Density effect and economic threshold of Japanese brome (*Bromus japonicus* Houtt.) in wheat

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ABSTRACT

Japanese brome (*Bromus japonicus* Houtt.) is a winter annual weed commonly found in the wheat (*Triticum aestivum* L.) fields of China. It is prevalent in northern China and produces obvious wheat yield losses. Information on the interference of Japanese brome on wheat density and its economic threshold (ET) is unknown; this information is useful to manage Japanese brome. Two-year field experiments were designed to determine the ET of Japanese brome in wheat. The dry weight of Japanese brome with a density of 320 plants m^{-2} was similar to the 'natural weeds including Japanese brome' treatments and higher than other Japanese brome densities, except for the 640 plants m^{-2} density which had the highest weed dry weight and yield loss. In the absence of Japanese brome, natural weed infestation was less competitive. The ET of Japanese brome in wheat was between 4 and 5 plants m^{-2} with 80% efficiency for the herbicide flucarbazone. It predicted that 4 plants m^{-2} of Japanese brome can cause 2.11% to 2.24% yield losses. This information can contribute to decision making for Japanese brome management. Given several production factors, this ET is more precise and reliable than the ET determined with only yield losses and can be used to develop better control strategies.

Key words: Economic threshold, interference, Japanese brome, *Triticum aestivum*, weed, wheat.

INTRODUCTION

Japanese brome (*Bromus japonicus* Houtt.) is a winter annual weed belonging to the brome family. It is native to Eurasia and commonly found on roadsides, floodplain wetlands, and farmlands such as wheat fields (Li, 1998). It has broader ecological amplitude (Li et al., 2015) and is widely distributed in Europe, North Africa, Australasia, north-central Pacific, America, and Asia (Che et al., 2010). Seedlings usually appear in September and October, flowering occurs in early May, and seed dispersal begins in early October (Baskin and Baskin, 1981). A Japanese brome plant can produce 1885 seeds on the average, which can be dispersed by water or wind because they are lightweight (Wang, 1986).

Wheat (*Triticum aestivum* L.) is widely cultivated in EU-27, China, India, the Russian Federation, USA, Canada, Pakistan, and Ukraine (USDA, 2014). In China, it is the third most important crop in terms of sown area (24.10 million ha) and production (126.00 million t). With the changes in farming systems and long-term use of herbicides in recent years, Japanese brome has become extensively distributed and is now found throughout the Huang-Huai-Hai Plain of China (Wei, 2010). It heavily infests wheat and is highly competitive with this crop; it can reduce yield by at least 30% in densely infested fields (Wei, 2010).

With the increasing use of herbicides, the concern about possible effects on the biodiversity and sustainability of natural and agricultural ecosystems has been raised (Andreasen and Andresen, 2011; Andreasen and Stryhn, 2012). Various weed management measures have been used to avoid the unnecessary use of herbicides. One alternative is to reduce herbicide application and only spray over weed areas, but this exceeds the economic threshold (ET) (Gerhards and Christensen, 2003; Christensen et al., 2009; Jeschke et al., 2011; Berge et al., 2012). Another option is to use mechanical control, but the ET is still applicable (Van Der Weide et al., 2008; Datta and Knezevic, 2013).

The ET concept is the fundamental principle of pest/weed population management, which rejects the eradication of pest/weed and supports the regulation of their populations at economically optimum levels (Wilkerson et al., 2002). It is a standard to determine whether a weed management measure is necessary and economical (Hazra et al., 2011; Dodamani and Das, 2013; Das et al., 2014). To be useful, the weed ET is calculated as the weed density at which the cost of control equals the benefits obtained from weed management (Cussans et al., 1986; Cousens, 1987). The ET has currently become the basis of most weed management

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decision models (Wilkerson et al., 2002). The ET-based weed management can significantly contribute to rationalizing herbicide use and reducing herbicide intake from the present levels by decreasing rates (Thomas et al., 2011). Information on the ET would be useful for wheat growers to choose appropriate measures for Japanese brome management.

