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Comparison of yield formation mechanism of different cultivation practices of wheat after rice in Southwest China

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ABSTRACT

A thorough understanding of winter wheat yield production to the most widespread cultivation practices under rice-wheat rotation system in Southwestern China is crucial for achieving sustainable agriculture. This study simulated 3 main cultivation practices namely as super high-yielding practice (SHY, no tillage, straw mulch, ~270 seedlings m^{-2}, 180 kg nitrogen ha^{-1} with 60% applied at base, 40% at jointing), traditional high-yielding practice (THY, no tillage, no mulch, ~180 seedlings m^{-2}, 180 kg nitrogen ha^{-1} with 70% applied at base, 30% at seedling) and farmers' practice (FP, no tillage, straw mulch, ~375 seedlings m^{-2}, 225 kg nitrogen ha^{-1} with 100% applied at base) using a field experiment initiated in 2013 and aimed to analysis the tiller population, grain yield (GY), economic profit, nitrogen use efficiency (NUE) and water use efficiency (WUE) performances. The results obtained show that SHY significantly increased GY, economic profit and dry matter (DM) when compared with THY and FP. Moreover, the relationship between GY and DM was well correlated (R^2 = 0.79), suggesting changes in GY were mainly due to changes in DM accumulation. SHY enhanced soil water storage and nitrogen use in the entire life cycle of wheat. Furthermore, under the condition of SHY, leaf senescence delayed, photosynthetic rate promoted, and optimizing leaf area index (LAI) development, which provided the dry matter basis for the grain number m^{-2} and grain weight development. Compared with THY and FP, the SHY showed more favorable impacts on WUE, nitrogen uptake efficiency (NupE), NUE and nitrogen fertilizer productivity (NfP). Due to higher planting density, FP showed a lower shoot dry matter weight and higher lodging ratio than SHY and THY. These results indicating that SHY can be successfully used for wheat production under rice-wheat rotation system in Southwest China and other similar environments.

INTRODUCTION

Common wheat (*Triticum aestivum* L.) is ranked as the second most widespread planted and the third highest produced food crops in China. To confront the challengingly increased population and limited arable lands, great efforts have been made to increase grain yield of wheat up to 9000 kg ha^{-1}, which by improving farming technologies and cultivation practices as well as the genetics of wheat cultivars in the past decades (Tang et al., 2014). Southwest China is one of the five major ecological regions for wheat production in China. Out of the 1.8 million hectares of wheat production acreage in this region, 0.92 million hectares of wheat are sown in paddy fields after rice (Ministry of Agriculture and Rural Affairs, 2017). So, rice-wheat (RW) rotation system is one of the predominant cropping systems in this agricultural area (Tang et al., 2012). To achieve a stable productivity and better yields for rice, normally, most farmers often choose intensive wet tillage (puddling) for rice cultivation (Erenstein and Laxmi, 2008), which leads to deteriorated soil structure and severe soil compaction (Mohanty et al., 2007). Meanwhile, due to the continuous of precipitation after rice harvest in Southwest China, soil becomes heavy-textured in accompany with high moisture and then difficult to tillage. No-tillage (NT), a combination of ancient and modern agricultural practices, was initially used in South America to minimize soil and wind erosion and has been rapidly adopted worldwide since around 1990 (Phillips et al., 1980; Triplett and Dick., 2008). In Southwestern China, NT was adopted because it was perceived as an efficient practice to accommodate wet soil condition and to complete sowing work timely. Today, approximately 85% of the wheat lands of RW rotation system in Southwest China is planted using NT practices (Tang et al., 2002).

Rice straw was used as fodders and fuels in rural areas before 1990s (Li et al., 2012; Tang et al., 2012). Wheat seeds were often only mulched with soil after sowing without the incorporation of rice straw, which is in favor of water evaporation and thus adverse to wheat yield (Zhang et al., 2007; Liu et al., 2014, 2017; Li et al., 2015; Zhang et al., 2015). The evapotranspiration from soil surface is approximately 400-500 mm during wheat growing season in this region, but the precipitation typically does not exceed 200 mm during the period for wheat growth, seasonal drought periods limited water availability in the mid and late stage of wheat growth. Avoid to soil water evaporation from soil surface and to increase water use efficiency (WUE) are then essential to the success of winter wheat production in the region. With the improvement of fuel resources supply in 1990s, rice straw has no longer been the main fuel source in rural areas and become somehow cumbersome. Coincidentally, Sichuan Academy of Agriculture Science developed a planting method that dibbles wheat seeds into no-till soil followed by mulching with rice straw (DSSM)to improve wheat yield, and this technique was used on about 60% of the RW system in Sichuan Basin (Li et al., 2012, 2014; Tang and Hang, 2003; Humphreys et al., 2005). Moreover, the DSSM was also combined to a precise sowing technique with improving hole number m^{-2} and lowering seed number per hole (5~8 seeds) to improve wheat population development (Li et al., 2012; Dong et al., 2017). To save labor work, however, some farmers also choose the method to broadcast over 375 seeds m^{-2} (Li et al., 2012).

Nitrogen is one of the key nutrients that limit crop growth and yield potential of cereals in many production systems. During the past two decades, N fertilizer application has increased drastically to pursuit higher wheat grain yields (Zhang et al., 2015; Wu et al., 2017). However, the excessive N fertilization has become a severe problem in the RW system (Wu et al., 2017). Previous studies have documented that the high N application beyond the nutrition needs of RW rotation system had promoted the losses of nitrogen to the environment, which hence reduced nitrogen use efficiency (Lenka et al., 2013; Yang et al., 2017). Up to now, various nitrogen management strategies are used for field production including totally basal dressing and top dressing (Wu et al., 2017). However, the appropriate N management involving different combinations of tillage, straw mulch and planting density remains poorly investigated in the Southwest China.

Briefly, there are several cultivation practices widely used for wheat production in RW system, such as: i) The SHY practices which became popular in the early 2010s, ii) The traditional high-yielding practice (THY), which was once popular in the early 1980s, and iii) The farmers' practice (FP) (Tang et al., 2012). However, the yield formation process in the field, the theoretical basis for the increase in wheat yield, of such cultivation practices remains poorly investigated. In this research, we simulated the 3 main cultivation practices in the field experiment initiated in 2013 to analyze their effects on the tiller population, micro-environment, yield formation, economic profit, and NUE and WUE performances and then to improve technological management for wheat production.

MATERIALS AND METHODS

Experimental design and growing conditions

Experiments were conducted at Lian Shan town of Guang Han county (31°00' N, 104°39' W, 450 m above sea level) in the northwest Chengdu Plain of Sichuan Province, PR China. The topsoil (0-20 cm) of the experimental field is a clay loam (29.7% sand, 28.8% silt, and 41.5% clay), with the content organic matter, available nitrogen, phosphorus, and potassium averaged at 4.75%, 241.5 mg kg^{-1}, 8.2 mg kg^{-1} and 120 mg kg^{-1}, respectively.

In the two growing seasons during 2013 to 2014 and 2014 to 2015, three treatments including SHY, THY, and FP were arranged in a randomized complete block design with three replications. Seeds of cv. "ChuanMai 104" was sown on October 28th in 2013 and 2014. Each plot was 4.6 m × 12 m separated by a 1 m wide buffer zone

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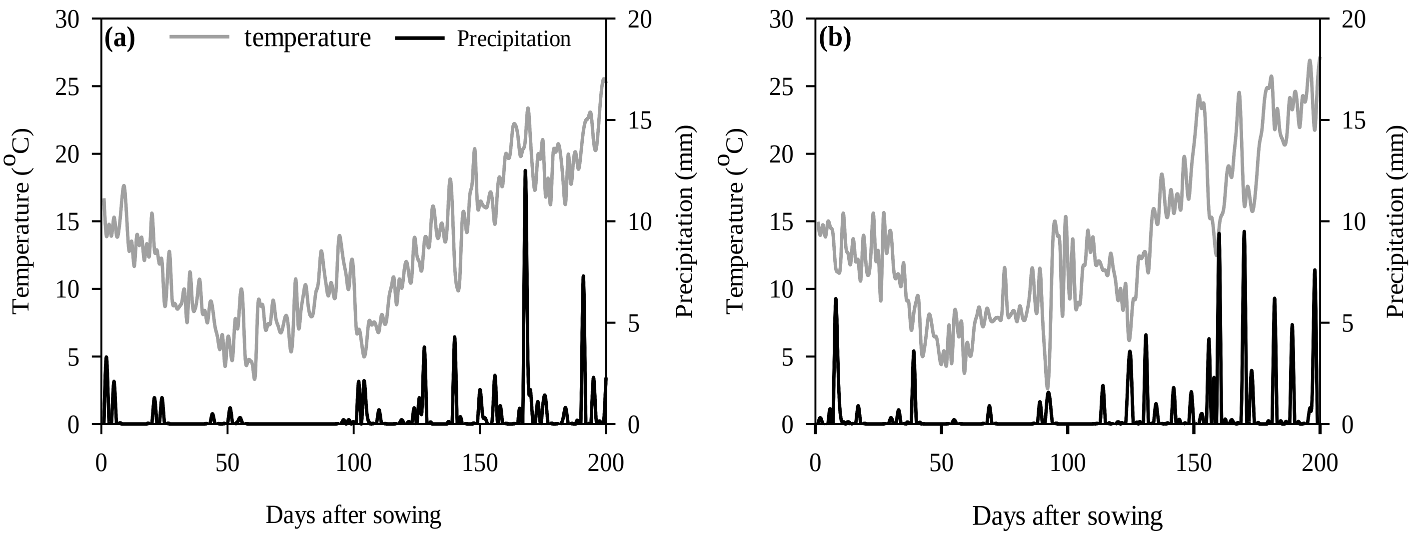

