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Synergy between breeding for yield in winter wheat and high-input agriculture in North-West China

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ABSTRACT

The aims of this paper were to explore the response of winter wheat grain yield and its components to supply of resources (nutrients, water), and how this response changed with varieties selected for yield in north-west China between 1970s and 2010s. Three varieties representing the decades 1980, 2000, and 2010 in season 2013–14, and five varieties representing the decades from 1970 to 2010 in season 2014-15 were combined factorially with 11 input levels (9 nutrient treatments under irrigation and 2 nutrient treatments in rainfed condition), returning a range of environmental mean yield from 1.1 to 7.3 t ha^{-1}. Yield ranged from 0.9 t ha^{-1} for the oldest variety under rainfed conditions and low input of nutrients to 8.3 t ha^{-1} for the newest variety under irrigation and high supply of nutrients, biomass ranged from 2.3 to 18.2 t ha^{-1}, and harvest index ranged from 0.33 to 0.49. The interactions between varieties and supply of resources were analysed from the perspective of phenotypic plasticity, quantified as the unitless slope of linear models relating the trait for each variety and the environmental mean of the trait. Plasticity of yield and plasticity of grain number increased with year of cultivar release, reflecting the enhanced ability of newer varieties to capture the benefits of higher inputs. Plasticity of harvest index declined with year of release, highlighting the stability of harvest index of newer varieties compared to their older counterparts. Our study demonstrates the synergy between breeding and agronomy whereby selection for yield has improved the ability of winter wheat to capture the benefits of higher inputs that has been a major feature of Chinese agriculture over the last six decades.

1. Introduction

World-wide, increase in crop yield on historical time scales has largely resulted from a combination of improved genetics and increased availability of nitrogen and water (Sinclair and Rufty, 2012), reflecting the synergy between breeding and agronomy (Fischer, 2009). Breeding and agronomy have dramatically increased productivity of Chinese agriculture over the last six decades; some synergies have been demonstrated but many have been overlooked (Zhang et al., 2015).

Genetic gains in wheat yield, and the changes in crop phenotype in response to breeding for yield have been quantified all over world, e.g. China (Zhou et al., 2007; Tian et al., 2011; Xiao et al., 2012; Sun et al., 2014), UK (Austin et al., 1980; Shearman et al., 2005), the United States (Donmez et al., 2001), Canada (Iqbal et al., 2016), Australia (Siddique et al., 1989; Sadras and Lawson, 2011), France (Brancourt-Hulmel et al., 2003), Spain (Sanchez-Garcia et al., 2013), Chile (del Pozo et al., 2014), Iran (Miri, 2009; Khodarahmi et al., 2010) and Argentina (Slafer and Andrade, 1989). A global comparison showed absolute genetic gain (kg ha^{-1} y^{-1}) for wheat has been larger in higher-yielding environments, with higher supply of water and nitrogen (Sadras et al., 2016).

Many studies have focused on the interaction between genetic improvement in wheat and fertilizer rates (Ortiz-Monasterio et al., 1997; Brancourt-Hulmel et al., 2003; Sylvester-Bradley and Kindred, 2009; Tian et al., 2011; Sadras et al., 2016). In France, 14 wheat cultivars released from 1946 to 1992 were tested in 26 environments; modern varieties had a good response to both high and low inputs (N rate, fungicide). Nevertheless, in solo N-input treatments, old varieties achieved a higher yield at low N rate, while modern cultivars achieved higher yield at high N rate (Brancourt-Hulmel et al., 2003). A similar cross over interaction was found for wheat varieties released between 1950 and 1985 in Mexico (Ortiz-Monasterio et al., 1997). In the UK, Sylvester-Bradley and Kindred (2009) found that the rate of N to achieve peak yield was greater in new cultivars (174 kg N ha^{-1}) than in the old ones (146 kg N ha^{-1}). In the Yangtze River Basin of China, wheat yield increased linearly with year of release from 1950s to 2000s and the annual rate of increment was higher at the highest N rate (Tian et al., 2011). Sadras et al. (2016) compared the impact of breeding for