The impact of different Japanese brome densities in wheat and the minimum density, which could cause economic losses, have never been investigated in China and very little worldwide. Therefore, the objective of this study was to find the degree of interference of Japanese brome for various density levels in wheat and determine its ET.

MATERIALS AND METHODS

Experimental sites

Two large-scale wheat field trials were conducted in a commercial field near Tai'an City (35°57' N, 117°3' E), Shandong Province, China, which was infested with Japanese brome. The studies were established during 2013 and 2014, respectively. The soil at the experimental site was a silt loam (Semi-Alfisols-Cinnamon soils) consisting of 38% sand, 61% silt, and 1% clay with organic matter content of 21.4 g kg^{-1} soil and pH 7.1. During the 3-yr experimentation, a cropping system with wheat (October-June) and corn (June-October) was used.

Treatments, plant sampling, and observations

Treatments consisted of eleven infestation levels of Japanese brome (JB) or weeds, which included nine JB pure stand densities (0, 5, 10, 20, 40, 80, 160, 320, and 640 plants m^{-2}) and two natural weed infestations including JB (UWC) and excluding JB (UWC-JB) (Table 1). The UWC and UWC-JB treatments were used to compare the interference of JB in pure stand densities with natural infestations with or without JB.

Information on JB density effect in wheat is scarce both in China and other countries; densities were arbitrarily chosen for their growth vigor in wheat fields. Treatments were laid out in a randomized complete block design with four replicates.

The required JB densities were maintained beginning at 20 d after sowing (DAS) the wheat by periodical counting and manually eliminating redundant weeds (Table 2). Weed-free controls (WFC) were managed throughout the crop growing period by manual weeding beginning at 10 DAS. The gross and net (i.e., actually harvested area) plot sizes were 2.0 m × 1.5 m and 1.0 m × 1.0 m, respectively. Wheat was harvested on 4 June and 10 June in 2013-2014 and 2014-2015, respectively.

Plant sampling and observations to assess weed infestation consisted of a quadrat (0.5 m × 0.5 m) that was randomly placed in each plot in which all the weeds were collected at 60 DAS and sun-dried for 2 d. Samples were then placed in an electric oven at 70 °C for 48 h and dry weight (DW) was recorded. At maturity, all the wheat from each treatment was harvested and threshed. Grains were then cleaned and yield was recorded. The observed yield losses (%) across treatments compared to weed-free control were calculated using Equation 1 (Das, 2008):

$$Yield\ loss = [(Y_{wf} - Y_t) * 100] / Y_{wf} \qquad [1]$$

where Y_{wf} and Y_t are wheat yields in weed-free control and treatment, respectively.

Table 1. **Treatments adopted in the experiment.**

Japanese brome (JB) or weed infestation level	Treatment description	Treatment code
JB 0 plant m^{-2} or weed-free control (WFC)	Free from all weeds including JB through periodic manual weeding	JB 0/WFC
JB 5 plants m^{-2}	No other weeds except JB were present; manual weeding of other weeds and excess Japanese brome population to maintain the required JB density from 20 DAS onward	JB 5
JB 10 plants m^{-2}		JB 10
JB 20 plants m^{-2}		JB 20
JB 40 plants m^{-2}		JB 40
JB 80 plants m^{-2}		JB 80
JB 160 plants m^{-2}		JB 160
JB 320 plants m^{-2}		JB 320
JB 640 plants m^{-2}		JB 640
All weeds including JB	Natural weed infestation of all weeds, unweeded control	UWC
All weeds excluding JB	Natural weed infestation without JB	UWC-JB

Table 2. Natural weed growth at 20 d after sowing (DAS) wheat for all weeds including Japanese brome (UWC).