Figure 1. Daily mean temperature and precipitation during winter wheat growing season in Guanghan (31°00' N, 104°39' W, 450 m above sea level) located in the Sichuan Province, PR China during 2013-2014 growing seasonal (a), and during 2014-2015 growing seasonal (b). Figure legend in (b) is same as in (a).

Table 1. Detail information of different cultivation practices.

Practices	Tillage	Planting density (m^{-2})	Sowing method	Straw mulching	Nitrogen rate (kg ha^{-1}) and allot			
					Total	Basal	Seedling	Jointing
FP	No-tillage	375 seedlings	Broadcast seeds by hand	Mulched with all the previous rice straw after sowing	225	225(100%)	0`	0
SHY	No-tillage	270 seedlings	Dibbling seeds by hand	Mulched with all the previous rice straw after sowing	180	108(60%)	0	72(40%)
THY	No-tillage	180 seedlings	Dibbling seeds by hand	All rice straw removed from field	180	126(70%)	54(30%)	0

to prevent possible nutrient movement from one plot to another. All rice straw was removed from the field before sowing, leaving stubbles heighted at 3-5 cm on the soil surface. The planting density was approximately 375,270 and 180 seedlings m^{-2} in FP, SHY and THY, respectively. Nitrogen was applied at 225, 180 and 180 kg ha^{-1} in FP, SHY and THY, respectively. For FP, 100% of N was applied as base fertilizer. For SHY, base and jointing fertilizer was applied in the proportions of 60%:40%. For THY, 70% of N was applied at base and the other 30% was applied at seedling stage (about 4-leaves old). More details of treatments refer to Table 1. Other fertilizers including 90 kg P_2O_5 ha^{-1} and 90 kg K_2O ha^{-1} were applied as base fertilizer in all treatments. After sowing, plots of FP and SHY were mulched with the previously removed and chopped rice straw. Holes in the THY plots were covered with paddy topsoil.

Micro-environment monitoring

The rainfall data and daily mean temperature was recorded using a standard weather station (ZENO-3200) and pluviometers located at the experimental site (Figure 1). Gravimetric soil water content was determined in each plot from five 54 mm dia. Soil cores at depths of 0–10 cm and 10–20 cm on a soil oven-dry mass basis according to the practices of Blake and Hartge (1986). Samples were collected at sowing, tillering, jointing, anthesis and maturity stages of the wheat crop. Canopy temperature and moisture were measured during grain filling by a CI-110 Plant Canopy Imageranalyzer (CID Bio-Science Inc.).

Population density and lodging ratio investigation

The number of tillers or spikes in five randomly selected 100 cm long rows for SHY and THY, and 0.25 m^2 for FP in each plot was counted every seven days after sowing to determine the dynamic of tiller and spike number. Wheat lodging was measured during grain filling. Lodging ratio, which was ranged from 0 (no lodging) to 100% (serious lodging), were recorded.

Dry matter and grain yield

At wheat maturity, wheat plants in area of 1 m^2 were collected, and the yield components (that is, spike number per unit area, grain number per spike and thousand kernel weight) at each plot were determined. After that, wheat plants were separated into fractions of leaves, stems and sheathes, glumes and rachis, and grain), chopped, and dried at 70°C in a stove for 72 h before constant weight were measured to determine D Mm^{-2} and harvest index (HI). Single shoot dry matter (SSDM) weight was estimated using the formula of total DM divided by total shoots. And each plant fraction was ground separately for analysis of the N content, which was determined by the Kjeldahl digestion method as described in European Union (2009). GY was determined by harvesting the plants of 12 m^2 area in each plot, and the GY per unit area (ha^{-1}) were calculated, with 13% standard moisture content.

Leaf area, photosynthetic rate, and leaf greenness measurement

At tillering, jointing, and flowering stages, as well as 10 days and 30 days post anthesis, all green leaves from two randomly selected 20 cm long rows were sampled to determine leaf area (LA). LAI was determined using the formula of leaf area divided by sampling area. The canopy apparent photosynthesis (CAP) was measured at initial and peak stage of anthesis as well as 10,30, 40 days post anthesis from 09:00-11:00. The method of the measurement of CAP was the same as that described by Tang et al. (2015). Leaf greenness of the top most, fully expanded lamina was also measured at the same times using a non-destructive, hand-held SPAD-502 chlorophyll meter (Konica Minolta Sensing Inc., Osaka, Japan). The SPAD readings were obtained from the one-third and two-third positions of each lamina. Thirty laminae were measured in each plot, and averages were calculated.

NUE and WUE determination

Fertilizer nitrogen use efficiency including the NupE, NfP and NUE was calculated as described by Guo et al. (2014):

NupE = Total N uptake/(N application rate+soil mineral N) (kg kg^{-1})

NfP = Grain yield/N application rate (kg kg^{-1})

NUE = Grain yield/Total N uptake (kg kg^{-1})

Water use efficiency (WUE; kg ha^{-1} mm^{-1}) = Grain yield/water consumption during the crop-growing season (ET), where $ET = P + I + \Delta S$ (Zhang et al., 2007), P is the rainfall (mm), I is the irrigation rate (mm), and ΔS is the difference in soil water storage of the 0-20 cm layer between harvest and sowing (mm). The soil water storage (in mm) was determined as a function of soil water content multiplied by soil bulk density and soil depth.

Statistical analysis

Statistical Analysis System (SAS version 8.0 for Windows, SAS Inc.) software package was used for the analysis of variance (ANOVA), significance analysis and Pearson correlation analysis. Statistical comparisons were significant at the 0.05 (*) and 0.01 (**) levels of probability. Mean comparisons between treatments were performed, and Duncan's multiple range test was used to separate significant differences of mean values at a 0.05 confidence level. The correlation analysis between the seed yield with above ground dry matter, as well as with WUE, NUE, NupE and NfP were carried out.

RESULTS

Micro-environment monitoring

During the wheat growth period of the 2013-2014 and 2014-2015, total rainfall was 68.7 mm and 90.2 mm, respectively (Figure 1). Compared to THY without straw mulching, the mean soil water content in 0–10 cm soil layer of FP and SHY significantly increased by 5.4 and 6.1% in 2013-2014 (Figure 2a) and 10.7 and 9.6% in 2014-2015 (Figure 2c), respectively. The mean soil water content in 10-20 cm soil layer of FP and SHY significantly increased by 4.6 and 5.2% in 2013-2014 (Figure 2b), and 7.1 and 7.3% in 2014-2015 (Figure 2d), respectively. While canopy temperature was not significantly different between treatments, the moisture above, in, and below the canopy in the FP plots were significantly higher than that in SHY and THY plots (Figure 3).

