Yield and water use efficiency of wheat in the Loess Plateau: Responses to root pruning and defoliation

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ABSTRACT

Improved crop yield and water use efficiency (yield per unit evapotranspiration) is important for food security in semiarid areas including the Loess Plateau of China, the focus of this study. We investigated the responses of winter wheat yield, evapotranspiration and water use efficiency to management practices aimed at modulating water use. Six treatments resulted from the factorial combination of practices, i.e. root pruning, defoliation and untreated control, and two seeding rates (15–19, 19–23 g m^{-2}). Crops were grown under straw mulching over two seasons; the drier season had 341 mm in-fallow rain and 160 mm in-season rain compared with the wetter season which had 392 and 252 mm, respectively.

Yield ranged from 2748 to 6669 kg ha^{-1} and responded to both management and the interaction between management and seeding rate. Relative to controls, root pruning increased grain yield by 28% in the dry season and by 8% in the wet season at high seeding rate; root pruning did not affect yield at low seeding rate. Seasonal evapotranspiration did not respond to any of the experimental sources of variation. Higher yield thus lead to increased water use efficiency of root-pruned crops in the dry season at high seeding rate. Defoliation did not affect yield in the dry season, but decreased biomass and grain yield in the wet season compared to the control. Water use efficiency was lower under defoliation at high seeding rate in the wet year. It is concluded that that root pruning could improve wheat yield and water use efficiency in dry conditions of winter wheat under stubble mulching. Considering forage from defoliation, the dual-purpose use of winter wheat may be possible without effect on grain yield in dry seasons but would reduce grain yield under the prevalent conditions of the Loess Plateau.

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1. Introduction

Many regions of the world rely on dryland farming for food production, hence the importance of agronomic practices to increase water use efficiency (Turner, 2004). In the semiarid Loess Plateau of China, water remains the most limiting factor for agricultural production following the improvements in soil fertility achieved with the increase of fertilizer application and return of crop stubble since 1980s. Winter wheat–summer fallow is a major cropping

system in the region. Owing to the seasonal distribution of rainfall, winter wheat depends heavily on the stored summer fallow rain. Straw mulching to conserve soil water and to increase soil fertility is widely used in the region (Zhang et al., 2009, 2013). However, new crop management practices to increase grain yield and water use efficiency are imperative.

Options to increase wheat grain yield and water use efficiency include the timely defoliation of crops to modify canopy size and structure and root pruning to shift the patterns of water use. Grazing of vegetative wheat is currently practiced in many countries (Rodríguez et al., 1990; Francia et al., 2006). Harrison et al. (2011) have reported from their review of 276 dual-purpose crop experiments that the effect of defoliation on grain yield ranges from 36% loss after sheep grazing in Victoria to 75% gain following clipping in Tasmania. This large variation is attributed to factors such as the type and rate of defoliation (e.g. Winter and Thompson, 1990;

Virgona et al., 2006; Miller et al., 2010), and the rate of water use (Harrison et al., 2010). In addition, plants defoliated at the two and four-leaf stages are less damaged by low temperature and yield as much as, or more than, non-defoliated plants when late frost occurs. Besides defoliation, de-tillering has also been reported to increase grain yield under dry conditions for wheat (Winward and Hanks, 1981) and barley (Jones and Kirby, 1977). In Australia, reduced tillering has been investigated as a means to shift the pattern of water use in spring wheat, with mostly neutral or slightly negative effects on yield, and some improvements on grain size depending on rainfall pattern (Mitchell et al., 2012; Sadras and Rebetzke, 2013). In the Loess Plateau, one investigation reported yield reduction of 17–28% following cutting before stem elongation under conventional tillage (Tian et al., 2012).

Root pruning could reduce water consumption during the vegetative stage and improve water use efficiency (WUE) but had no marked effect on wheat grain yield in the Loess Plateau (Wang et al., 2007; Ma et al., 2008). In contrast, Fang et al. (2010a,b) have documented root pruning in winter or early spring significantly increased grain yield in the same region.