		Weed growth in UWC	
Botanical name of weed	Common name of weed	Weed density[a]	Weed dry weight[a]
		nr m^{-2}	g m^{-2}
Bromus japonicus Houtt.	Japanese brome	114 ± 8.2	3.42 ± 0.15
Phleum paniculatum Huds.	British timothy	89 ± 6.8	3.56 ± 0.21
Capsella bursa-pastoris (L.) Medik.	Shepherd's-purse	64 ± 4.1	2.13 ± 0.13
Stellaria media (L.) Vill.	Common chickweed	28 ± 3.8	0.54 ± 0.14
Alopecurus aequalis Sobol.	Short-awn Foxtail	17 ± 1.6	0.25 ± 0.06
Galium aparine L.	Catchweed	11 ± 2.3	0.21 ± 0.08
Total weeds		323	10.11

[a] Mean (± SD) weed data of eight [four replicates × 2 yr (2013 and 2014)] quadrats (each with 0.5 × 0.5 m area).

Simulation of wheat yield and yield loss

A rectangular hyperbolic model (Equation 2) (Cousens, 1985) was used to simulate wheat yields (Y) across JB densities (d).

$$Y = Y_{wf}\,[1 - id / 100(1 + id / A)] \qquad [2]$$

where Y is simulated wheat yield at d weed density, Y_{wf} is weed-free crop yield, i is percentage yield loss per unit weed density (d) as $d \to 0$, and A is the asymptotic value of the maximum yield loss (%) as $d \to \infty$.

Natural weed infestations UWC and UWC-JB did not have a fixed JB density. Therefore, they were not considered in the simulation of wheat yield and yield losses (using Equation 2), in the study of correlations between observed and simulated yields and yield losses, and in the analysis of wheat yield and JB density.

Determination of Japanese brome economic threshold

The ET of JB (Cousens, 1987) was determined using the following quadratic equation (Equation 3).

$$1 + (i / A)\,[2 - H - (YPAH / C)]\,T + (i / A)^2 (1 - H)\,T^2 = 0 \qquad [3]$$

where i and A are defined above, Y is weed-free wheat yield, P is the unit price of wheat grain (i.e., minimum support price by the Government of China), H is the efficiency of herbicide flucarbazone (4,5-dihydro-3-methoxy-4-methyl-5-oxo-*N*-(2-trifluoromethoxyphenylsulfonyl)-1*H*-1,2,4-triazole-1-carboxamide), C is the cost of JB control (i.e., cost of flucarbazone and its application), and T is economic threshold density.

Flucarbazone is highly effective against JB and selective to wheat (Gao et al., 2011). It was applied at 0.0315 kg ha^{-1} 20 DAS in 450 L water with a knapsack sprayer fitted with a flat fan nozzle; wheat was grown in four extra plots to determine JB control efficiency (H), which was required to determine the ET of JB in wheat.

Statistical analysis

Wheat and JB/weeds data were analyzed by the ANOVA technique for a randomized complete block design. The JB/weeds DW data were subjected to a square root transformation before performing ANOVA. Significance was tested by the variance ratio (i.e., F value) at $P \leq 0.05$ (Gomez and Gomez, 1984). Standard error of difference between means (SE) was calculated for each of the studied JB/weeds and wheat variables to compare treatment means. Curve estimation was performed to determine the relationship between JB densities and wheat yield with SPSS version 17.0 (IBM, Armonk, New York, USA). Correlation coefficients between observed yields and simulated equations were calculated to obtain a logical conclusion of the simulated data.