Tiller population growth

Changes in tiller populations in different cultivation

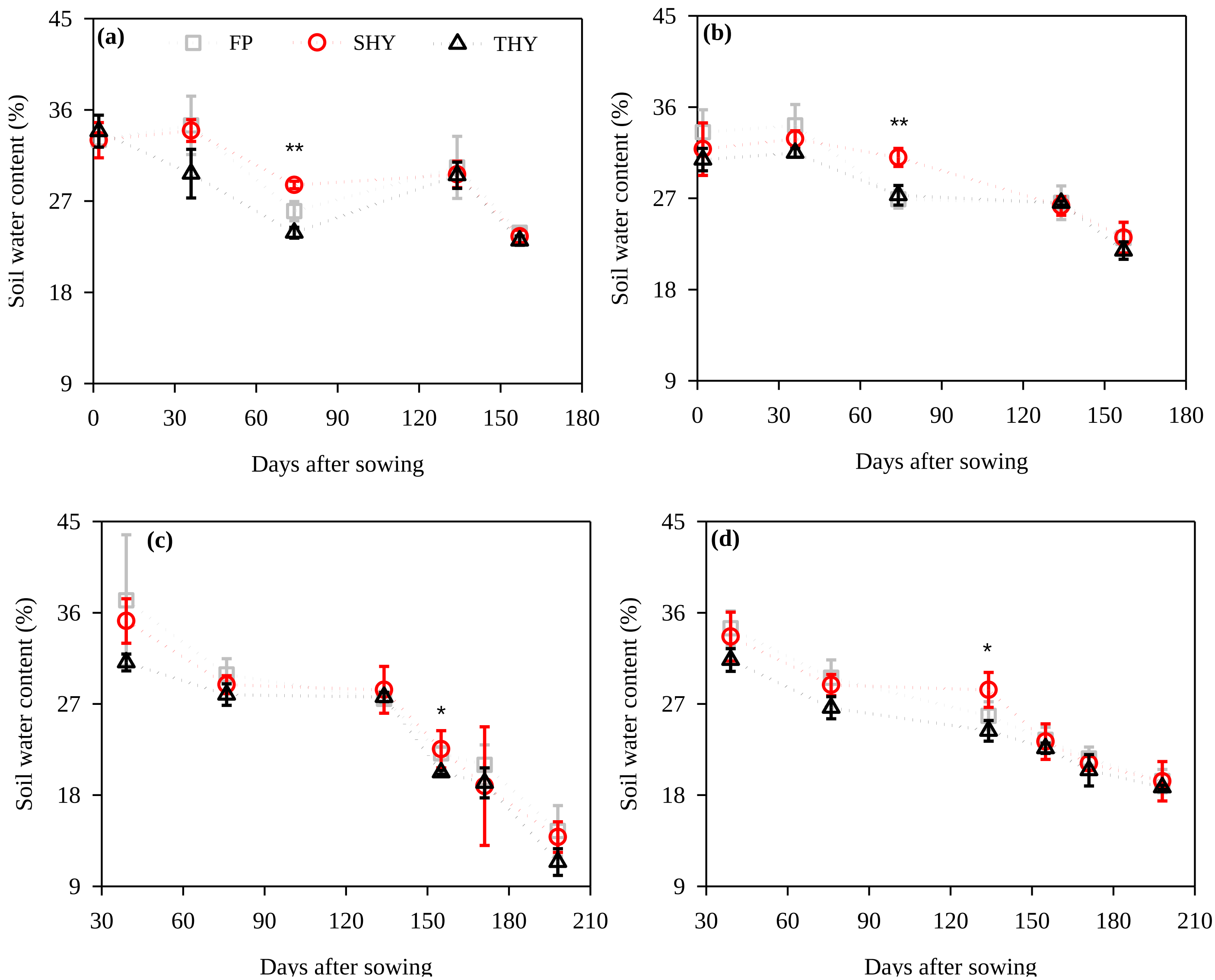

Figure 2. Effect of different cultivation practices on soil water content in 0-10 cm (a), 10-20 cm (b) during 2013-2014 growing season, and 0-10 cm (c), 10-20 cm (d) during 2014-2015 growing season. For the interaction terms: *, ** show the significance at 0.05 and 0.01 levels, NS not significant. Figure legends in (b), (c), (d) are same as in (a).

practices showed similar time course trends as shown in Figure 4. Tiller populations in each practice rapidly increased until a maximum at the jointing stage and then drastically decreased after anthesis. The maximum tiller population of FP, SHY and THY was 1653 m^{-2}, 1463 m^{-2}, 948 m^{-2} during 2013-2014, and 1328 m^{-2}, 941 m^{-2}, 628 m^{-2} during 2014-2015, respectively. During the growing season of 2013-2014, the tiller population from jointing stage to maturity decreased by 70.8, 67.9 and 56% of FP, SHY and THY, respectively. During the 2014-2015, the tiller population from jointing stage to maturity decreased of 62.3, 50.8 and 37.5% of FP, SHY and THY, respectively.

Grain yield and economic profit

Significant differences in GY, SN m^{-2}, GN m^{-2} and thousand kernel weight (TKW) had been observed between the different cultivation practices but not in GN $skike^{-1}$ (Table 2). For the yield of wheat, SHY significantly enhanced GY and it increased by 4.3 and 2.7% in 2013-2014, and by 5.7 and 14.4% in 2014-2015 when compared to FP and THY, respectively. In both years, FP resulted in the highest SN m^{-2} and GN m^{-2}, while THY resulted in the lowest SN m^{-2} and GN m^{-2}. However, TKW in SHY and THY plots was 6.5 and9.7%, respectively, higher than that in FP plots in 2013-2014, and 16.9%,

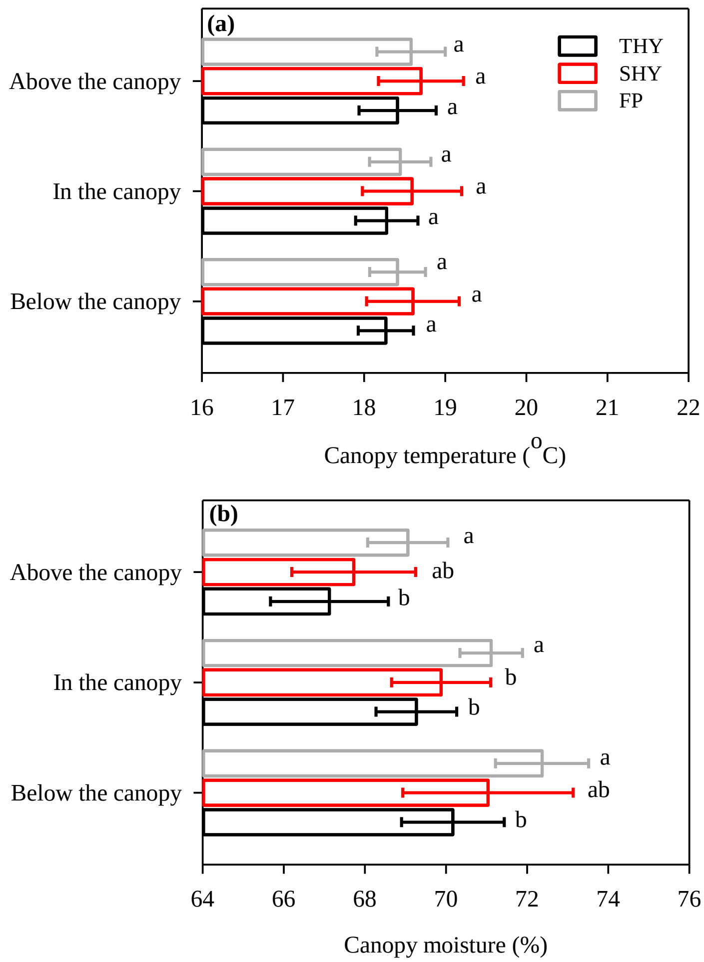

Figure 3. Canopy temperature (a) and moisture (b) measured above the canopy, canopy and below the canopy during grain filling in 2014-2015. Different letters within the same column indicate significant differences between the means determined by Duncan's multiple range test (p<0.05). Figure legend in (b) is same as in (a).

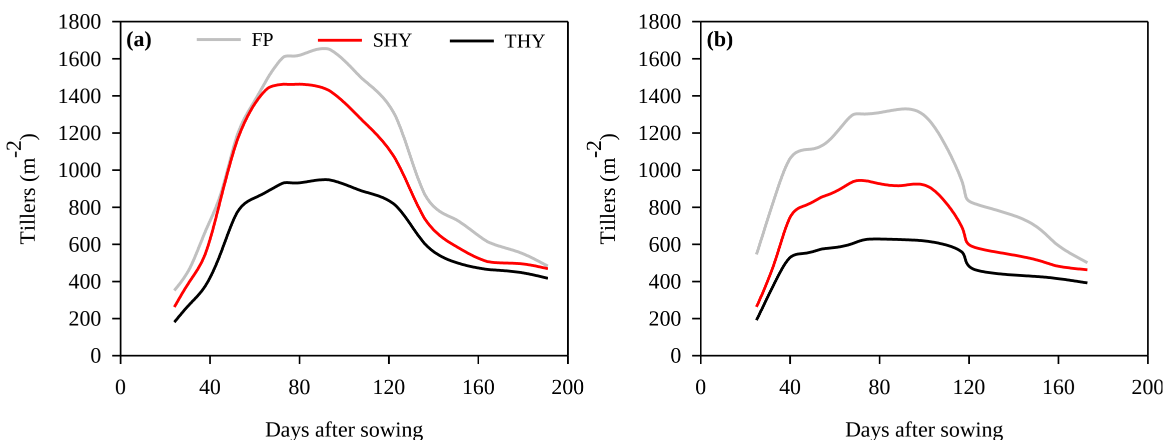

Figure 4. Changes in tiller population in wheat cultivated by different practices during 2013-2014 (a) and 2014-2015 (b) Figure legend in (b) is same as in (a).

