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Does a mixture of old and modern winter wheat cultivars increase yield and water use efficiency in water-limited environments?

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Use of mixtures of cultivars is an alternative to a monocultural crop and is considered one option to reduce the risks for producers. The objective of this study was to evaluate the grain yield and water use efficiency of a range of proportions of two winter wheat cultivars – an old landrace (Pingliang 40, PL) and a modern cultivar (Changwu 135, CW). Field experiments were conducted in 2004–2005 and 2005–2006 at Changwu Agricultural Research Station on the Loess Plateau of China. Along with pure stands of each genotype, four mixed stands, 20% PL and 80% CW (PL_2:CW_8), 40% PL and 60% CW (PL_4:CW_6), 60% PL and 40% CW (PL_6:CW_4), 80% PL and 20% CW (PL_8:CW_2), were established in the first year and a single mixture of 50% PL and 50% CW (PL_5:CW_5) was established in the second year. The grain yield of the mixtures fell between the yields of the respective monocultures under mild drought condition in 2005, while the yield of PL_5:CW_5 was not significantly different from that of the modern cultivar, CW, but higher than that of the landrace PL under the more unfavorable conditions (moderate drought) of 2006 ($P < 0.05$). At the same proportions in the mixture, greater grain yield in PL than that in CW was associated with the higher spike density, higher grain number and larger grains. In 2005, the water use efficiency for grain (WUE_g) of CW was significantly higher than that of PL, while the WUE_g of the mixtures, except PL_8:CW_2, was intermediate between the WUE_g of the two monocultures. In 2006, the WUE_g of PL_5:CW_5 was higher than both PL and CW ($P < 0.05$). In the mixtures, plant height increased in PL, but was reduced in CW, while the flag leaf area increased in both cultivars. The mixtures increased the aboveground biomass, the root biomass was reduced, so that the root-to-shoot biomass ratio (R:S) and root respiration of the mixtures were lower than that of the monocultures ($P < 0.05$). For CW, the rate of leaf photosynthesis and leaf water use efficiency (WUE_{leaf}) both decreased in mixture compared to the values in the monocultures. When the proportion in the mixture was the same, the rate of photosynthesis of the flag leaf and WUE_{leaf} of PL was significantly greater than CW. In 2006, the root biomass in the PL_5:CW_5 mixture decreased by 29% and 17% ($P < 0.01$) in the upper soil layer (0–0.4 m) and increased by 70% and 99% ($P < 0.01$) in the deep soil layer (0.6–1.0 m) in PL and CW, respectively, compared with the individual cultivars in pure stand. The mixtures had reduced water use before stem elongation, but increased water use from deep soil layers after anthesis. These results indicate that under unfavorable conditions, mixtures offer benefits in conserving soil water before stem elongation, and may provide opportunity for greater niche exploitation and more effective resource use efficiency, especially the extraction of water deep in the soil profile. We suggest that the use of a mixture of cultivars in a serious drought season will ensure greater availability of water after stem elongation stage, resulting in higher yields and WUE_g than in cultivars grown as a monoculture.

1. Introduction

Using a mixture of cultivars is considered important in self-sustaining, low-input subsistence agricultural systems (Altieri, 1999; Zajac et al., 2013). It has been proposed as a means of using newly developed lines to increase within-crop heterogeneity and

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thereby give the crop a greater capacity to adjust to various biotic and abiotic stresses (Kiaer et al., 2012). Although it is absent in modern commercial agriculture (Malézieux et al., 2009), the use of intraspecific mixtures has been suggested to increase yields, decrease risk and the need for pest management. In most cases, the productivity of crop mixtures has been shown to be greater than monocultures, ultimately leading to greater yield stability, higher yields, higher disease resistance and better end-use quality over cultivars in monoculture (Chowdhry et al., 1998; Malézieux et al., 2009; Kiaer et al., 2012). Although numerous studies have shown that the performance of a mixture was superior to that of a pure line, many negative mixing effects have also been reported, and often both positive and negative mixing effects have been observed in the same area (Treder et al., 2008; Lithourgidis et al., 2011). For example, Rajeswara Rao and Prasad (1984) found no advantage to the grain yield of spring wheat mixtures.

According to Stützel and Aufhammer (1990), more efficient utilization of available resources (light, CO_2, H_2O, nutrients) has been proposed as advantages for the use of heterogeneous populations instead of pure-stands. Mixtures can use limited resources more efficiently than monocultures, thus showing resource complementarity (Naudin et al., 2010), and yields are also said to be more stable across environments (Malézieux et al., 2009), but this result is debated (Hauggaard-Nielsen et al., 2008; Pridham and Entz, 2008). Higher biological efficiency of mixtures may be due to differences in the growth cycle and root architecture (Ponce, 2002), while the utilization of light resources was more efficient in a mixed stand when the component plants were similar (Francis, 1989). However, mixtures inevitably result in competition between the components, which in wheat has been found to trigger changes in the composition of the mixture (Tapaswi et al., 1991; Treder et al., 2008). Khalifa and Qualset (1974) found that the yield of the short-statured component of a mixture was lower than expected and the loss of yield was attributed to poorer competitive ability. Taller components were able to intercept more light, leading to higher yields for tall components and poorer yields for short components. Several traits, such as tiller number per plant, grain yield per tiller, and kernel weight, were considered indices of the increases in the yield of the dominant component of the mixture (Valentine, 1982; Asghar et al., 2011).