Importantly, previous studies on defoliation and root pruning were done under conventional tillage; a gap remains on the impact of these practices under stubble mulching, as the altered pattern of soil evaporation and water use under stubble may interact with the effect of these practices on canopy and root growth. Furthermore, most farmers in the Loess Plateau use higher than recommended seeding rates, hence the question of how defoliation and root pruning interact with stand density.

The present study, therefore, assessed the effects of defoliation and root pruning at different seeding rates under straw mulching in field conditions in Loess Plateau with special attention to grain yield and water use efficiency. Crop responses to practices and seeding rate were evaluated in two seasons with contrasting rainfall.

2. Materials and methods

2.1. Site description and crop husbandry

The study was conducted from July in 2012 to July in 2014 at a site (35.14N, 107.41E and 1206 m above sea level) in Changwu county of Shaanxi Province, in the Loess Plateau. The average annual precipitation of the site is 578 mm, with 55% falling between July and September and the annual average temperature is 9.3 °C. The water table is at a depth of more than 60 m and thus, groundwater is unavailable for crops. The soil had a silt loam texture according to the USDA texture classification system. Soil organic carbon content, total nitrogen, available phosphorus, available potassium and bulk density at 0–20 cm depth were 14.4 g kg^{-1}, 0.95 g kg^{-1}, 19 mg kg^{-1}, 157 mg kg^{-1}, and 1.21 g cm^{-3}, respectively.

Wheat crops (cv Changhan 58) were sown on 21st of September 2012, and harvested on 23rd of June 2013 in the first season; crops were sown on 29th of September 2013, and harvested on 4th of July 2014 in the second season. Fertiliser included 150 kg N ha^{-1} and 75 kg P$_2$O$_5$ ha^{-1} applied before sowing each season. Wheat straw mulching started on July 2012 with a weight of 6 t ha^{-1}; at sowing, all wheat straw was removed out of plots, fertilizers were incorporated into soil, and wheat sowed manually. After sowing, wheat straw was spread evenly in the plot and some straw was added after harvest to compensate the losses.

2.2. Treatments and experimental design

The experiment included six treatments resulting from the factorial combination of three practices, i.e. root pruning, defoliation and untreated control, and two seeding rates. Treatments were arranged in a randomized block design with four replicates. Plot size was 20 m^2 including 20 rows with row space of 25 cm.

Root pruning was carried out at re-green stage in spring; roots were cut with a spade in a section at 3 cm away from wheat rows down to 13 cm depth, as in Ma et al. (2008). Defoliation was also at re-green stage in spring; canopies were clipped with shears to 5 cm height as in Zhu et al. (2004). Sowing rates were 150 kg ha^{-1} and 187.5 kg ha^{-1} in the first season and 187.5 kg ha^{-1} and 225 kg ha^{-1} in the second season based on seed quality. The low seeding rate here was recommended rate by local agronomists.

2.3. Sampling and measurements

Stems or ears were counted at emergence, tiller stage in winter, jointing stage, heading and harvest in 0.5 m^2 sections in each plot. Soil moisture in the soil profile (0–3.6 m for first season and 0–3 m for second season) was measured gravimetrically at sowing and harvest. At maturity, grain yield, shoot biomass, thousand-kernel-weight, the number of ears, and grains per ear were measured, and harvest index (HI) was calculated. The yield estimation was based on an area of 5 m^2 per plot, ear number was based on 0.5 m^2, and grains per ear were counted on ten ears per plot.

2.4. Calculations and statistical analyses

Evapotranspiration (ET) was calculated as precipitation plus changes in water storage between sowing and harvest in soil profile (Zhang et al., 2013, 2014). The experimental plots were flat, hence the assumption of negligible runoff. For the rainfall and soil combinations under study, rainfall infiltration was mostly limited to the top 2 m; as we measured soil moisture to 3 m, deep percolation was considered negligible. Water use efficiency was calculated as grain yield divided by ET.