Table 2. Effects of different cultivation practices on grain yield (GY) and yield components in 2014 and 2015.

Year	Cultivation practice	GY kg ha^{-1}	SN m^{-2}	GN $spike^{-1}$	$GN10^2m^{-2}$	TKW
2013-2014	FP	8445a	483a	45.6a	224.0a	44.5b
	SHY	8812a	469a	46.1a	216.4b	47.4a
	THY	8578a	417b	48.4a	202.1b	48.8a
2014-2015	FP	9056ab	501a	42.2a	228.2a	40.9c
	SHY	9571a	464b	42.4a	190.9b	47.8b
	THY	8367b	392c	43.7a	171.3c	50.1a
Year (Y)		*	NS	**	*	*
Planting pattern (P)		**	**	NS	**	**
Y×P		*	*	NS	NS	NS

SN, spike number; GN, grain number; TKW, thousand kernel weight. Different letters within the same column indicate significant differences between the means determined by Duncan's multiple range test ($p<0.05$). For the interaction terms: *, ** show the significance at 0.05 and 0.01 levels, NS not significant.

Table 3. Economic profits of different cultivation practices.

Year	Economic cost (CNY ha^{-1})			Economic income (CNY ha^{-1})			Economic profits (CNY ha^{-1})		
	FP	SHY	THY	FP	SHY	THY	FP	SHY	THY
2013-2014	13848	14223	14133	16891a	17624a	17155a	3043a	3401a	3022a
2014-2015	13773	14397	14289	19924ab	21057 a	18408b	6151a	6660a	4119b
Average	13811	14310	14211	18408	19341	17782	4597	5031	3571

Economic cost including the cost of fertilizer, machine, labor, seeds, and pesticide. Economic income is the income of grain yields. Economic profits = Economic income-Economic cost. Exchange rate: 1CNY = 0. 146US $. Different letters within the same column indicate significant differences between the means determined by Duncan's multiple range test ($p<0.05$).

Table 4. Effects of different cultivation practices on dry matter production and wheat lodging in 2014 and 2015.

Year	Cultivation practice	Single shoot dry matter (g)	Above ground dry matter (kg ha^{-1})	Harvest index (HI)	Lodging ratio (%)
2013-2014	FP	3.43b	15652b	0.47b	81.7a
	SHY	3.84a	16520a	0.46b	39.3a
	THY	3.86a	15176b	0.49a	3.3b
2014-2015	FP	3.79b	15956ab	0.49a	85.6a
	SHY	4.04ab	17268a	0.48a	43.7b
	THY	4.28a	14656b	0.50a	15.6c
Year (Y)		**	NG	**	NG
Planting pattern (P)		**	**	**	**
Y×P		*	NG	*	*

22.5% higher than in latter plots in 2014-2015. There was no significant difference between any of the cultivation practices with respect to the GN $spike^{-1}$.

Based on the economic cost and income for each treatment, the net profit was determined (Table 3). In both years, SHY exhibited the greatest economic profit (3401CNY ha^{-1} in 2013-2014 and 6660CNY ha^{-1} in 2014-2015), followed by FP (3043CNY ha^{-1} in 2013-2014 and 6151yuan ha^{-1} in 2014-2015). In both years, SHY showed the highest economic cost (14223CNY ha^{-1} in 2013-2014 and 14397CNY ha^{-1} in 2014-2015), due to labor cost of hole-making and additional seeds.

Dry matter production and wheat lodging

Table 4 shows the SSDM, aboveground DM at maturity, HI and wheat lodging. For both years, THY resulted in the

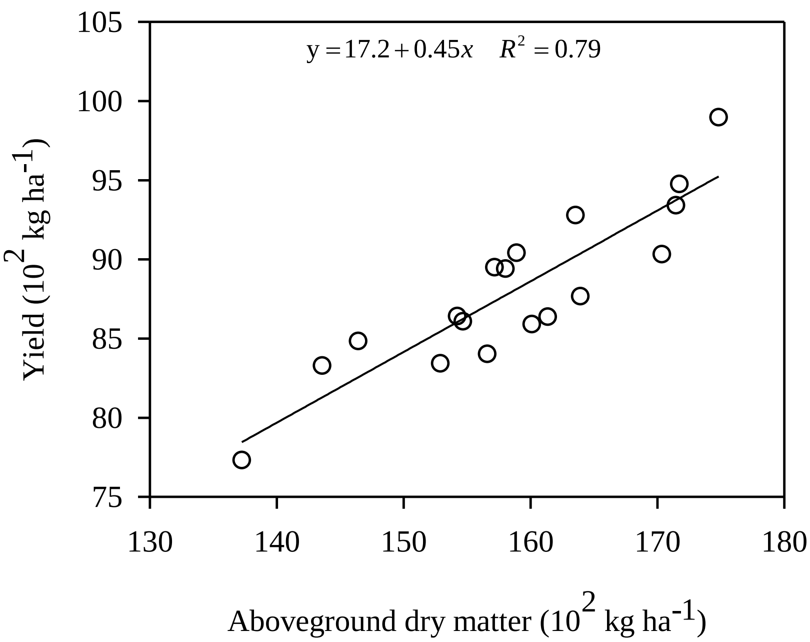

Figure 5. The correlation between above ground dry matter at maturity and grain yield.

highest SSDM (3.86g in 2013-2014 and 4.28 g in 2014-2015) and SHY resulted in the highest DM (16520 kg ha^{-1} in 2013-2014 and 17268 kg ha^{-1} in 2014-2015). The DM followed the order SHY>FP>THY, while the SSDM followed the order THY>SHY>FP. There was a significant relationship between grain yield and DM (P<0.01; Figure 5).

The HI followed the order THY>FP>SHY. FP had the highest lodging ration, followed by SHY, while THY had little lodging.

Leaf area, photosynthetic rate, and Leaf greenness

The LAI increased from 30 to 130 days after sowing and then decreased (Figure 6a and b). The maximum values were higher in the FP than SHY and THY. However, the LAI decreased rapidly in FP after anthesis, and in remained higher in SHY after anthesis than in FP and THY. In both growing seasons, CPA and SPAD reading in SHY after jointing were both higher than FP and THY, and they declined slower in SHY from anthesis to maturity than in FP and THY (Figure 6c, d, e and f).

NUE and WUE

For the WUE, SHY significantly enhanced the WUE and it increased by 27.5 and 19.2% in 2013-2014, and by 33.6 and 15.7% in 2014-2015 when compared to FP and THY, respectively (Figure 7a). The NupE under SHY was significantly increased by 30.9 and 20% in 2013-2014, and by 24 and 19.3% in 2014-2015 when compared to FP and THY, respectively (Figure 7b). Compared to FP, the NUE was significantly increased by 9.8 and 16% for SHY and THY in 2013-2014 growing seasons, and by 6.4 and 11% in 2014-2015. SHY and THY showed no significant effect on NUE in both years (Figure 7c). In 2014-2015, SHY significantly enhanced the NfP and it increased by 32.1 and 14.4% when compared to FP and THY, respectively. While, SHY showed fewer NfP than THY, and it had significantly more NfP than FP in 2013-2014 growing seasons (Figure 7d).

There was a significant relationship between grain yield and WUE (P<0.05; Figure 8a). Also, similar to grain yield and NupE (P<0.05; Figure 8b), NfP (P<0.05; Figure 8d), but not NUE (P=0.312; Figure 8c).

DISCUSSION

Grain yield and economic profit

The yield of wheat might be a function of the GN m^{-2} and grain weight (Lynch et al., 2017). According to this two-year study, SHY significantly increased GN m^{-2} and thus increased GY, while TKW was decreased when compared to that in THY. However, FP showed a significant decrease in GY due to their lowest TKW. This supports the findings of Fischer (2011) and Tang et al.