The present study was initiated to assess the performance of a mixture of an old landrace and a modern winter wheat cultivar with the performance of the individual cultivars grown in monoculture. The study area was located on the Loess Plateau, where the average annual precipitation ranges from 300 to 600 mm with over 60% of the annual rainfall occurring from July to September, and where the total annual rainfall also varies significantly from year to year (Kang et al., 2003). In the region, winter wheat is generally grown in monoculture as a single cultivar, with the use of mixtures being very limited, especially in the areas with insufficient water for irrigation. To date, most studies of mixtures have concentrated on the advantages of mixtures on yield, while in semi-arid areas such as the Loess Plateau with limited rainfall and irrigation, water use efficiency (WUE) may be more important. Higher grain yield and higher water use efficiency (WUE) are two equally important goals of wheat cultivation in arid and semi-arid areas. Thus, the present experiment aimed to elucidate the factors affecting the yield and WUE of a mixture of an old tall drought-sensitive landrace with a large root system and a modern semi-dwarf, drought-tolerant cultivar with a small root system, compared with the two cultivars in monoculture. The hypothesis tested was that in a semi-arid environment a mixture of the two cultivars would have a higher yield than the individual cultivars in monoculture because of greater resource-use efficiency, particularly higher WUE, improved physiological performance or morphological changes arising from the interplant competition in mixture.

2. Materials and methods

2.1. Plant materials

Two winter wheat (*Triticum aestivum* L.) cultivars were grown in monoculture and mixtures in the field. The two cultivars were bred for the semi-arid dryland agricultural area of the Loess Plateau and, based on the area cropped and the length of the period of cultivation in the region, were the most successful releases of their respective periods. Pingliang 40 (PL) is an old landrace that was very widely grown from the 1980s to 1990s, and Changwu 135 (CW) is a modern cultivar released in 1998 and is currently the most common wheat cultivar grown on the Loess Plateau. PL is a typical long-stemmed, drought-sensitive cultivar and has a large root system, while CW is a semi-dwarf, drought-tolerant cultivar, with a small root system. The two cultivars have similar phenologies, but are easily distinguished. Seeds of PL and CW were obtained from the Institute of Crop Germplasm Resources, Chinese Academy of Agricultural Sciences, Beijing, China.

2.2. Site description

Field experiments were conducted over two growing seasons, October 2004 to June 2005 and October 2005 to June 2006, at the Changwu Agricultural Research Station (107°40′30″ E, 35°14′30″ N, altitude 1200 m) of the Chinese Academy of Sciences, which is located in a typical semi-arid area of the Loess Plateau, in Shaanxi province, China. The mean annual temperature is 9.1 °C, the cumulative temperature above 10 °C is 3030 °C, and the average annual frost-free period is 171 d. The long-term (1957–2001) mean annual precipitation (rain and snow) for the site is 577 mm. The soil is a Heilu soil (Calcic Kastanozems, FAO) with a bulk density of 1.36 g cm^{-3}, a gravimetric field capacity of 26%, and a permanent wilting percentage of 10%. Before sowing the winter wheat, 120 kg N ha^{-1}, 60 kg P ha^{-1}, and 48 kg K ha^{-1} were applied in both years.

2.3. Experiment design

The two cultivars of winter wheat, PL and CW, were combined in proportion of 0:100% (CW), 20%:80% (PL_2:CW_8), 40%:60% (PL_4:CW_6), 60%:40% (PL_6:CW_4), 80%:20% (PL_8:CW_2), and 100%:0 (PL) PL:CW in 2004–2005, and 0:100% (CW), 50%:50% (PL_5:CW_5), and 100%:0 (PL), PL:CW in 2004–2006 in plots 2 m × 2 m. Each plot was surrounded by an access path 0.5 m wide. The planting arrangements are shown in Fig. 1. Seeds were sown individually by hand in rows 0.2 m apart, giving a density of 225 seeds m^{-2} in both pure stands and mixtures. To distinguish the cultivars in the mixtures, nylon strings were laid on the ground between the cultivars in each row at sowing time (Fig. 1). Each combination employed a randomized complete block design with three replicates.

2.4. Plant sampling

In each year, plants within a 0.5 m × 0.5 m area at anthesis and physiological maturity in each plot were manually cut at ground level. The area sampled at anthesis was randomly chosen in the corner of each plot with 0.3 m space away from the plot border, and sufficient space was left for the area sampled at physiological maturity to be bordered by plants. The samples from all plant parts were dried in a forced draft oven at 75 °C and weighed. At anthesis, 20 representative plants of each cultivar were sampled to measure the leaf area (CID Inc., Camas, WA, USA), plant height, tiller number and aboveground biomass. At maturity, grain yield and thousand-kernel weight (TKW) were also determined, and the