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Enhancement of root systems improves productivity and sustainability in water saving ground cover rice production system

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ABSTRACT

In rice growing regions where water and temperature are growth limiting factors, the use of the innovative water-saving ground cover rice production system (GCRPS) leads to a substantial increase in yields and water use efficiency. However, so far the effect of GCRPS on root growth and its possible contribution to the observed increases in yield and water use efficiency remained unclear. In order to fill in this knowledge gap, we conducted a three-year experiment comparing two production systems: traditional paddy (Paddy) and GCRPS combined with two nitrogen fertilizer regimes (0, 150 kg N ha^{-1}). The parameters investigated were root dry matter, length density and surface area at maximum tillering and flowering stage as well as grain yield and water use efficiency. Our study revealed the following findings: 1) Root dry matter, root length density and surface area were significantly higher in GCRPS than in Paddy at all soil depths. 2) Across the production systems, root dry matter, root length density and surface area at soil depth of 0–40 cm at flowering stage were significant positively correlated to grain yield and total water use efficiency which suggested that improved root morphology traits, especially at flowering stage, contribute to higher grain yield and water use efficiency in GCRPS. Our results show that GCRPS has a positive effect on the development of rice roots and that the improved root development is of vital importance for higher yields. Furthermore, the improved root development in GCRPS may avoid potential lodging phenomena and increase soil organic carbon stocks, thus improving key soil functions.

1. Introduction

Global agriculture nowadays is facing two major challenges: increasing food demand to feed the rapidly growing world population and declining global water resource availability (Bouman, 2007; Thakur et al., 2011). World population is estimated to reach nine billion by 2050. To feed an additional two billion people during the next 40 years major increases in crop production are needed (Ashikari and Ma, 2015). Rice, as one of the world's three major food crops, is the second most-produced cereal after maize. It represents 26% of harvested area and accounts for 31% of the overall production of the three major crops (rice, maize and wheat) (FAO, 2012). However, traditional paddy rice cultivation consumes more than half of the water used for irrigation in Asia (Bouman, 2001) and the water footprint, i.e. the amount of water needed to produce a quantity of grain is estimated to be 3 times higher than that of wheat and maize (Pimentel et al., 2004). Owing to such low irrigation water use efficiency and increasing requirement for rice production, the demand of irrigation water for rice production is predicted to increase by 13.6% by 2025 (Rosegrant and Cai, 2002). However, the pressure on water is even further increasing, as 8–15% of fresh water currently used in agriculture will in the future be used to meet the growing domestic and industry water demand (Chartzoulakis and Bertaki, 2015). In order to meet the growing scarcity of fresh water for rice production, a series of water-saving technologies have been developed and tested. One of them is the so called Ground Cover Rice Production System (GCRPS), which was introduced in Central China in the late 20th century (Lin et al., 2002).

In GCRPS the soil surface is covered during the entire growing season by a 5–7 µm thick plastic film. This plastic film minimizes soil water evaporative losses, increases soil temperature and reduces weed

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growth (Shen et al., 1997). The system is characterized by the absence of standing water on the soil surface throughout the entire growth period. It should be noted that all fertilizers are applied in a single dose before transplanting due to the difficulty of topdressing under the plastic film cover. With regard to agronomic and environmental evaluation of GCRPS, the following findings from previous studies are summarized: 1) Rice grain yields increase significantly in mountainous regions (Liu et al., 2013; Tao et al., 2014) and in the cold areas of Heilongjiang province with soils having a high content on soil organic matter (Liu et al., 2014); 2) Water and nitrogen use efficiencies improve significantly (Tao et al., 2015); 3) Increase of emissions of the greenhouse gas nitrous oxide are compensated by strong reductions in the emissions of methane, so that the resulting greenhouse gases balance shows a significant decrease in the global warming potential (Yao et al., 2014). 4) A regional study with 50 paired sites showed that soil organic carbon (SOC) stocks increase significantly for GCRPS as compared to paddy rice (Liu et al., 2015) which contradicts previous site-scale studies (Tian et al., 2013). Liu et al. (2015) explained the observed increase in SOC stocks by an improved physical protection of soil organic matter (SOM), a lowered SOM mineralization rate in GCRPS as compared to conventional Paddy cultivation. However, up to now quantitative estimates of the effects of GCRPS on root development are scarce or lacking, though root parameters such as dry matter, rooting length or root morphology are known to be decisive for the productivity and sustainability of rice based cropping systems (Bauhus and Messier, 1999; Henry et al., 2011).

