Field Crops Research 168 (2014) 135–147

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

High-yielding traits of heavy panicle varieties under triangle planting geometry: A new plant spatial configuration for hybrid rice in China

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ARTICLE INFO

Article history:
Received 22 May 2014
Received in revised form 28 July 2014
Accepted 29 July 2014
Available online 23 August 2014

Keywords:
Rice (*Oryza sativa* L.)
Triangle planting geometry (TPG)
Heavy panicle varieties
Planting geometry (PG)
Grain yield

ABSTRACT

Triangle planting geometry (TPG) is a new rice arrangement mode, whereby plants form a "dense intra-hill, sparse inter-hill" group structure. This allows them to have more spatial options, thus avoiding excessive infra-hill competition when compared to conventional row configurations. However, there is limited information on how TPG might affect rice production, especially for newly-bred varieties featuring a heavy panicle size (5 g $panicle^{-1}$). This study was conducted to evaluate grain yield performance and yield component changes of heavy panicle varieties under TPG. Moreover, to identify any promising agronomy traits and population structural features that might explain the difference in yield performance as well as to probe whether the high-yielding performance of TPG is reproducible in other circumstances. In 2012, Eryou498 (a heavy panicle variety) was grown under four planting geometries (PGs) in two fields that had similar soil fertility, but that were conducted with either conventional tillage or zero-tillage systems. In 2013, two heavy panicle varieties and two medium panicle varieties (2–5 g $panicle^{-1}$) were grown under three PGs in two ecological regions. Grain yield and effective panicles were significantly affected by both variety and PG. A significant interaction of PG and variety was seen on grain yield, but the high-yielding performance of TPG was consistent with all varieties. Sufficient total spikelets were the basis of achieving a high grain yield. Effective panicles predominantly attributed to total spikelets across all four experiments. Robust spikelets were crucial when grain yield was at a high level. Heavy panicle varieties and TPG showed some similar high-yielding traits. These included rapid crop growth rate (CGR) during the two weeks before full heading, plenty non-structural carbohydrate (NSC) accumulated at full heading, mass NSC output in two weeks after full heading, and high radiation use efficiency (RUE). Rice under TPG presented a more compact top three leaves as well as more stretched lower leaves when compared to other PGs. Overall, all leaves of heavy panicle varieties were more stretched than those found in medium ones. Heavy panicle varieties accumulated more nitrogen (N) in leaves from elongation to 30 days after full heading while PG showed no significant effect on leaf N concentration during the late grain-filling period. These results suggest that the high-yielding performance of TPG is reproducible in other circumstances. The combination of TPG and heavy panicle varieties is advantageous, allowing for a more efficient canopy structure for heavy panicle varieties and a more robust photosynthetic ability at late grain-filling period under TPG.

1. Introduction

Rice (*Oryza sativa* L.) is a staple food for the majority of the global population. Due to this fundamental role, world rice production will have to increase by approximately 1% annually to meet the growing demand that will arise from future population growth and economic development (Rosegrant et al., 1995). This global rate is dwarfed by China's specific needs, where rice production will need to increase by 14% from 2010 to 2030 to meet the future population's rice requirements (Cheng et al., 2007). Since it is nearly impossible to provide extra land for rice production, most of these required increases would depend on generating higher average yields (Cassman, 1999; Tilman et al., 2002). To this end, both rice variety and agronomic practices are the two key factors to achieve these growth goals.

Nowadays, China's superior high-yielding breeding as well as International Rice Research Institute's (IRRI) new plant type (NPT)

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http://dx.doi.org/10.1016/j.fcr.2014.07.017
0378-4290/

breeding are two representative rice breeding projects. These two projects have the common goal of generating large panicle size, which has been tied to higher rice yields (Yang et al., 1996; Huang, 2001; Zhou, 1995; Yuan, 1997; Peng et al., 2004). The current classification for the panicle size of rice ranges from small to medium to heavy panicle variety, which refer to those which produce 2 g of grain per panicle, 2–5 g, or 5 g or more (Zhou, 1995). Interestingly, higher hybrid yield has been attributed to their larger panicle size when compared to standard, inbred varieties. Even among hybrids, those who produced a heavier panicle under low solar radiation had the highest yield (Laza et al., 2004; Islam et al., 2010). Consequently, large panicle size is, and will continue to be, a key characteristic of rice varieties. More specifically, hybrids with a large panicle size will have an even higher yield, especially in areas of limited solar radiation.

Planting geometry is an ancient agronomic practice. It refers to the spatial arrangement of plants and determines the structure of a given crop community. Nonuniform geometry, such as seedling throwing, is aimed at reducing the labor intensity without concurrent grain yield loss (Peiris, 1956). Contrastingly, uniform geometry, such as row configurations (e.g. single, twin, or skip row), is commonly used in large crop production, (e.g. corn, sorghum, peanut, soybean, wheat and rice). Such techniques can show marked effects on grain yield if there is efficient weed control (Whish et al., 2005; Karlen and Camp, 1985; Gozubenli et al., 2004; Steiner, 1986; Brecke and Stephenson, 2006; Janovicek et al., 2006; Bjarko and Line, 1988; Mahajan and Chauhan, 2011; Phillips and Norman, 1962; Myers and Foale, 1981; Holland and Mcnamara, 1982). Low-tillering crops, such as corn and sorghum, see a consistent effect of row configuration. Under favorable conditions, plants arranged in rows with narrow spacing will achieve canopy closure early and maximize both light interception and productivity while reducing the occurrence of weeds. In dryland production systems, wide row spacing increases intra-row competition while providing additional resources in between rows. Early intra-row competition in the plant's life cycle limits the supply of water and nutrients to the plant, thereby suppressing vegetative growth, and delaying access to inter-row reserves of water and nutrients until reproductive growth.