RESULTS

Growth of Japanese brome/weeds

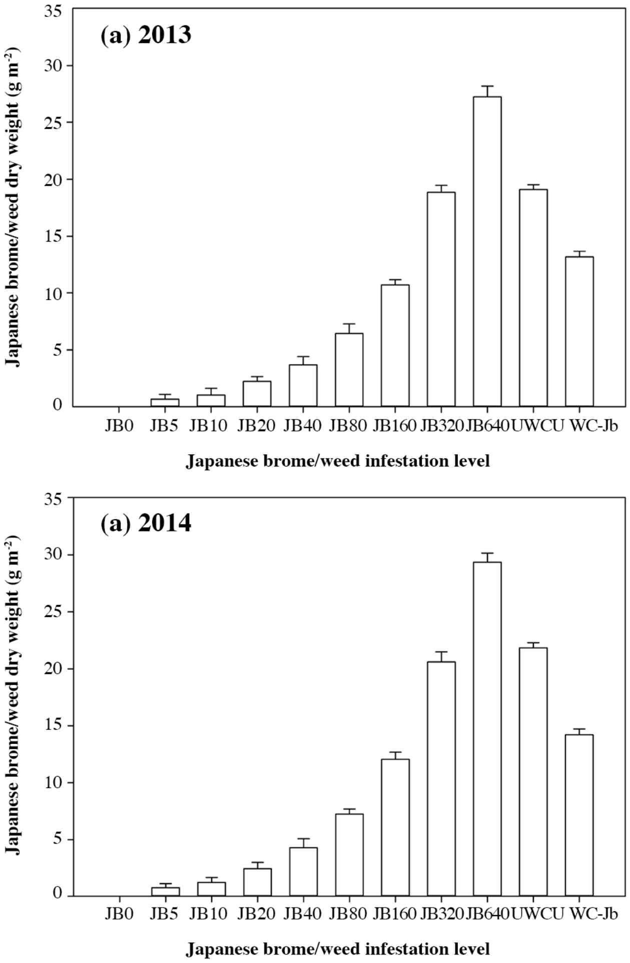
Natural weed infestation in wheat (Table 2) included six weed species, namely, Japanese brome (*Bromus japonicus* Houtt.), common chickweed (*Stellaria media* [L.] Vill.), British timothy (*Phleum paniculatum* Huds.), shepherd's-purse (*Capsella bursa-pastoris* [L.] Medik.), short-awn foxtail (*Alopecurus aequalis* Sobol.), and catchweed (*Galium aparine* L.) Among these (UWC), JB exhibited the highest density of 114 ± 4.2 plants m^{-2} and 35.3% of the total weed population, which accumulated a DW of 3.42 ± 0.45 g m^{-2} (Table 2).

Increasing JB density from JB 5 to JB 640 resulted in a significant increase in its DW (Figures 1a and 1b). For any one particular density, DW was much higher than at lower densities and much lower than at the higher densities. Total weed DW was higher in JB 640 followed by JB 320 and UWC with values not differing among them.

Wheat growth and yield

Wheat yield differed significantly across years and treatments. All the JB densities resulted in a significant reduction in wheat spike number (Table 3, Figure 2a) in both years compared to the weed-free control (WFC). The trend was similar in the 2-yr wheat yields (Table 3, Figure 2b). Of all JB densities, JB 640 caused the greatest reduction in these variables.

Figure 1. Japanese brome/weed dry weight in different Japanese brome/weed infestation levels in 2013 (a) and 2014 (b).



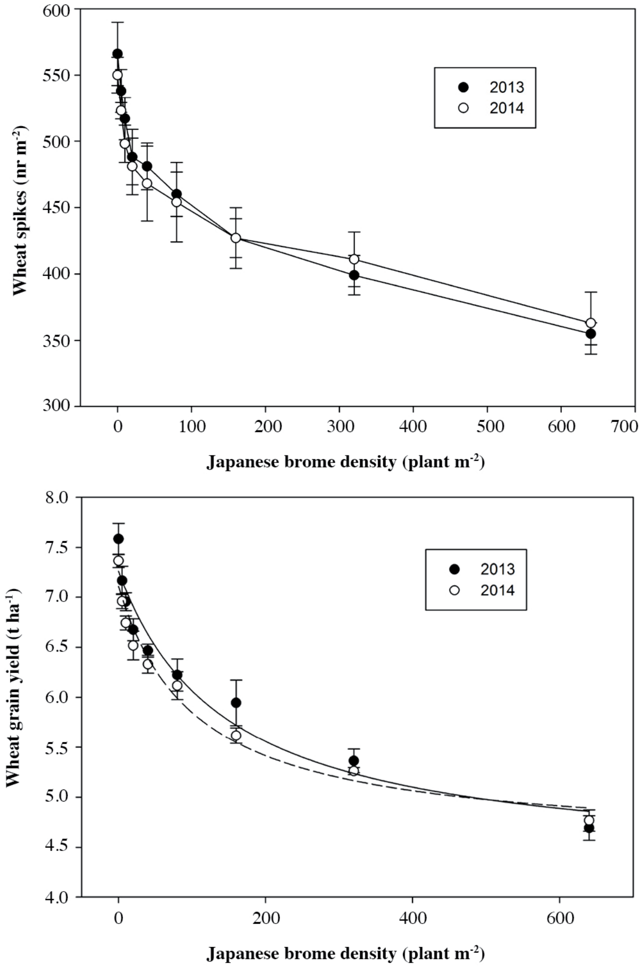
Vertical bars represent standard errors of the means.