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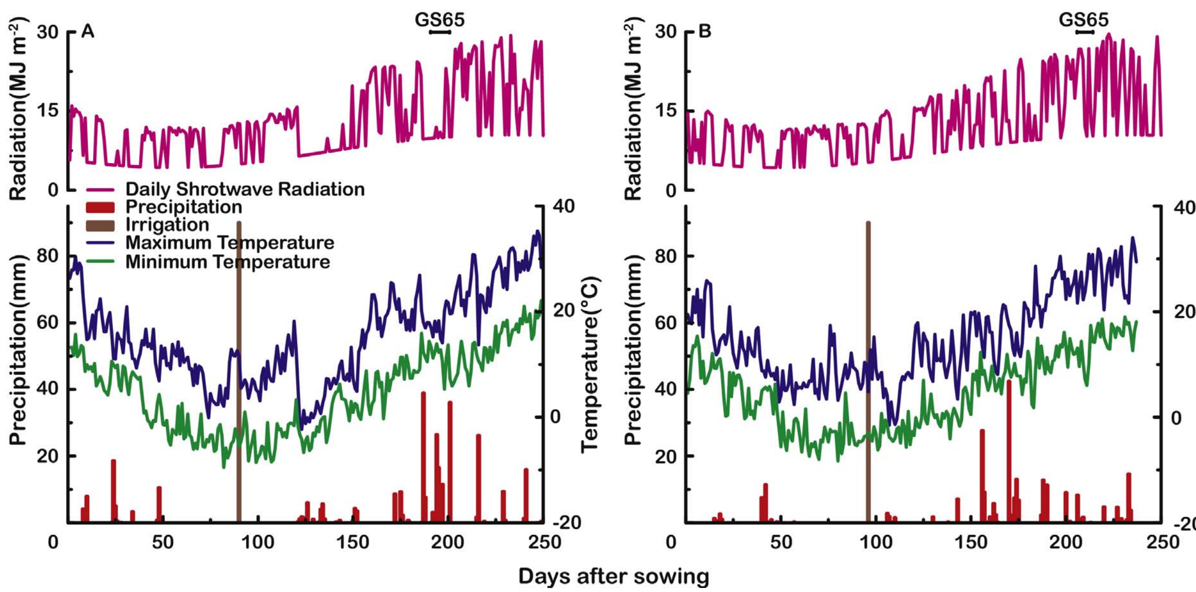

Fig. 1. Daily shortwave radiation, maximum and minimum temperatures, rainfall and irrigation during the period of wheat growth in 2013–2014 (A) and 2014–2015 (B). The horizontal bar represents the range of anthesis (GS65) for all the varieties.
Source: National Meteorological Observing Station in Yangling, Shaanxi province, China.

Table 1
Eleven growing environments from the combination of nutrient and water inputs Application rates are in kg ha^{-1}. Top 9 treatments from Control to M2N2P2 are irrigated, dControl and dMNPK are rainfed. Fertilizers were applied 2–3 days before sowing.

Treatment	Manure			Fertilizer			Total		
	N	P	K	N	P	K	N	P	K
Control	0	0	0	0	0	0	0	0	0
N1P1	0	0	0	75	13	0	75	13	0
N2P2	0	0	0	120	26	0	120	26	0
M1	75	31	34	0	0	0	75	31	34
M1N1P1	75	31	34	75	13	0	150	44	34
M1N2P2	75	31	34	120	26	0	195	57	34
M2	120	50	55	0	0	0	120	50	55
M2N1P1	120	50	55	75	13	0	195	63	55
M2N2P2	120	50	55	120	26	0	240	76	55
dControl	0	0	0	0	0	0	0	0	0
dMNPK	95	39	43	40	47	56	135	87	99

Table 2
Winter wheat varieties released in Guanzhong Plain between 1970s and 2010s. Plant height and flowering time (mean ± s.e.) are reported for the lowest (dControl: rainfed, unfertilised) and highest input (M2N2P2 receiving 240 kg N ha^{-1}, 76 kg P ha^{-1}and 55 kg K ha^{-1} under irrigation) environments. In 2013–2014 we used the varieties released in 1980s, 2000s and 2010s; all five varieties were used in 2014–2015.

