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Water consumption and water-saving characteristics of a ground cover rice production system

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SUMMARY

The ground cover rice production system (GCRPS) offers a potentially water-saving alternative to the traditional paddy rice production system (TPRPS) by furrow irrigating mulched soil beds and maintaining soils under predominately unsaturated conditions. The guiding hypothesis of this study was that a GCRPS would decrease both physiological and non-physiological water consumption of rice compared to a TPRPS while either maintaining or enhancing production. This was tested in a two-year field experiment with three treatments (TPRPS, $GCRPS_{sat}$ keeping root zone average soil water content near saturated, and $GCRPS_{80\%}$ keeping root zone average soil water content as 80–100% of field water capacity) and a greenhouse experiment with four treatments (TPRPS, $GCRPS_{sat}$, $GCRPS_{fwc}$ keeping root zone average soil water content close to field water capacity, and $GCRPS_{80\%}$). The water-saving characteristics of GCRPS were analyzed as a function of the measured soil water conditions, plant parameters regarding growth and production, and water input and consumption. In the field experiment, significant reduction in both physiological and non-physiological water consumption under GCRPS lead to savings in irrigation water of ~61–84% and reduction in total input water of ~35–47%. Compared to TPRPS, deep drainage was reduced ~72–88%, evaporation was lessened ~83–89% and transpiration was limited ~6–10% under GCRPS. In addition to saving water, plant growth and grain yield were enhanced under GCRPS due to increased soil temperature in the root zone. Therefore, water use efficiencies (WUEs), based on transpiration, irrigation and total input water, were respectively improved as much as 27%, 609% and 110% under GCRPS. Increased yield attributed to up to ~19%, decreased deep drainage accounted for ~75%, decreased evaporation accounted for ~14% and reduced transpiration for ~5% of the enhancement in WUE of input water under GCRPS, while increased runoff and water storage had negative influence on WUE (−7.5 and −3.7%, respectively) for GCRPS compared to TPRPS. The greenhouse experiment validated the results obtained in the field by simplifying the non-physiological water consumption processes, and thus confirming the relative importance of physiological processes and increased WUE under GCRPS.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important grain crops for almost half the world's population, and it is predicted that an annual increase of 8–10 million tons in rice production will be required to meet future needs (IRRI, 2011). Nevertheless, 15–20 million ha of rice will likely suffer from drought stress by 2025 due to water scarcity resulting from increasing competition from urban and industrial water utilization (Belder et al., 2005; Bouman, 2007). As the largest rice producer and consumer in the world, China cultivates 29 million ha of rice, representing about 30% of its total farmland and about 70% of its total agricultural water resource consumption (FAOSTAT, 2011). Water shortage in China is estimated to reach 400 billion m^3 by 2050, roughly representing 80% of its current annual capacity (Tso, 2004). Therefore, exploration of rice production technologies to meet the requirements of increased production coupled with decreased water consumption is imperative.

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Currently, most rice in the world is cultured using the traditional paddy rice production system (TPRPS) (Bouman and Tuong, 2001; Cabangon et al., 2002), in which water consumption per unit area is about 3–5 times that of alternative dry-land crop production systems (Bouman and Tuong, 2001). Over the last decades, several innovative technologies have been developed to reduce water consumption for rice cultivation (Peng et al., 1999; Belder et al., 2004; Liu et al., 2005). The ground cover rice production system (GCRPS), proposed in 1980s (Lin et al., 2002), has been found to reduce water application, enhance soil temperature, inhibit weed growth, and increase rice production (Fan et al., 2005; Liu et al., 2005, 2013; Tao et al., 2006; Li et al., 2007; Qu et al., 2012) and is therefore regarded as one of the most promising water-saving technologies for rice (IRRI, 2011). The GCRPS is currently applied on more than 4 million ha in China (Tao et al., 2015). In a GCRPS, strip soil beds are mulched by plastic film or crop straw, and rice, irrigated via the furrows between soil beds, is cultivated in predominantly unsaturated soil (Qu et al., 2012). However, knowledge regarding the water consumption and water-saving characteristics of GCRPS, essential for its improvement and application to irrigation scheduling, is insufficient.

In a soil–plant system, water consumption can be divided into physiological (e.g. transpiration) and non-physiological (e.g. evaporation, deep drainage, runoff, and increase in water storage) components. Physiological consumption is commonly regarded as effective while non-physiological losses are considered ineffective water use (Bouman and Tuong, 2001). In a TPRPS without runoff, only about 30% of the total input water is consumed effectively through transpiration, whereas the remainder is lost through deep drainage (about 57%) and evaporation (about 13%) (Bouman et al., 2005). The most significant aspects discriminating TPRPS from GCRPS lie in the transformation of root zone soil water status from completely saturated and anaerobic to partially unsaturated and aerobic and the additional coverage on the soil beds. Consequently, deep drainage and evaporation are expected to be substantively decreased in a GCRPS (Peng et al., 1999). However, evaporation and deep drainage in GCRPS reported in the literature have only been analyzed qualitatively (Fan et al., 2002; Liu et al., 2005; Tao et al., 2006, 2015). Due to the mulch on the soil beds, the lower than field capacity soil water content and previously published data (Li et al., 2000; Huang et al., 2003), evaporation and deep drainage were assumed negligible for cases where quantification was required for water balance evaluation in a GCRPS. In fact, while it would be reasonable to neglect the evaporation from soil beds mulched by plastic film, evaporation is expected to occur from the furrows, where water is consistently or intermittently maintained for irrigation. Deep drainage, driven by the gradient of soil water potential, will almost always takes place even in the unsaturated lower root zone (Qin et al., 2006; Bouman et al., 2007).