In more than 6000 cultivation years, rice has been adapted to grow best in flooded soils providing high availability of water and nutrients. As a result of it, rice plants have a shallow rooting system with most roots being found in the top soil layer above the compacted hard pan (Cao et al., 2006; Fageria et al., 2014). Root growth is controlled genetically and also influenced by environmental factors. It is known that changes in soil temperature and soil aeration will directly affect the allocation of photosynthetic products and thus, indirectly affect root growth and distribution (Huang et al., 1998). Furthermore, nitrogen nutrient has long been recognized as a limiting resource to nutrient cycling dynamics and carbohydrate allocation from above- into belowground in most ecosystems (Hendricks et al., 2000). However, the effect of N supply on root morphology is complex and interactively influenced by soil water conditions. Nitrogen deficiency could lead to relatively more photosynthetic allocation to roots (Fageria et al., 2014). In our study we hypothesized that root development will increase in GCRPS as compared to Paddy cultivation due to two main reasons. 1) Increased soil temperature and decreased soil water availability (Qu et al., 2012; Jin et al., 2016) in GCRPS are assumed to support rice root growth and dry matter accumulation. 2) Significant increases in aboveground biomass require a stronger root systems to support the increasing demand for water and nutrients (Schenk and Jackson, 2002). This is in agreement with the concept of plant functional equilibrium, i.e. that plant responds to a decline of resources for root growth with increased allocation of assimilates to the rooting system (Tilman, 1986; Poorter and Nagel, 2000). Accordingly, a decline of water and nutrient availability (Tao et al., 2007; Liu et al., 2013; Tao et al., 2015) should stimulate increased allocation of assimilates from aboveground to belowground. This was indirectly confirmed by Tian et al. (2013) in pot experiments comparing GCRPS and paddy. The study showed that root exudation increased with GCRPS. Furthermore, SOC stocks were significantly higher in GCRPS fields as compared to Paddy in a regional scale study in Central China (Liu et al., 2015).

These findings ask for a better characterization of the effect of GCRPS on root morphological traits so as to explain the observations of higher yields and enhanced resistance against lodging. It is frequently reported that rice grain yields can be strongly reduced by lodging or disease under unsuitable water management or over-fertilization (Wardana et al., 2013). Interestingly, lodging problems are rarely observed in GCRPS, which adds to environmental and financial benefits derived from the lower need for using pesticides against rice blast in these innovative production systems (Shen et al., 1997). This might be due to a better development of the rooting system and the maintenance of soil water contents below saturation.

Rice lodging may develop in moist sticky soil when the anchorage of plants is weakened and thus the roots and crowns yield to the torque created by the wind (Pinthus, 1973). Suitable water and nitrogen management can develop enhanced roots in deeper soil layers (Mahajan et al., 2012; Terashima et al., 1994), especially after the heading stage. In cereal crops, the greatest likelihood of lodging coincides with the heading and the early grain development stages (Manzur et al., 2014). Developing an improved rooting system at the heading stage could improve resistance to rice lodging, due to the higher rates of dry matter allocated to roots and the higher crop growth rates (Terashima, 1997). On the other hand, recent reports demonstrate that keeping soil water content at about 80% of soil water capacity in GCRPS during the period between the tillering and maturity stages, may still result in significant increases in grain yield and water use efficiency (Tao et al., 2015). If this aspect also affects air humidity within the stand remains unclear, but such reduction in air humidity would increase the resistance to fungal growth and disease development with potential positive effects on grain yield and quality (Islam et al., 2007).

The objective of our study was to investigate if GCRPS significantly affect root traits. The hypotheses of our study are therefore: 1) root dry matter and root length density increases under GCRPS as compared to traditional Paddy cultivation, especially in deeper soil depth; 2) which contributes to the improvement of rice grain yield and water use efficiency in GCRPS.

2. Materials and methods

2.1. Experimental site

The field experiment was conducted in Fangxian County (32°07′N, 110°43′E, and 440 m a.s.l.) in the northwest of Hubei Province, central China, during the 2012–2014 rice growing seasons. The soils at the depth of 0–20 cm at the experimental site have a silty loam texture, 20.3% sand (0.05–2 mm), 60.0% silt (0.002–0.05 mm) and 19.8% clay (< 0.002 mm) (Jin et al., 2016); The amount of organic matter at the 0–20 cm depth interval is 21.3 g kg^{-1}, while total N is 1.31 g kg^{-1} and the pH is 6.0. Weather data were collected every thirty minutes during the growing seasons of 2012–2014 by a meteorological station (Weather Hawk Division Campbell Scientific Inc., USA) located in direct vicinity of the experimental site. The averaged solar radiation during the growth season of rice were 8.5 ± 0.8 MJ m^{-2} d^{-1} across the experimental years. Daily average air temperature and rainfall are given in Fig. 1. Weather risks limiting crop growth in this district are low temperature in spring, drought in summer and cold weather with rain in autumn.

2.2. Experimental design

The field experiment was arranged in a block design with 4 treatments (two production systems combined with two N treatments) and replicated three times. Within each block, all four treatments are randomized. The two rice production systems were: (1) Paddy, the traditional paddy rice production system. Fields were flood irrigated in such a way that a 3-cm water layer above the soil surface was kept from the moment of transplanting until two weeks before harvest. (2) GCRPS, water-saving ground cover rice production system. The soil water content in the topsoil was kept saturated, but without standing water on top. However, ditches between the raised beds were filled with water from the moment of transplanting until two weeks before harvest. The two N treatments were: (1) no nitrogen fertilizer; (2) basal application of urea at 150 kg N ha^{-1}.

The size of each plot was 9 m × 10 m in width and length. Each plot