Variety	Year of release	Plant height (cm)		Flowering time (days after sowing)	
		dControl	M2N2P2	dControl	M2N2P2
Aifeng 3	1970s	56 ± 1.9	77 ± 1.7	202 ± 0.7	196 ± 0.0
Xiaoyan 6	1980s	65 ± 2.9	87 ± 3.2	202 ± 0.6	196 ± 0.6
Shaan 229	1990s	58 ± 2.8	79 ± 2.6	202 ± 0.3	198 ± 0.0
Xiaoyan 22	2000s	59 ± 0.8	85 ± 1.2	202 ± 0.6	196 ± 0.3
Xinong 979	2010s	52 ± 1.7	80 ± 2.4	202 ± 0.6	196 ± 0.3

yield in the nitrogen economy of wheat in Australia, UK, Italy and Argentina. They found that the rate of increase in nitrogen uptake matched the rate of increase in grain yield with genetic improvement only in Australia. In the UK, Italy and Argentina, the rate of change in nitrogen uptake was lower than the rate of increase in yield, and this resulted in lower protein concentration in grain.

More broadly, where the combined effects of breeding and agronomy have been tested, yield gains have often been larger under more favorable conditions (Lobell et al., 2014; Richards et al., 2014), e.g. for wheat in Australia, yield increased at 9 kg ha^{-1} year^{-1} under drought and 13.2 kg ha^{-1} year^{-1} under more favorable conditions (Richards et al., 2014). For sorghum in Australia, however, combined breeding and agronomy improved yield faster under drought than under more favorable conditions (Potgieter et al., 2016). The direction of the interaction between availability of resources and yield improvement as driven by breeding, agronomy or both is thus variable, and needs direct assessment.

In this study, we quantified the interaction between breeding for yield and availability of resources in a setting of long-term soil fertility experiments (Yang et al., 2011a,b). We compared three (season 2013–2014) and five (season 2014–2015) milestone cultivars released from 1970s to 2010s in the Guanzhong region of Shaanxi province. Varieties factorially combined with 11 levels of input each season: nine long-term fertilizer treatments under irrigation and two fertilized treatments under rainfed conditions. The irrigated fertilizer experiment was established in 1980 (Yang et al., 2011a) and the rain-fed trail was established in 1990 (Yang et al., 2011b).

2. Materials and methods

2.1. Experimental site and crop husbandry

Experiments were conducted in Yangling, on the Guanzhong Plain, near the southern edge of Loess Plateau (34°17′51″N, 108°00′48″E, 534 m asl) during two seasons. Crops were hand-sown on October 10, 2013 and October 14, 2014, with stand density of 270 plants m^{-2}. Weeds were controlled by hand, insecticides for control of aphids were applied during grain filling, and no disease symptoms were apparent.

The soil is a silt clay loam Anthrosols (clay 32%, silt 52% and sand 16%) with a terric horizon derived from manure and loess material (FAO, 2014). The site is managed by the Chinese National Soil and Fertilizer Efficiency Monitoring Base for Loessial Soil (Yang et al., 2011a,b). Two long-term fertilizer experiments provided the background to this study. The first was set up in the summer of 1980 and involved a winter wheat/summer maize (*Triticum aestivum* L., *Zea mays* L.) double cropping system with irrigation. The second was set up in the autumn of 1990 and involved rainfed winter wheat/summer fallow. As a result of these long-term treatments, soil organic matter ranged from