Physiological water consumption in a GCRPS is also expected to be influenced due to its alteration of root zone conditions and probable effects on rice growth (Allen et al., 1998; Bouman et al., 2005). Significant reduction in evapotranspiration has been reported for GCRPS when compared to TPRPS (Li et al., 2000; Huang et al., 2003) but this could be simply due to reduced evaporation. Regarding just transpiration there is little published information. Relative to TPRPS, significant limitation on leaf stomatal conductance has been observed under GCRPS due to drought stress (Yang et al., 2007; Zhang et al., 2008, 2009). In contrast, leaf area under GCRPS has been found to be greatly enlarged as a result of increased soil temperature (Tao et al., 2006; Xu et al., 2007; Qu et al., 2012). The overall effect of GCRPS on plant transpiration is therefore still unknown.

Water use efficiency (WUE), defined at different scales for different water related parameters, is an important evaluator of the water-saving characteristics of a crop production system (Belder et al., 2005; Bouman, 2007; Ali and Talukder, 2008; Qiu et al., 2008). At a field-scale, WUE is usually used to evaluate the practical productivity of total input water as (Bouman et al., 2007; Sudhir et al., 2011):

$$WUE_{I+P} = 1000 \times Y/(I + P) \tag{1}$$

where WUE_{I+P} is the WUE of input water (including irrigation and precipitation) (kg m^{-3}); Y is the grain yield (kg m^{-2}); I is the irrigation amount (mm); P is the precipitation (mm); the number of 1000 is the unit conversion factor from m to mm. When precipitation is negligible or similar under various situations, Eq. (1) can be simplified to compare the practical productivity of irrigation water as (Qin et al., 2006; Sudhir et al., 2011):

$$WUE_I = 1000 \times Y/I \tag{2}$$

where WUE_I is the WUE of irrigation water (kg m^{-3}). At a plant-scale, WUE is also widely adopted to describe the relationship between physiological water consumption and photosynthetic product as (Hsiao, 1993; Shi et al., 2014):

$$WUE_T = 1000 \times B_a/T \tag{3}$$

where WUE_T is the WUE of transpiration water (kg m^{-3}); B_a is the total dry biomass of crop, sometimes including only the above-ground biomass (kg m^{-2}); T is the transpiration (mm). Generally speaking, either WUE_I or WUE_{I+P} reflects the combined efficiency of both physiological and non-physiological water consumption, while WUE_T exclusively implies the efficiency of physiological water consumption. Up to now, many studies have evaluated the WUE of GCRPS with WUE_{I+P} and WUE_I rather than WUE_T, and indicated an increase of 70–106% and 273–520% in comparison to TPRPS, respectively (Fan et al., 2005; Liu et al., 2005; Tao et al., 2006, 2015; Li et al., 2007; Xu et al., 2007; Zhang et al., 2008).

The guiding hypothesis of this study was that a GCRPS would decrease both physiological and non-physiological water consumption in comparison to a TPRPS while maintaining or enhancing rice production. The objective was to test this hypothesis by quantifying water consumption and WUE in field trials and greenhouse soil column experiments through comparing GCRPS with TPRPS.

2. Materials and methods

2.1. Field experiment (Exp. 1)

2.1.1. Experimental conditions and treatments

A field experiment was conducted from April to September (the local growing season of rice) in both 2013 and 2014 at a farm of the Fangxian Agricultural Bureau (32°07′11″N, 110°42′45″E, and altitude 440 m), Shiyan, Hubei province, China. The experimental site was located in the Qinbashan Mountains with a northern subtropical monsoon climate condition. As one of the main crops in this region, rice often suffers from low temperatures during its early growing season and can face seasonal water scarcity in spite of a local annual average rainfall reaching 830 mm (Liu et al., 2013; Tao et al., 2015). For example, the average rainfall of about 100 mm during April and May (the early growing season of rice) from 2009 to 2014 is less than 20% of the rainfall throughout the growing season, representing less than half of the total water requirement for TPRPS.

The average air temperature and solar radiation (WeatherHawk 500, Campbell Scientific, USA) from transplantation to harvest were 23.6 °C and 9.4 MJ m^{-2} d^{-1} in 2013, and 22.2 °C and 6.7 MJ m^{-2} d^{-1} in 2014. Grain maturity was delayed around one week in 2014 compared to 2013. The soil profile from 0 to 60 cm contained two layers of silt loam (0–20 and 20–60 cm), with a