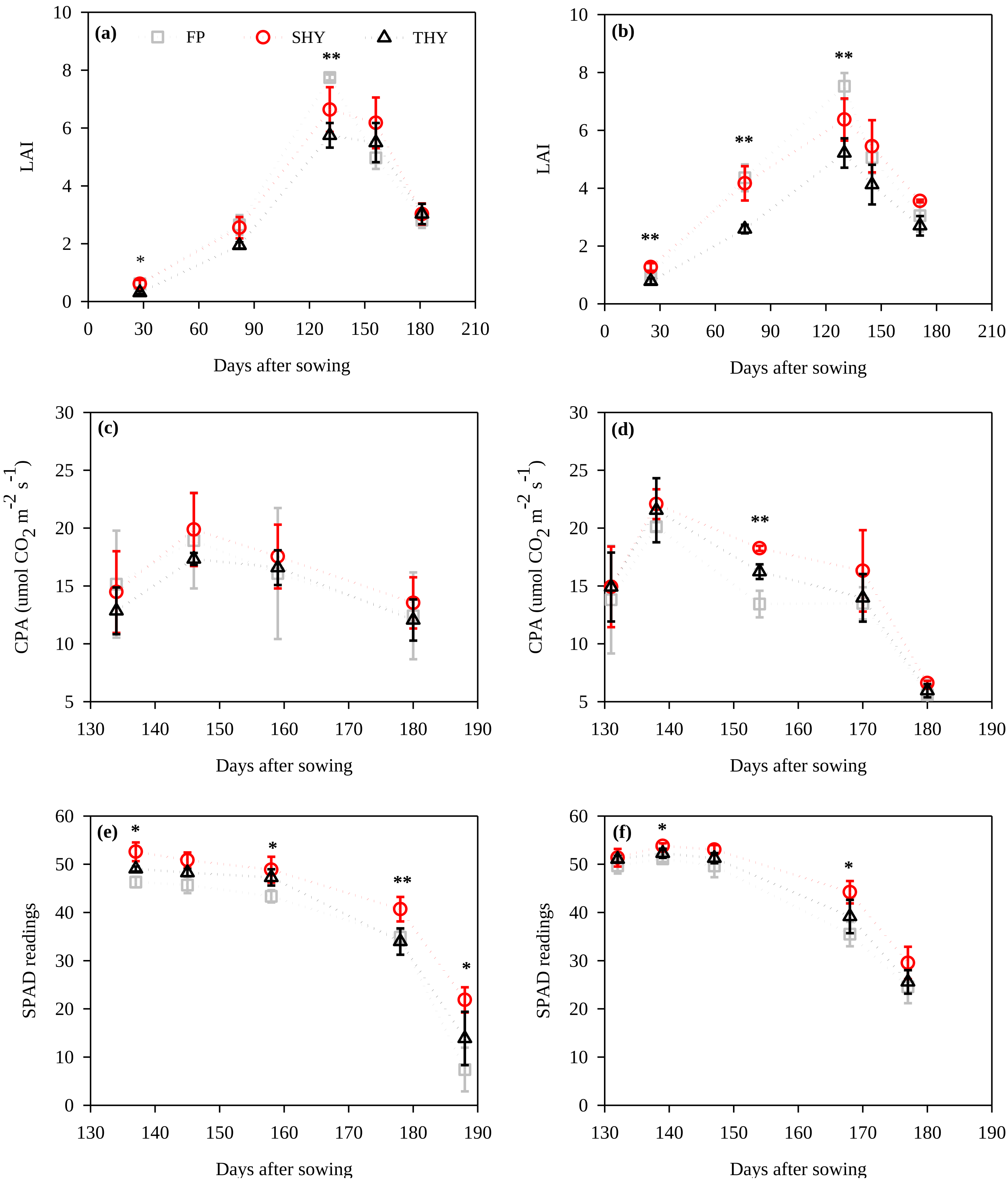

Figure 6. The dynamic variation of LAI during 2013-2014 (a) and 2014-2015 (b), canopy apparent photosynthetic rate (CPA) during 2013-2014 (c) and 2014-2015 (d), leaf greenness (SPAD reading) during 2013-2014 (e) and 2014-2015 (f) in different cultivation practices. For the interaction terms: *, ** show the significance at 0.05 and 0.01 levels, NS not significant. Figure legends in from (b) to (f) are same as in (a).

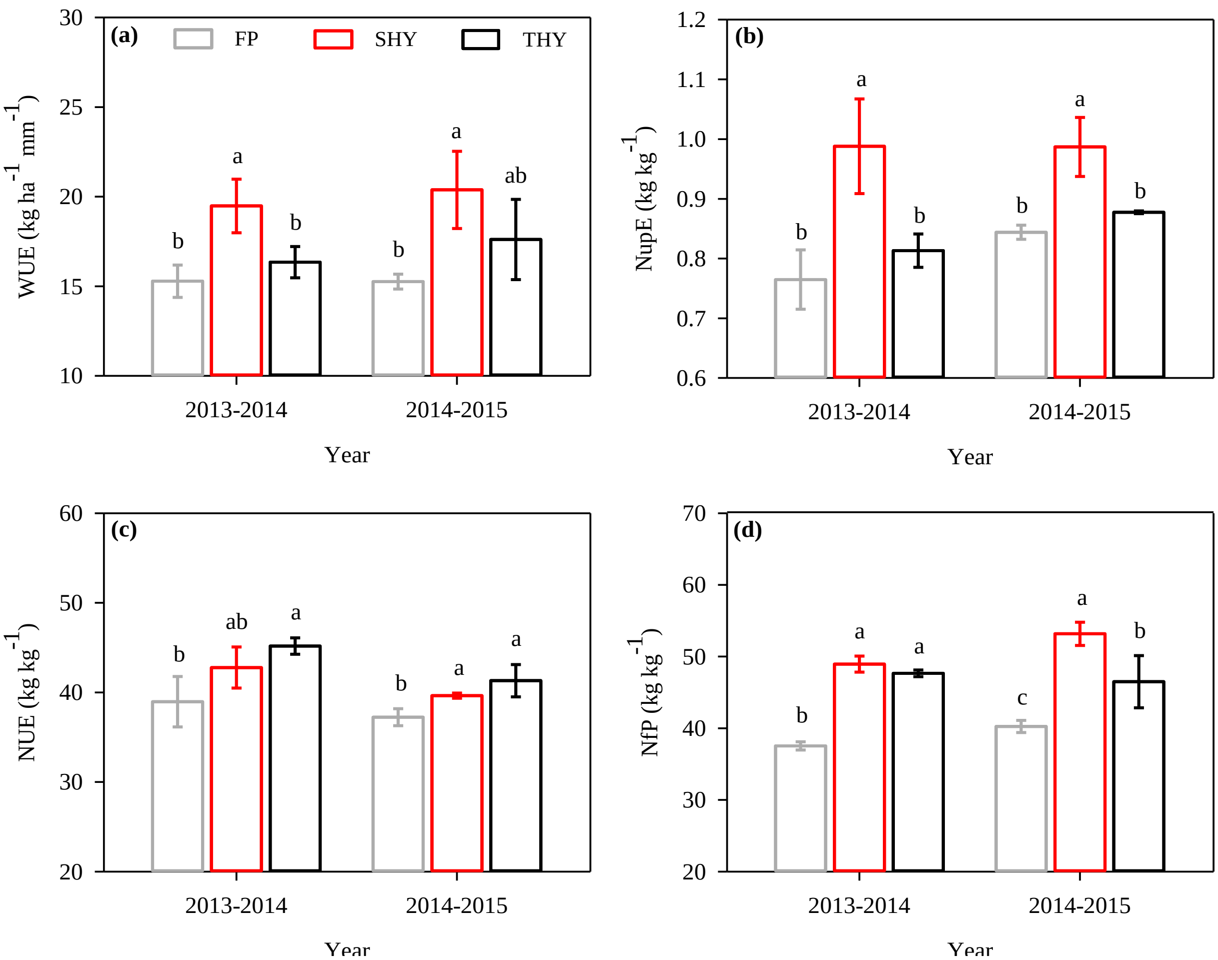

Figure 7. Water use efficiency (a), Nitrogen uptake efficiency (b), nitrogen use efficiency (c) and nitrogen fertilizer productivity (d) in different cultivation practices during the 2013-2014 and 2014-2015. Different letters indicate significant differences at p<0.05 between treatment groups according to Duncan's test. Figure legends in (b), (c), (d) are same as in (a).