Table 3. Wheat spike number and wheat yields across treatments and years.

	Spike		Wheat yield	
Treatment	2013	2014	2013	2014
	nr m^{-2}		t ha^{-1}	
JB 0	566a	550a	7.585a	7.367a
JB 5	538b	523b	7.170b	6.960b
JB 10	517c	498c	6.955c	6.743c
JB 20	488d	481d	6.675d	6.517d
JB 40	481d	468de	6.468e	6.330e
JB 80	460e	454e	6.223f	6.117f
JB 160	427f	427f	5.945g	5.617g
JB 320	399g	411fg	5.363i	5.260i
JB 640	355i	363h	4.693j	4.767k
UWC	379h	398g	5.190i	5.127j
UWC-JB	415fg	419f	5.570h	5.440h

JB: Japanese brome, UWC: natural weed infestations including JB, UWC-JB: natural weed infestations excluding JB.

Figure 2. Relationship between Japanese brome densities and wheat spike number and wheat grain yield for 2013 and 2014.



Vertical bars represent standard errors of the means.

These treatments reduced spike number and yearly yield in both years and were comparable to 'all weed including JB (UWC)', which caused the highest reduction and ranked second behind JB 640 (Table 3).

Wheat yield and JB density were inversely related, and there was a significant yield decrease with increasing JB density in both years (Figure 2b).

Simulation of yield and yield loss and economic threshold

The simulation equations for wheat yields across the years were $Y = 7.585\{1-[0.558d/100(1 + 0.558d/37.197)]\}$ and $Y = 7.367\{1 - [0.599d/100(1 + 0.599d/35.084)]\}$. The simulation equations of yield loss were $Y_L = 0.558d/100(1 + 0.558d/37.197)$ and $Y_L = 0.599d/100(1 + 0.599d/35.084)$ during the first and second years.

On the whole, observed yields and simulated equations (Table 4) were better correlated ($R^2 = 0.929$ and 0.951 in 2013 and 2014, respectively) leading to small differences between observed and simulated yields (Figure 3).

The ET of JB was 5 and 4 plants m^{-2} during first and second years, respectively (Table 5) and the equation for ET was $0.000045T^2 - 0.204T + 1 = 0$; $0.0000578T^2 - 0.2322T + 1 = 0$.

Table 4. Simulation equations of wheat yields and yield loss.

Parameters	2013	2014
i	0.558 ± 0.139	0.599 ± 0.124
A	37.197 ± 3.682	35.084 ± 2.749
R^2	0.929	0.951

i: Percent yield loss per unit of weed density, A: asymptotic value of the maximum yield loss (%).
R^2 = 1 - (residual sum of squares)/(corrected sum of squares).

Figure 3. Observed and simulated yield losses (%) of wheat for Japanese brome densities in 2013 (a) and 2014 (b).