The effects of the treatments, seasons and their interactions on the measured variables were evaluated using one- and three-way ANOVA. When F-values were significant, the least significant difference (LSD) test was used to compare means. All statistical analysis was performed through SPSS software.

3. Results

3.1. Growing conditions

In the first, drier experimental year (2012–2013), total precipitation was 501 mm, and fallow and in-crop rainfall were 341 mm and 160 mm, respectively. In the second, wetter experimental year (2013–2014), total precipitation was 644 mm, and fallow and in-crop rainfall were 392 mm and 252 mm, respectively. The fallow rainfall accounted for 68% (2012–2013) and 61% (2013–2014) of annual precipitation during the experimental period, respectively. According to the classification of precipitation made by Guo et al. (2012), fallows belonged to wet conditions in both seasons, and the first wheat season fell into very dry condition and the second wheat season was relatively wet. Frost occurred in early April in 2013 at the beginning of jointing.

3.2. Wheat population dynamics

The seeding rates showed different effects on population size in two experimental years (Fig. 1). In 2012–2013, high seeding rate presented higher population size than low seeding rate before jointing (Fig. 1A and B), but there was no difference at harvest. In 2013–2014, there were no differences in population size at any growing stage between seeding rates. The populations peaked at winter before dormancy in the first season, and at jointing in the
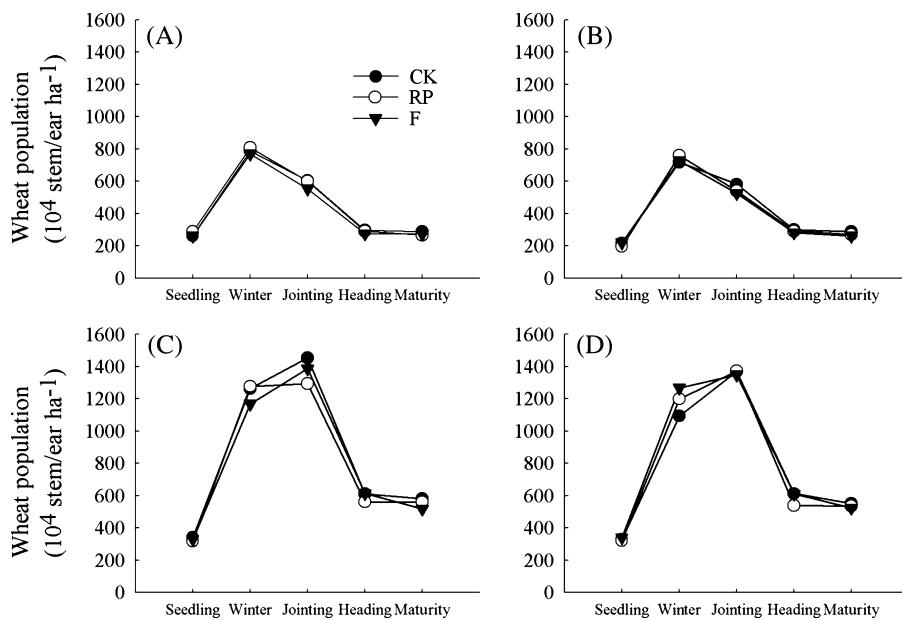
Fig. 1. Changes in wheat population size (10^4 stem/ear ha^{-1}) under root pruning (RP), defoliation (D) and untreated control (CK) at high (A) and low (B) seeding rates in 2012–2013 season and corresponding (C) and (D) in 2013–2014 season, respectively. There were no differences in population size between treatments at any stage at same seeding rate in both seasons ($P > 0.05$).

second season. Root pruning or defoliation did not affect wheat population size (Table 1).