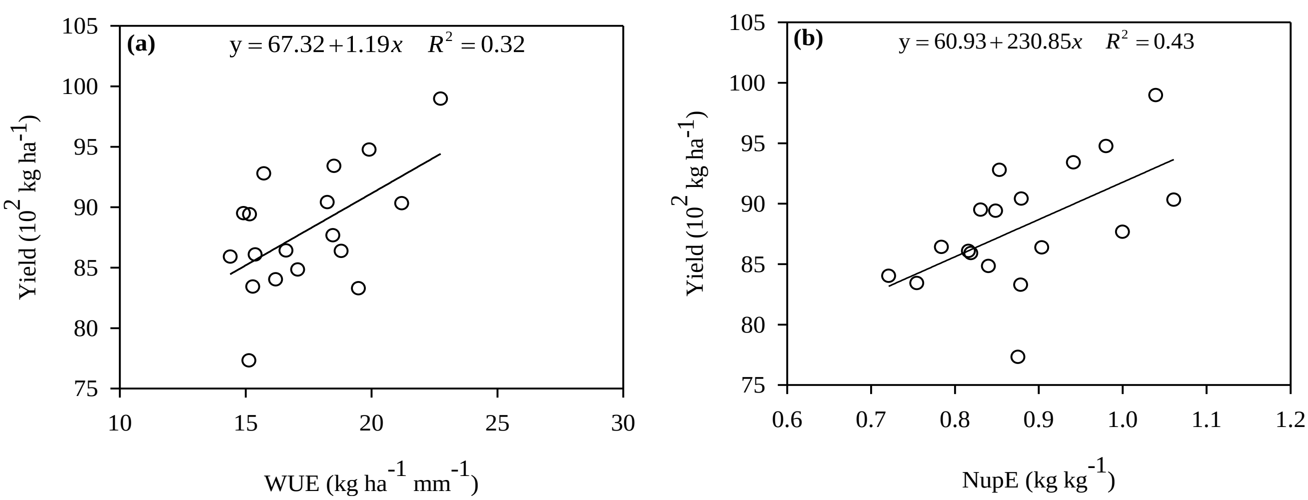

Figure 8. Regression of grain yield over WUE (a), NupE (b), NUE (c) and NfP (d) across the 2013-2014 and 2014-2015 growing seasons.

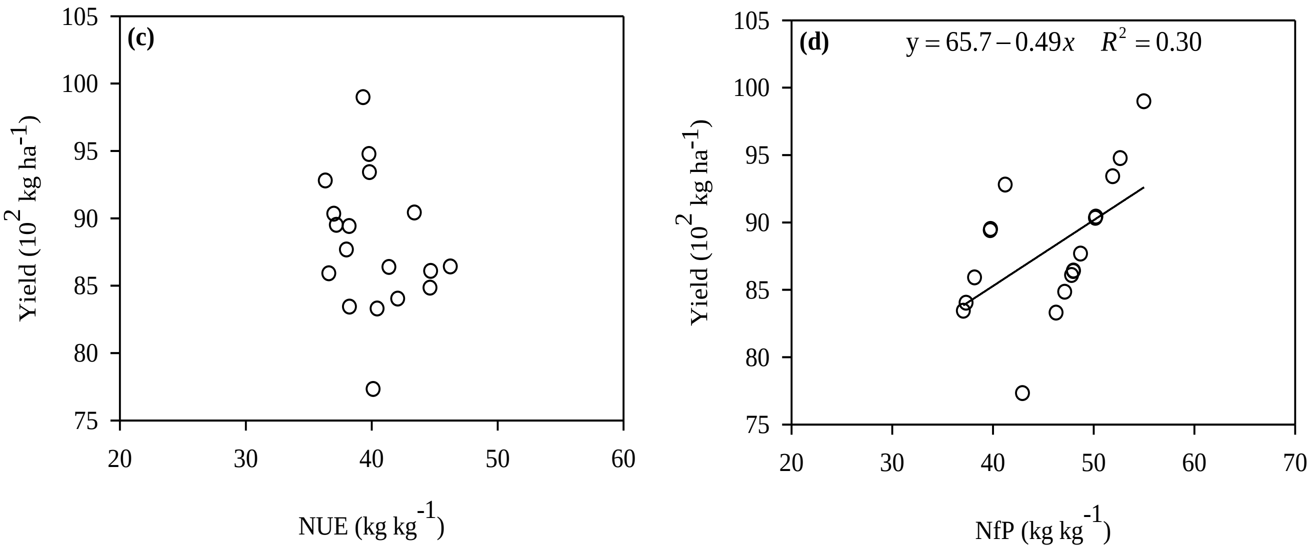

Figure 8. Contd.

(2015) that increasing GN m^{-2}, whilst maintaining or even slightly reducing grain weight, could be a major driver of yield during the last century. GN m^{-2} is a product of the SN m^{-2} and the GN $spike^{-1}$(Lynch et al., 2017). Results from the present study indicated that increases in the GN m^{-2} were primarily attributed to increases in SN m^{-2} with little variation in GN $spike^{-1}$, indicating that SN m^{-2}had a greater influence on GN m^{-2}than GN $spike^{-1}$.Compared to the practices of THY, SHY significantly increased SN m^{-2}at harvest, this may be mainly due to the optimized plant establishment, enough soil water and nutrient availability for spike survival (Assuero and Tognetti, 2010). However, the higher planting density in FP plots have decreased SN m^{-2} and TKW. Therefore, future yield increase will depend on increasing GN m^{-2} whilst maintaining a high grain weight (Foulkes et al., 2011; Tang et al., 2015; Lynch et al.,2017).

Economic benefit is vital to the success of any agriculture business. Agriculturalists must be able to predict or estimate future returns and profits to help them make decisions (Feng et al., 2017). Overall, the economic cost of SHY and THY was higher than FP due to their higher labor cost. However, the SHY had the highest economic income by its highest GY, which can offset this little increment of cost. It is rational to develop direct drilling and stubble mulching machinery to reduce the labor cost (Li et al., 2014).

Dry matter production

Previous researches have demonstrated that the increase in leaf area, leaf life, photosynthetic rate, or a combination of all these factors frequently leads to a considerable increase in final dry matter (Parry et al., 2011). Delayed leaf senescence could be as a mean to increase leaf life and photosynthetic rates (Lim et al., 2007). Gao et al. (2007) reported that early senescence of flag leaves during the mid-filling period reduced grain yield by 1-5%. Drought and nutrient deficit were the most serious external factors that accelerate leaf senescence and limit the productivity of agricultural crops (Hensel et al.,1993; Ansari and Chen, 2011). For water storage, numerous studies have demonstrated that mulch with crop straw is an effective way to reduce water loss via evaporation (Tang and Gang, 2003; Humphreys et al., 2005; Sharma et al., 2011; Liu et al., 2014; Zhang et al., 2015; Huang et al., 2015). For nutrient availability, it is well known from numerous straw mulch experiments that straw mulch could not only decrease NO^{3-}-N leaching (Huang et al., 2015; Liu et al., 2017), but also could increase soil organic carbon content (Havlin et al., 1990; Saroa and Lal, 2003). Therefore, straw mulch can help the amelioration of soil structure and, in turn, improving the root growth for nitrogen up-taking (Mulumba and Lal, 2008). Moreover, proper top dressing of N fertilizer can meet crop's nutrient requirement (Liu et al., 2017) and minimize the environmental risks caused by NO^{3-}-N leaching(Chen et al., 2014). In the present study, SHY practice delayed the decline of SPAD values in comparison to the practices of FP and THY, leading to delay the senescence process of wheat leaves and increased photosynthetic rate. This may be due to the sufficient nutrient and water supply in the SHY practices for wheat growth during the entire life cycle of wheat. However, in the practices of FP, N was used as basal fertilizer but not top dressing at other growth stage, which not only had the risk for increasing NO^{3-}-N leaching losses at early growth stage, but also resulted in N deficiency after anthesis (Wu et al., 2017). THY practices without straw mulching, led to high NO^{3-}-N leaching losses and water evaporation and consequently resulted in water and N deficiency and earlier leaf senescence.

SHY practices gave rise to a rapid leaf area growth and significantly higher LAI than that of THY. This may be due to the higher planting density in the treatment of SHY. Moreover, SHY significantly increased the storage of soil water, which created favorable environments for the growth of rapid leaf areas (Gomez-del-Campo et al., 2002). However, increasing the leaf area beyond a certain level does not greatly improve light interception (Parry et al., 2011). Parry et al. (2011) found that light interception reaches about 70% at a leaf area index of 3, but a leaf area index of 6 may be required to achieve the light interception as high as 85%. Moreover, Li et al. (2017a) have revealed that increasing plant density to a certain degree could increase shades onto the older leaves in the lower part of the canopy and lead to an increase in respiration loss which is required to maintain greater leaf area. These indicated that increased the leaf area beyond a certain level does not greatly improve light interception and light use efficiency. In conclusion, SHY practices combined no tillage, higher planting density, straw mulch, and top dressing at jointing, could delay leaf senescence, improve the photosynthesis activity, create an appropriate LAI for light interception and thereby enhance the matter production capacity, and ultimately increase the grain yield.