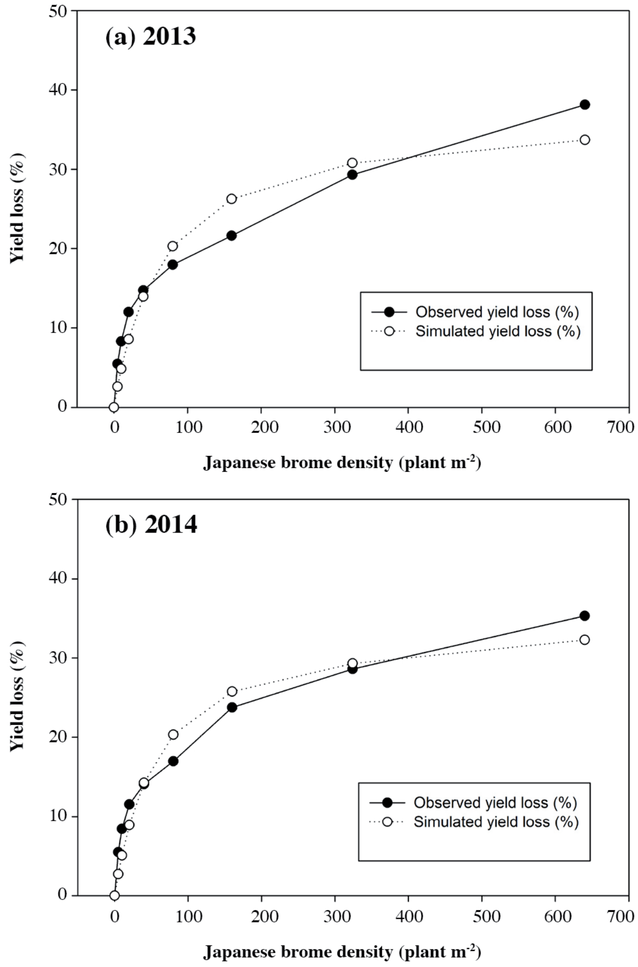


Table 5. Simulation of economic threshold level of Japanese brome in wheat.

Parameters	2013	2014
Y (observed weed-free yield), t ha^{-1}	7.585	7.367
i, %	0.558	0.599
A, %	37.197	35.084
C (cost of control with flucarbazone at 31.5 g ha^{-1}), CNY ha$^{-1(a)}$	320	320
H (flucarbazone efficiency), %	80	80
P (wheat grain price, CNY kg^{-1})	2.1	2.3
ET equation^{b}	$0.000045T^2 - 0.204T + 1 = 0$	$0.0000578T^2 - 0.2322T + 1 = 0$
T (economic threshold level)	4.9(~ 5.0)	4.3(~ 4.0)
R^2	0.929	0.951

[a] 1 US$ = 6.38 CNY (approx.)

[b] Derived from Equation $1 + (i/A)[2 - H - (YPAH/C)]\,T + (i/A)^2\,(1 - H)\,T^2 = 0$ using the values of parameters mentioned in this Table.

Y: Simulated wheat yield, i: percent yield loss per unit of weed density, A: asymptotic value of maximum yield loss (%).

DISCUSSION

Density effect on Japanese brome and weed interference

Japanese brome is naturalized in the wheat microclimate. It has numerous tillers and high fertility. A large seed bank of this weed exists in the soil and this leads to continual germination under favorable moisture and temperature conditions (Wang, 1986; Li et al., 2015). These factors might be responsible for its dominance over other weeds in wheat (Table 1) in the present study.

The degree of weed interference is highly related to the weed species, population, and its DW, which is finally reflected in crop yield (Das and Yaduraju, 1999). Yield losses are generally proportional to the sum total of water, light, and nutrients that weeds use when competing with the crop (Zimdahl, 2004). The present study exhibited an evident level of interference.

The density effect of JB on wheat spike number and yield in the present study were significantly reduced at the lowest JB 5 density (Table 3). The order of negative effect of the treatments on the 2-yr mean yield was JB 640 > UWC > JB 320 > UWC-JB > JB 160 > JB 80 > JB 40 > JB 20 > JB 10 > JB 5. The increasing density resulted in an obvious development of DW in JB. The order of competitiveness based on the 2-yr mean DW accumulated by weeds/JB was JB 640 > UWC > JB 320 > UWC-JB > JB 160 > JB 80 > JB 40 > JB 20 > JB 10 > JB 5.

The highest density, JB640, exhibited the most serious negative effect with the highest JB DW and the highest yield loss. The pure stand density of JB 320 caused a yield loss similar to that of natural weed infestation (UWC). Weed biomass in these two treatments were almost equal (Figures 1a and 1b) and weed traits were probably sufficiently similar for the mixed population to act as a pure stand of JB with the same biomass.