3.3. Wheat yield and yield components

Root pruning increased wheat grain yield and harvest index at high seeding rate (2012–2013: $P < 0.05$; 2013–2014: $P < 0.1$), but no effects were observed at low seeding rate compared with control (Fig. 2). Defoliation reduced biomass regardless of seeding rates in both seasons, did not affect harvest index and reduced grain yield in the second season (Fig. 3). Irrespective

of practices, low seeding rate produced higher grain yield and harvest index than high seeding rate in the first but not in the second season (Fig. 3).

Yield components varied with management practices (Table 1). Root pruning had more kernels per ear than the control at high seeding rate; but no significant differences in kernels per ear were observed between defoliation and control. Ear number was similar between practices and the control, and kernel weight was also similar between crop management practices and the control in the first season. In the second season significant lower kernel weight was detected under defoliation than under control at high seeding

Table 1
Wheat yield components, evapotranspiration (ET) and water use efficiency (WUE) under root pruning (RP) or defoliation (F) and control (CK) at high (HS) and low (LS) seeding rates.

Year	Seeding rate	Treatment	Ear no. (10^4 ha^{-1})	Kernels per ear	kernel weight (mg)	ET (mm)	WUE (kg ha^{-1} mm^{-1})
2012–2013	HS	CK	288a	28b	45.9a	556a	5.0b
		RP	265a	34a	45.3a	520a	6.8a
		F	272a	29b	45.8a	529a	4.8b
	LS	CK	287a	33a	45.9a	515a	7.3a
		RP	269a	35a	45.1a	507a	6.6a
		F	261a	35a	45.7a	540a	6.9a
2013–2014	HS	CK	581a	31b	38.0a	500a	12.3a
		RP	560a	38a	37.3ab	515a	13.0a
		F	517a	32b	34.1b	533a	10.0b
	LS	CK	552a	38ab	33.4b	500a	12.1a
		RP	535a	44a	35.1a	532a	11.3a
		F	523a	34b	34.3ab	522a	10.9a
2012–2013	HS		275a	30b	45.7a	535a	5.5b
	LS		272a	34a	45.6a	521a	6.9a
		CK	287a	31a	45.9a	536a	6.1a
		RP	267a	35a	45.2a	513a	6.7a
		F	267a	32a	45.7a	535a	5.8a
2013–2014	HS		553a	33b	36.4a	516a	11.8a
	LS		538a	39a	34.3b	518a	11.5a
		CK	564a	35b	35.7a	500a	12.2a
		RP	547ab	41a	36.2a	524a	12.2a
		F	520b	33b	34.2a	528a	10.5b