Wheat lodging

Lodging is a persistent phenomenon in wheat production that reduces harvestable yield by up to 80% as well as reduce the quality of the harvested grains. Therefore, any comprehensive strategy to improve wheat yield potential must take the lodging resistance into consideration (Foulkes et al., 2011). Berry et al. (2007) found that a typical plant population required for a crop yield at 8 t ha^{-1} should be 500 shoots m^{-2} and 200 plants m^{-2} and the average plant spacing will be at 71 mm. From the data of Berry et al. (2007), it could be estimated that a lodging proof ideotype will require at least 3.81 and 1.13 g of single shootdry matter and single stem dry matter weight, respectively, which will give an above-ground HI of only 0.42. In the present study, FP practices gave rise to a weak single shoot dry matter accumulation and high HI, due to high competition under high planting density, and have resulted in higher lodging ratio and lower GY. These indicated that increase wheat GY and lodging resistance must depend upon the balance between population DM production and single shoot DM production (Shearman et al., 2005; Berry et al., 2007; Foulkes et al., 2011).

NUE and WUE

Residue retention or straw mulching has been reported to increase WUE by up to 25–46% (Huang et al., 2005; Liu et al., 2010). Mulch with straw could enhance effective soil water content provide more suitable conditions for wheat emergence and growth, and consequently result in high grain yield (Gomez-del-Campo et al., 2002). WUE in SHY plots, in our study, was significantly higher than that in the THY and FP plots, which has not only been reflected by the increased soil water stage, but also been reflected by the increased grain yield.

Over application of nitrogen in cereal crops leads to low N utilization efficiency and risk of NO^{3-} pollution of ground water (Chen et al., 2014; Khalid et al., 2014; Zhang et al., 2015; Wu et al., 2017). SHY practices with 180 kg N ha^{-1} have exhibited considerably higher NupE than that of FP of 225 kg N ha^{-1}, which is probably due to that FP practices tend to apply nitrogen fertilizer in excessive of the requirements as basal fertilizer without top dressing at other stages, resulting in nitrogen leaching and poor N uptake by plants at later development stage. Such results confirmed the previous findings of Li et al. (2017b) that the high N rate at 240 kg N ha^{-1} substantially decreased NupE compared to the lower N rate at 120 kg N ha^{-1} regardless of tillage-mulch systems over three consecutive maize-wheat growing cycles. Shi and Yu (2006) were also found that nitrogen fertilizer rate at 168 kg ha^{-1} and the ratio of base and top dressing at 1:2 heightened N utilization efficiency and minimized the risk of NO^{3-} leaching. The appreciably higher N uptake was observed under SHY treatments than that of THY mainly because SHY practices optimized plant density and improved the micro-environment to increase N uptake capacity.

NUE, which is the ability of a crop to produce yield per unit of N taken up (Paponov et al., 1996; Caviglia et al., 2014), under the treatments of SHY and THYwere slightly higher than that under FP treatments in both years. In 2015, NUE in SHY plots was significantly higher than that in THY plots. In all, SHY increased N uptake and use efficiency and thereby enhanced NfP.

Conclusion

SHY treatments enhanced soil water and nitrogen use in the entire life cycle of wheat. Under the condition of SHY, the delayed leaf senescence promoted photosynthetic rate, and optimized leaf area development led to the higher photosynthetic productivity by a large margin and finally the increases in dry matter production. Compared to the practices of THY and FP, the SHY treatments have resulted in better WUE, NupE, NUE and NfP. Consequently, the mean grain yield in the plots of SHY was increased by 8.49 and 5.04% in comparison to THY and FP, respectively. This leads to an increase in the economic profit by 8.5 and 5.0%, respectively. Taken together, our findings indicated that SHY optimized grain yield and economic profit under rice-wheat rotation system in Southwest China. Obviously, the mechanization of sowing to save labor cost but maintain the seed density will further increase the economic efficiency of the SHY practices.

Abbreviations: SHY, Super high yielding practice; **THY,** traditional high-yielding practice; **FP,** farmers' practice; **LAI,** leaf area index; **CAP,** canopy apparent photosynthesis; **DM,** dry matter; **SSDM,** single shoot dry matter; **GY,** grain yield; **GN,** grain number; **SN,** spike number, **TKW,** thousand kernel weight; **NUE,** nitrogen use efficiency; **NupE,** nitrogen uptake efficiency; **NfP,** nitrogen fertilizer productivity; **WUE,** Water use efficiency.

Disclosure statement

No potential conflict of interest was reported by the authors.

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REFERENCES

Ansari M. I. & Chen S. C. (2011). Leaf senescence-an overview. International Journal of Recent Trends in Science and Technology. 1(3):110-114.

Assuero S. G. & Tognetti J. A. (2010). Tillering regulation by endogenous and environmental factors and its agricultural management. Am. J. Plant Sci. Biotechnol. 4:35-48.

Berry P. M., Sylvester-Bradley R. & Berry S. (2007). Ideotype for lodging resistant wheat. Euphytica. 154:165-179.

Blake G. R. & Hartge K. H. (1986). Bulk density, in: Klute, A. (Ed), Methods of soil analysis, Part I. Physical and mineralogical methods. SSSA Inc. and ASA Inc., Madison, WI, USA. Pp. 363-382.

Caviglia O. P., Melchiori R. J. M. & Sadras V. O. (2014). Nitrogen utilization efficiency in maize as affected by hybrid and N rate in late-sown crops. Field Crops Res. 168:27-37.

Chen X. P., Cui Z. L., Fan M. S., Vitousek P., Zhao M., Ma W., Wang Z., Zhang W., Yan X., Yang J., Deng X., Gao Q., Zhang Q., Guo S., Ren J., Li S. Ye Y., Wang Z., Huang J., Tang Q., Sun Y., Peng P., Zhang J., He M., Zhu Y., Xue J., Wang G., Wu L., An N., Wu L., Ma L., Zhang W. & Zhang F. S. (2014). Producing more grain with lower environmental costs. Nature 514:486-489.

Dong F., Dang J. Y., Wang J. A., Zhang D. Y. & Pei X. X. (2017). Effect of sowing patterns on yield components and its components, grain quality and water use efficiency of winter wheat. J. Shanxi Agric. Sci. 45:944-948. (in Chinese).

Erenstein O. & Laxmi V. (2008). Zero tillage impacts in India's rice-wheat systems: A review. Soil. Tillag. Res. 100:1-4.

European Union (2009). Commission regulation (EC) No 152/2009 Laying down the methods of sampling and analysis for the official control of feed.

Feng L., Dai J. L., Tian L. W., Zhang H. J., Li W. J. & Dong H. Z. (2017). Review of the technology for high-yielding and efficient cotton cultivation in the northwest inland cotton-growing region of China. Field Crops Res. 208:18-26.

Fischer R. A. (2011). Wheat physiology: A review of recent developments. Crop Pasture Science 62:95-114.

Foulkes M. J., Slafer G. A., Davies W. J., Berry P. M., Sylvester Bradley R., Martre P., Calderini D. F., Grifths S. & Reynolds M. P. (2011). Raising yield potential of wheat. III. Optimizing partitioning to grain while maintaining lodging resistance. J. Exp. Bot. 62:469-486.

Gao M. S., Liao Y. C., Yin Z. Y., Yu X. S. & Wu Q. L. (2007). Effects of returning straw into field on next year winter wheat root system development and leaf senescence. Acta Botanica Boreali-occidentalia Sinica. 27:303-308. (in Chinese).

Gomez-del-Campo M., Ruiz C. & Lissarague J. R. (2002). Effect of water stress on leaf area development, photosynthesis, and productivity in Chardonnay and Airen´ grapevines. Am. J. Enol. Viticult. 53:138-143.

Guo Z. J., Zhang Y. L., Zhao J. Y., Shi Y. & Yu Z. W. (2014). Nitrogen use by winter wheat and changes in soil nitrate nitrogen levels with supplemental irrigation based on measurement of moisture content in various soil layers. Field Crops Res. 164:117-125.

Havlin J. L., Kissel D. E., Maddus L. D., Claassen M. M. & Long J. H. (1990). Crop rotation and tillage effects on soil organic carbon and nitrogen. Soil Sci. Soc. Am. J. 54:448-452.