In comparison, high-tillering crops like rice and wheat, have a more complicated response to both inter- and intra-row spacing changes due to their strong tillering ability. In fertile environments, narrow row spacing will cause mutual shading earlier than wide row spacing, thus restricting excess tillering. This progress involves a shortage of carbohydrates, morphogenetic shade-avoidance response, and blue, red, and far-red radiation intensity variations (Luquet et al., 2006; Ballaré, 1999; Casal et al., 1986; Smith and Whitelam, 1997). Although there is excellent self-regulation by tillering and there exists successful artificial control by row spacing, the effect of row configuration on high-tillering crops is more ambiguous (Lampayan et al., 2010; Chauhan and Johnson, 2010). This is particularly relevant for rice. Currently, relatively little is known of the planting geometry on rice. Most is aimed at a use of row spacing to allow for mechanized field operations without grain yield loss, thus limiting the application of planting geometry to rice production.

As a low-cost agricultural strategy, expanding the application of planting geometry would help to raise revenue in rice production. However, two major challenges remain to be surmounted before it can be implemented: excessive tillering capacity and inefficient planting geometry. To this end, in addition to large panicle size, China's superior high-yielding breeding and IRRI's NPT breeding, also share the quality of lower tillering capacity (Peng et al., 2004; Yuan, 2011). Even if the breeding objective has not realized, recently bred heavy panicle varieties have shown low to moderate tillering capacity, which is lower than that of small or medium panicle varieties. This combination of heavy panicle varieties with reduced tillering would benefit from a more efficient use of horizontal row spacing (Janoria, 1989).

Since little advanced have been made in utilizing row configuration on rice production, it is necessary to explore a new plant spatial configuration to more effectively increase grain yield. Triangle planting geometry (TPG) is a new rice planting geometry in which three single seedlings are transplanted in an equilateral triangle. This triangle occurs once per hill, with one hill made to face the space formed by the two hills of the adjacent row. This, in turn, forms a bigger triangle. Rice plants arranged using TPG form a "dense intra-hill, sparse inter-hill" group structure, which allows plants to have more spatial options to avoid excessive intra-hill competition when compared to standard row configurations (Sun et al., 2012). As of now, TPG application has covered more than 1.7 million hectares and produced approximately 20% more grain when compared to other planting geometries.

Given the success of TPG and as well as current data on panicle size and tillering characteristics, it is essential to study the impact of TPG on heavy panicle varieties. Thus, the objective of this study were three-fold: (i) to evaluate how TPG alters grain yield performance and yield components of heavy panicle rice varieties, (ii) to identify promising agronomy traits and population structural features explaining the differences in yield performance, (iii) to probe whether the high yield performance of TPG is reproducible and might be generalized to other agronomic conditions.

2. Materials and methods

2.1. Experimental sites, soil characteristics, and rice varieties

This study was comprised of four field experiments that occurred in two different locations over the span of two years. Experiments 1 (Exp. 1) and 2 were conducted during the 2012 growing season while experiments 3 (Exp. 3) and 4 (Exp. 4) occurred during the 2013 growing season. Exps. 1–3 were carried out in Wenjiang, Sichuan Province, China (30°71′N, 103°87′E, 538 m altitude), while Exp. 4 was conducted in Santai, Sichuan Province, China (31°12′N, 104°89′E, 423 m altitude). The geography of Wenjiang and Santai contained the typical plain and hill characteristics of Southwest China, respectively. Climatic conditions during the experiments are shown in Fig. 1.

The soil types of the two separate trial fields were sandy loam in Wenjiang and sandy clay loam in Santai. All soil measurements were taken prior to the start of any experiments. The organic matter content was determined by the Schollenberger method and the total nitrogen content determined by the Kjeldah method. Additionally, soil phosphorus content was quantified using the Olsen-*P* test and continuous-flow analysis used to evaluate both the NH_4OAc-extractable potassium and the mineralised nitrogen content. Based on the content analyses of nitrogen, phosphorous, potassium, and organic matter, the soil in Exps. 3 and 4 were more fertile than that in Exps. 1 and 2 (Table 1). Moreover, the varied field capacities indicated differences in the water conservation among all experimental fields.

Eryou 498 (E498) is a heavy panicle hybrid rice variety with an average 5.5 g grain panicle^{-1}. This particular variety showed advantages in grain yield, adaptability, as well as pest-resistance and was used as the test variety in Exps.1 and 2. Exps. 3 and 4 used a wider subset of rice varieties that had been bred onto different genetic backgrounds. These experiments focused solely on the heavy panicle varieties of Chuannongyou 498 (C498) and Gangyou