Note: The different lowercase letters represent significant different between treatments at same seeding rate each year ($P < 0.05$) or between seeding rates or between crop management practices (RP, F and CK) each year ($P < 0.05$).
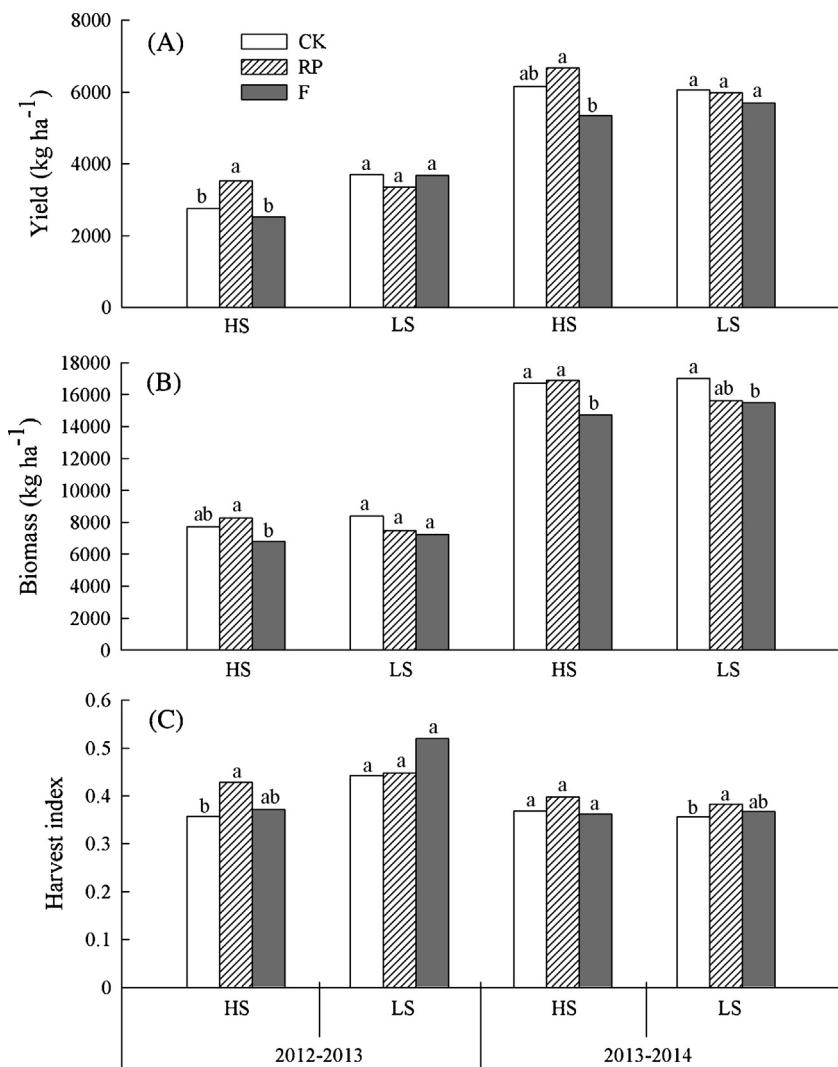
Fig. 2. Wheat grain yield (A) biomass yield (B) and harvest index (C) under root pruning (RP) and defoliation (F) and control (CK) at high (HS) and low (LS) seeding rates in 2012–2013 and 2013–2014 seasons. Different letters mean significant difference between treatments at same seeding rate each year ($P < 0.05$).

rate, and markedly higher number was found under root pruning than under control at low seeding rate (Table 1). Regardless of seeding rates, crop management practices had no significant effects on yield components in the first season, but root pruning increased grains per ear and defoliation decreased ear population in the second season (Table 1). Irrespective of crop management practices, low seeding rate had more grains per ear than high seeding rate in both seasons, and lower kernel weight in the second season (Table 1).

Yield, its components and harvest index were different between the wet and dry years (Table 2). The seeding rates impacted grain yield ($P < 0.1$), harvest index ($P < 0.05$), kernels per ear and kernel weight ($P < 0.01$). The crop management practices also influenced wheat yield ($P < 0.01$), ear number ($P < 0.1$) and kernels per ear ($P < 0.01$).

3.4. Water use and water use efficiency

The crop management practices and seeding rates had no effects on water use during two experimental years (Table 1). Water use efficiency generally followed the same pattern as grain yield. Root pruning significantly increased WUE at high seeding rate in only in the first season (Table 1). Defoliation reduced WUE at high seeding rate in the second season. Regardless of seeding rates, root pruning

had no effect on WUE in both seasons and defoliation significantly decreased WUE in the second season (Table 1).

4. Discussion

Seasonal conditions including rainfall and frost generated significant variation in yield and water use efficiency. Consistent with previous studies of Fang et al. (2010a,b) in this region, the lower seeding rate increased yield, harvest index and WUE in dry season (Fig. 3, Table 1). The lower yield with higher seeding rate could be related to more severe water stress as observed under conventional tillage by Wang (2010) and Fang et al. (2010a) (Table 1, Fang et al., 2010a) and grain weight (Fang et al., 2010a,b). In our case, slightly lower ET at low seeding rate compared with high seeding rate reflects less water requirement (Table 1), and possibly higher ratio of post to pre-anthesis ET (Fang et al., 2010b).