As a result of the high population in UWC, inter-competitiveness between six weed species and intra-competitiveness between JB plants might have reduced overall interference (Cousens, 1985, 1987). This confirms the fact that moderate weed infestation can be as serious as heavy infestation (Das, 2008). In addition, the increase in the DW of JB was not as proportional as the increase in its density. Density increased 128 times (from 5 to 640 JB plants m^{-2}), but the increase in DW (Figure 1) was only approximately fortyfold. The intraspecific and interspecific competition at higher densities might be responsible for reduced individual DW (Zimdahl, 2004; Das, 2008).

Natural weed infestation without JB (UWC-JB) caused less interference and was inferior to UWC, JB 320, and JB 640 based on yield loss. The reason could be that total weed population was less than in these treatments (Table 2). The seeds of JB are always maturity in June in accordance with wheat which is later than other weeds for a long time (Baskin and Baskin, 1981). This consistent growth leads JB to compete with wheat for a longer period of time up to wheat maturity.

Simulation of yield and yield loss and economic threshold

The crop yield-density model is widely used (Cousens, 1985), and weed density can easily be calculated by farmers.

The ET indicates the weed density at which the economic advantage of the treatment is in equilibrium with the cost of weed management. To confirm whether weed control measures are necessary, weed interference in a crop should be predicted as soon as possible (Hazra et al., 2011). The ET provides baseline information to make weed control decisions based on economics (Cousens, 1987), and it plays an important role in establishing an integrated weed management program (Wilkerson et al., 2002).

We observed that the ET of JB varied from 4 to 5 plants m^{-2} across both years (Table 5). Such a variation in ET can be due to the changes in crop and weed growth and crop price (Fischer et al., 2004; Cheema and Akhtar, 2006; Hazra et al., 2011; Dodamani and Das, 2013; Das et al., 2014).

Currently, yield loss in most ET determinations was the sole criterion. Based on yield losses, an ET of 6-7 *Phalaris minor* Retz. plants m^{-2} (Hussain et al., 2015), 7-12 *Avena sterilis* L. plants m^{-2}, 25-35 *Lolium multiflorum* Lam. plants m^{-2}, and less than 40 *Bromus sterilis* L. plants m^{-2} (Zanin et al., 1993) have been reported in wheat.

In contrast, the present study adopted a quadratic equation (Equation 3) that took into account several factors to determine the ET, such as yield, crop price, herbicide efficiency, and weed control cost (Cousens, 1987).

Therefore, this method might be more reliable and rational because the abovementioned factors affect the ET (Cheema and Akhtar, 2006).

The ET is generally based on the profits and losses of the current year. Certain benefits accruing from ET are not considered. The benefits for subsequent years of the adopted herbicide and management measures, which might affect future weed populations by reducing their seed bank in the soil, are also ignored (Cussans et al., 1986; Norris, 1992). These benefits are not easily quantified, but including them can make ET more useful.

The 2-yr ET mean (Table 5) in the present study was 4.5 (~ 4 plants m^{-2}). Considering that 5.47% and 5.52% yield losses in the first and second years, respectively, at JB 5 plants m^{-2} (Figures 3a and 3b), the yield loss would be 2.11% to 2.24% at JB 4 plants m^{-2}. This explains why even a 2% yield loss is an economic loss in this situation. This is mainly because of the high cost of herbicide performance and high wheat price. Wheat benefited from government price support and flucarbazone has an almost fixed price throughout China. Therefore, ET could be very useful in other parts of China.

CONCLUSIONS

In summary, our results show that a pure stand of Japanese brome (JB) with 320 plants m^{-2} was as competitive as natural weed infestation including JB. They both caused a consistent interference in wheat. The economic threshold (ET) was between 4 and 5 JB plants m^{-2}, considering a post-emergence treatment of flucarbazone with 80% efficiency. This information would be useful to make JB control decisions and play an important role in establishing an integrated management program.

Overall, taking into account several factors, the ET would be more economical and helpful. Using this ET to control JB would reduce future weed populations, rationalize herbicide use, and lead to the development of better control strategies.

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