerle et al., 2008) and methodological problems in applying DI (Shahrokhnia and Sepaskhah, 2017). Especially, the effect of application of DI is uncertain in tropical humid monsoon areas (Renault et al., 2001; Trigo-Córdoba et al., 2015), since such climates have relatively high annual rainfall with distinct wet and dry seasons and heterogeneous soils, and long-term high relative air humidity during leaf expansion hampers stomatal responsiveness to closing stimuli (Arve et al., 2013; Carvalho et al., 2016), resulting in uncontrolled water stress when species/varieties with higher stomatal sensitivity to high relative air humidity are transferred to of high evaporative demand conditions (Fanourakis et al., 2016).

Likewise, crop nutrient status often depends on soil nutrient and water availabilities (Jiao et al., 2012; Afshar et al., 2016); fertilization is a critical component of Sacha Inchi yield production (Yang et al., 2014). If both soil moisture and fertilizer are managed properly, a synergistic interaction between them could probably increase crop yield, WUE and nutrient use efficiency (NUE) (Quemada and Gabriel, 2016). In this paper, we conducted field experiments to investigate the effects of different levels of DI and fertilization on the physiological traits, plant growth, yield, and resource use efficiency (i.e., WUE and NUE) of *P. volubilis* plants in Xishuangbanna, a tropical humid monsoon area in southwest China. The overall goal was to provide a better understanding of irrigation and fertilizer managements for this species at both the local and regional levels, and thus to increase seed and oil yields for commercial-scale oil production.

2. Materials and methods

2.1. Study site and experimental design

The study was carried out in Xishuangbanna Tropical Botanical Garden (21°56′N, 101°15′E, altitude 560 m), Chinese Academy of Sciences, Yunnan, southwest China. The climate at Xishuangbanna is dominated by the southwest monsoon with two distinct seasons (a wet season from May to October, and a dry season from November to April). The average annual temperature is 22.9 °C and the mean annual precipitation is 1500 mm, of which approx. 85% occurs in the wet season. The minimum and maximum temperatures are about 8.7 and 34.2 °C in January and April, respectively; the relative air humidity is very high over the years (> 74%). According to the mean monthly air temperature, the dry season can be divided into the cool and dry season (November to January) and the hot and dry season (February to April) (Zhang, 1963; Cai et al., 2007), with heavy fog partially compensating for the shortage of rainfall during the cool and dry season (Liu et al., 2005).

The field experiments were arranged in a split-plot design with randomized complete blocks and 3 replications in a 2 m × 40 m sized plot, using 2-year-old *P. volubilis* plants cultivated in open site at intra- and inter-row spacing of 2.0 m and 2.0 m, over two consecutive growth seasons (2015 and 2016). Since *P. volubilis* is a liana species, all plants were supported to a height of 1.6 m using steel wires. The soil was a red-brown type and the characteristics of the top (0–20 cm) layer of soil were: field capacity 26% on gravimetric base; pH 5.42; organic carbon 5.65% (w/v); total nitrogen 0.34 g kg^{-1}; available N 46.0 mg kg^{-1}; available P 14.1 mg kg^{-1}; and available K 22.0 mg kg^{-1}. Rainfall can meet water requirement of *P. volubilis* plants during the wet season (Cai et al., 2007); thus, irrigation treatment was only investigated in the dry season. Weeding was done monthly, pest and insect was controlled in early May.

Fertilization rates were assigned to the main plots and consisted of 0 and 200 kg ha^{-1} of a 1:1:1 (w/w/w) mix of $N:P_2O_5:K_2O$ spread in an approx. 1.0 m-wide zone in June in 2014 and 2015, respectively, according to previous research (Yang et al., 2014). Irrigation was assigned to the sub-plots included rainfed (control) and four levels of irrigation regimes [DI20, DI50, DI100, and full irrigation (i.e., irrigation of water saturated soil); with irrigation amount of 20%, 50%, 100% and approx. averaged 147% crop evapotranspiration (ETc), respectively] from early December to late April in the dry season; irrigated once every second week. Irrigation was built between blocks, and the amount of irrigation water was monitored with flow meters (LXSG-50 Flow meter, Shanghai Water Meter Manufacturing Factory, Shanghai, China) installed in the irrigation pipelines. Each sub-plot was irrigated independently. Two pipelines with emitters were joined at both sides to the trunk and placed underneath each row; irrigation water was supplied simultaneously to both sides of the root system. Deep leakage did not occur because of shallow depth of wetted-soil of irrigation in this experiment. Crop evapotranspiration ($ETc = ET_0 \times K_c$) was estimated using crop coefficients (K_c) based on those proposed by the FAO and reference evapotranspiration (ET_0) values, calculated by the Penman-Monteith-FAO method (Allen et al., 1998) and using the daily climatic data collected in the Xishuangbanna Station for Tropical Rain Forest Ecosystem Studies (XSTRES) nearby belonging to Xishuangbanna Tropical Botanical Garden, Chinese Academy of Sciences. Crop coefficient (K_c) of the field-grown *P. volubilis* plants in this study was estimated as 1.0 with the reference to tropical fruit trees and grapevine.

2.2. Measurements

Leaf gas exchange parameters (net photosynthetic rate, Pn; transpiration rate, Tr; and stomatal conductance, Gs) were measured under light-saturating irradiance (photosynthetic photon flux density = 1800 μmol m^{-2} s^{-1}) and ambient CO_2 concentration on