Root pruning improved grain yield and WUE at high seeding rate especially in the dry year, but had no effect under the lower seeding rate. In the same region, Fang et al. (2010a,b) have reported higher grain yield under root pruning in dry seasons under conventional tillage. Ma et al. (2008) have also found similar grain yields at normal seeding rate between root pruning and control in dry seasons under conventional tillage. The positive effect of root pruning might be related to restricted water use early in the season and
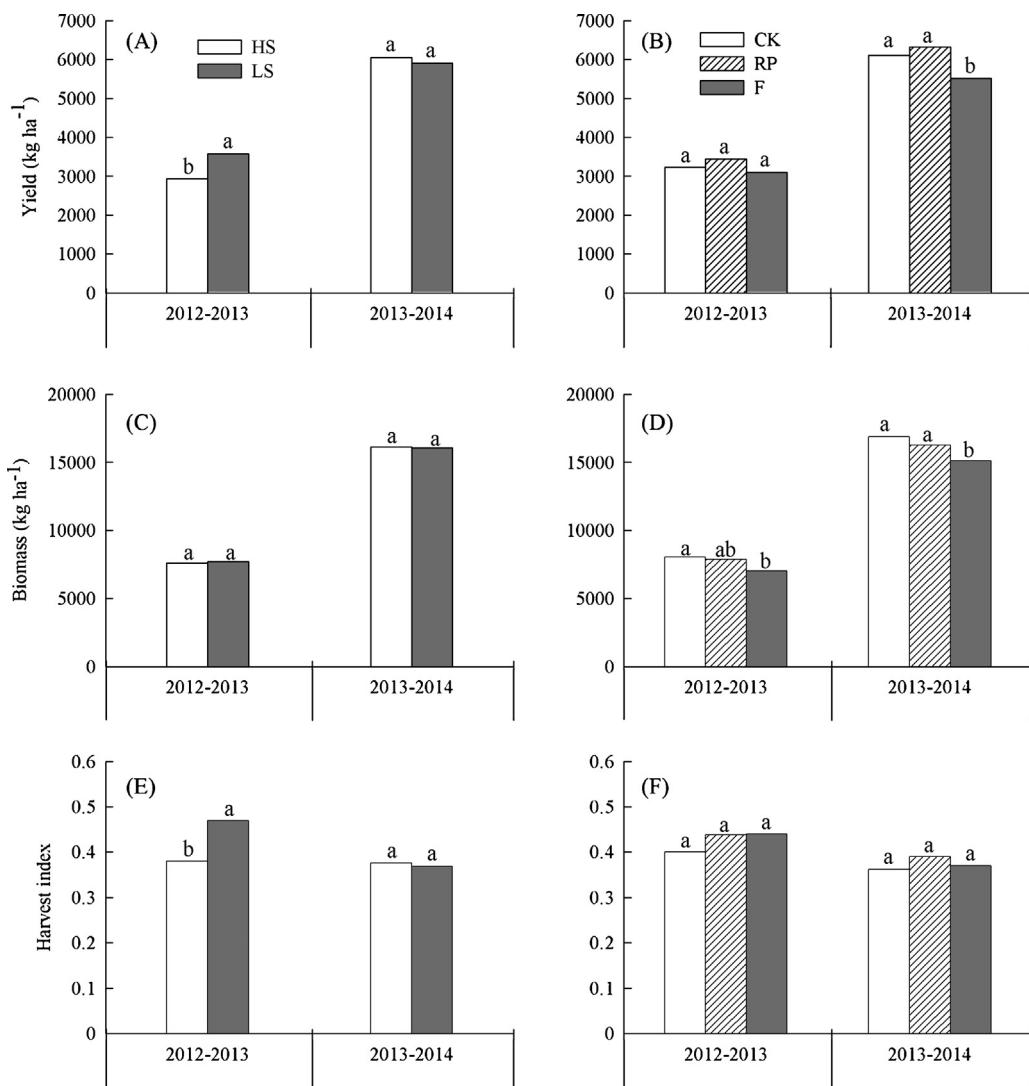
Fig. 3. Wheat grain (A), biomass (C) yields and harvest index (E) at high (HS) and low (LS) seeding rates regardless of crop management practices and corresponding (B), (D) and (F) under root pruning (RP) and defoliation (F) and control (CK) regardless of seeding rates, respectively. Different letters mean significant difference between treatments at same year (P < 0.05).