Hensel L. L., Grbic V., Baumgarten D. A. & Bleecker A. B. (1993). Developmental and age related processes that influence the longevity and senescence of photosynthetic tissue in Arabidopsis. Plant Cell. 5:553-564.

Huang M. X., Liang T., Wang L. Q. & Zhou C. H. (2015). No-tillage and fertilization management on crop yields and nitrate leaching in North China plain. Ecol. Evolut. 5:1143-1155.

Humphreys E., Meisner C., Gupta R., Timsina J., Beecher H. G., Tang Y. L., Singh Y., Gill M. A., Masih I., Zheng J. G. & Thompson J. A. (2005). Water savings in rice-wheat systems. Plant Prod. Sci. 8:242-258.

Khalid U., Ejaz A. K., Niamatullah K., Abdur R., Fazal Y. & Saleem U. D. (2014). Response of wheat to tillage plus rice residue and nitrogen management in rice-wheat system. J. Integr. Agric. 13:2389-2398.

Lenka S., Singh A. K. & Lenka N. K. (2013). Soil water and nitrogen interaction effect on residual soil nitrate and crop nitrogen recovery under maize-wheat cropping system in the semi-arid region of northern India. Agric. Ecosyst. Environ. 179:108-115.

Li C. J., Wang C. J., Wen X. X., Qin X. L., Liu Y., Han J., Li Y. J., Liao Y. C. & Wu W. (2017b). Ridge-furrow with plastic film mulching practice improves maize productivity and resource use efficiency under the wheat-maize double-cropping system in dry semi-humid areas. Field Crops Res. 203:201-211.

Li C. S., Tang Y., Huang G., Wu C. & Ma X. L. (2012). Effect of different annual tillage patterns on crop yield and soil properties in wheat-rice rotation system. Southwest China J. Agric. Sci. 25:786-791. (in Chinese)

Li C. S., Tang Y., Wu C., Wu X. L. & Huang G. (2014). Effect of rice straw returning pattern and mulching amount on mechanical sowing quality and yield formation of wheat. Southwest China J. Agric. Sci. 27:996-1002. (in Chinese)

Li M., Naeem M., Shafaqat Ali S., Zhang L., Liu L., Ma N. & Zhang C. (2017a). Leaf senescence, root morphology, and seed yield of winter oilseed rape (*Brassica napus* L.) at varying plant densities. BioMed Res Int. 2017:1-16. doi: 10.1155/2017/8581072.

Li S. X., Wang Z. H., Li S. Q. & Gao Y. J. (2015). Effect of nitrogen fertilization under plastic mulched and non-plastic mulched conditions on water use by maize plants in dry land areas of China. Agric. Water

Manage.162:15-32.
Lim P. O., Kim H. J. & Nam H. G. (2007). Leaf senescence. Ann. Rev. Plant Biol. 58:115-136.
Liu C. A., Zhou L. M., Jia J. J., Wang L. J., Si J. T., Li X., Pan C. C., Siddique K. & Li F. M. (2014). Maize yield and water balance is affected by nitrogen application in a film-mulching ridge-furrow system in a semiarid region of China. Eur. J. Agron. 52:103-111.
Liu W. Z., Zhang X. C., Dang T. H., Ouyang Z., Li Z., Wang J., Wang R. & Gao C. Q. (2010). Soil water dynamics and deep soil recharge in a record wet year in the southern Loess Plateau of China. Agric. Water Manage. 97:1133-1138.
Liu Z. J., Chen Z. J., Ma P. Y., Meng Y. & Zhou J. B. (2017). Effects of tillage, mulching and N management on yield, water productivity, N uptake and residual soil nitrate in a long-term wheat-summer maize cropping system. Field Crops Res. 213:154-164.
Lynch J. P., Doyle D., McAuley S., McHardy F., Danneels Q., Black L. C., White E. M. & Spink J. (2017). The impact of variation in grain number and individual grain weight on winter wheat yield in the high yield potential environment of Ireland. Eur. J. Agron. 87:40-49.
Ministry of agriculture and rural affairs (2017). China 2016 agriculture statistical report. China Agriculture Press, Beijing, China.
Mohanty M., Painuli D. K., Misra A. K. & Ghosh P. K. (2007). Soil quality effects of tillage and residue under rice-wheat cropping on a vertisol in india. Soil Tillag. Res. 92:243-250.
Mulumba L. N. & Lal R. (2008). Mulching effects on selected soil physical properties. Soil Tillag. Res. 98:106-111.
Paponov I., Aufhammer W., Kaul H. P. & Ehmele F. P. (1996). Nitrogen efficiency components of winter cereals. Eur. J. Agron. 5:115-124.
Parry M. A., Reynolds M., Salvucci M. E., Raines C., Andralojc P. J., Zhu X. G., Price G. D., Condon A. G. & Furbank R. T. (2011). Raising yield potential of wheat. II. Increasing photosynthetic capacity and efficiency. J. Exp. Bot. 62:453-467.
Phillips R. E., Blevins R. L., Tomas G. W., Frye W. W. & Phillips S. H. (1980). No-tillage agriculture. Science 208:1108-1113.
Saroa G. S. & Lal R. (2003). Soil restorative effects of mulching on aggregation and carbon sequestration in a Miamian soil in Central Ohio. Land Degrad. Dev. 14:481-493.
Sharma P., Abrol V. & Sharma R. K. (2011). Impact of tillage and mulch management on economics, energy requirement and crop performance in maize-wheat rotation in rain fed sub-humid inceptisols, India. Eur. J. Agron. 34:46-51.
Shearman V., Sylvester-Bradley R., Scott R. K. & Foulkes J. (2005). Changes in physiological processes associated with recent genetic increases in grain yield of winter wheat in the UK. Crop Sci. 45:175-185.
Shi Y. & Yu Z. W. (2006). Effects of nitrogen fertilizer rate and ratio of base and topdressing on yield of wheat, content of soil nitrate and nitrogen balance. Acta Ecologica Sinica 26:3661-3669.
Tang Y. & Hang G. (2003). Analysis of biological effect of the wheat sown through surface seeding and mulching straw. Southwest China J. Agric. Sci. 16:37-41. (in Chinese)
Tang Y. L., Huang G., Yuan L. X., Zhao Y. T. & Wang S. H. (2002). Studies on the technology of surface seeding and mulching straw for wheat after rice--I. Analysis of yield and benefit effect on wheat and subsequent rice. Southwest China J. Agric. Sci. 15:32-36. (in Chinese).
Tang Y. L., Rosewarne G. M., Li C. S., Wu X. L., Yang W. Y. & Wu C. (2015). Physiological factors underpinning grain yield improvements of synthetic derived wheat in Southwestern China. Crop Sci. 55:98-112.
Tang Y., Li C. S., Wu C., Ma X. L. & Huang G. (2012). Long-lasting effect of year-round tillage patterns on yield and grain quality of wheat in Chengdu plain of China. Scientia Agricultura Sinica. 45: 3721-3732. (in Chinese)
Tang Y., Li C. S., Wu C., Wu X. L., Huang G. & He G. (2014). Yield component and dry matter accumulation in wheat varieties with 9000 kg ha-1 yield potential in Sichuan Basin. Acta Agronomica Sinica 40:134-142. (in Chinese)
Triplett G. B. & Dick W. A. (2008). No-tillage crop production: A revolution in agriculture. Agron. J..100:153-165.
Wu X. L., Li C. S., Tang Y., Liu Y., Li B., Fan G. & Xiong T. (2017). Effect of nitrogen management modes on grain yield, nitrogen use efficiency and light use efficiency of wheat. Chinese J. Appl. Ecol. 28:1889-1898. (in Chinese)
Yang X. L., Lu Y. L., Ding Y., Yin X. F., Raza S. & Tong Y. A. (2017). Optimising nitrogen fertilization: a key to improving nitrogen-use efficiency and minimizing nitrate leaching losses in an intensive wheat/maize rotation (2008–2014). Field Crops Res. 206:1-10.
Zhang J. Y., Sun J. S., Duan A. W., Wang J. L., Shen X. J. & Liu X. F. (2007). Effects of different planting patterns on water use and yield performance of winter wheat in the Huang-Huai-Hai plain of China. Agric. Water Manage. 92:41-47.
Zhang S. L., Gao P. C., Tong Y. A., Norse D., Lu Y. L. & Powlson D. (2015). Overcoming nitrogen fertilizer over-use through technical and advisory approaches: A case study from Shaanxi Province, Northwest China. Agric. Ecosyst. Environ. 209:89-99.