higher soil water content at critical reproductive stages (Fang et al., 2010a,b; Ma et al., 2010) and lower root respiration (Ma et al., 2008, 2010; Fang et al., 2010a). Moreover, Fang et al. (2010b) found that root pruning decreased root biomass in the top layer (0–0.4 m), but increased the proportion and actual root biomass in deeper soil layers (0.4–1.2 m), which could be beneficial for water uptake from deeper layers and thus alleviation of water stress. In our case, higher yield was also related to more kernels per ear that overrided the effect of slight reduction in ear number (Table 1) which indicated a more favourable condition in the pre-flowering period of kernel set (Fischer, 1985).

Defoliation decreased grain yield in the wet season and reduced biomass in both dry and wet season. In the same region, Tian et al. (2012) document that defoliation down to ground level at various growing stages all decreased wheat biomass and grain yield under both dry and wet seasons in conventional tillage. The reduction of yield was mainly attributed to reduction in ear number (Table 1 and Tian et al., 2012). In comparison with Tian et al. (2012), we found a smaller reduction in yield after defoliation. This could be associated with differences in intensity of defoliation, differences in the intensity of water stress and the presence of mulching in our crops. Grazing of winter wheat can relieve plant water stress

Table 2
P-values from ANOVA testing effect of year (Y), seeding rate (S), crop management practice (CP) and their interaction on wheat grain yield, shoot biomass, harvest index (HI), yield components, evapotranspiration (ET) and water use efficiency (WUE, yield per unit ET).

Item	Yield	Biomass	HI	Ears no.	Kernels per ear	Kernel weight	ET	WUE
Y	0.000	0.000	0.003	0.000	0.000	0.000	0.690	0.000
S	0.076	0.952	0.025	0.427	0.000	0.005	0.942	0.285
CP	0.006	0.001	0.247	0.090	0.000	0.144	0.623	0.026
Y × S	0.007	0.751	0.008	0.571	0.444	0.010	0.231	0.028
Y × CP	0.288	0.573	0.585	0.596	0.087	0.036	0.198	0.258
S × CP	0.004	0.041	0.203	0.910	0.485	0.047	0.433	0.051
Y × S × CP	0.706	0.803	0.460	0.687	0.129	0.046	0.859	0.518

and transiently enhance photosynthesis (Harrison et al., 2010), and reduce root respiration (Liu et al., 2006). These positive effects may compensate defoliation to some extent, but not in favourable environmental conditions, such as wet season in present study. In Australia, Zhu et al. (2004) concluded that defoliation is preferable with late maturity wheat cultivars, for early maturity cultivars are less likely to respond positively. Hence, defoliation effects on yield are related to timing and intensity of defoliation, weather and varieties. In addition, Tian et al. (2012) showed the potential to produce 0.8–1.6 t DM ha^{-1} of wheat forage when cut before stem elongation with grain yield reduction by 17% to 28% in conventional tillage. In our case, wheat forage produced about 0.6 t DM ha^{-1} in average of two years with yield reduction not statistically significant in dry condition under straw mulching. Kelman and Dove (2009) concluded that the dual-purpose option increases the gross margin over the grain-only option in all their tested comparisons in Australia.

5. Conclusions

Root pruning increased wheat grain yield and water use efficiency in dry year, especially at high seeding rate. Defoliation reduced grain yield in wet condition. To further assess the suitability of dual-purpose winter wheat under straw mulching in our region, studies are required that compare the economic performance of different combinations of varieties, timing, and intensity of defoliation.

Acknowledgements

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