Weed Technology

cambridge.org/wet

Weed Biology and Competition

Cite this article: Wang H, Huang Y, Zhang L, Liu W, Wang J (2018) Japanese Foxtail (*Alopecurus japonicus*) Management in Wheat in China: Seed Germination, Seedling Emergence, and Response to Herbicide Treatments. Weed Technol 32:211–220. doi: 10.1017/wet.2017.87

Received: 30 June 2017
Accepted: 4 September 2017

Associate Editor:
Lawrence E. Steckel, University of Tennessee

Nomenclature:
Clodinafop-propargyl; isoproturon; mesosulfuron-methyl; pinoxaden; pyroxsulam; Japanese foxtail, *Alopecurus japonicus* Steud ALOJA

Key words:
Burial depth; heat shock; light; osmotic potential; pH; postemergence; residue; salt stress; temperature

Authors for correspondence:
Jinxin Wang, Key Laboratory of Pesticide Toxicology and Application Technique, College of Plant Protection, Shandong Agricultural University, Shandong Tai'an 271018, PR China. (E-mail: wangjx@sdau.edu.cn)

Weitang Liu, Key Laboratory of Pesticide Toxicology and Application Technique, College of Plant Protection, Shandong Agricultural University, Shandong Tai'an 271018, PR China. (E-mail: liuwt@sdau.edu.cn)

Japanese Foxtail (*Alopecurus japonicus*) Management in Wheat in China: Seed Germination, Seedling Emergence, and Response to Herbicide Treatments

Hengzhi Wang[1], Yizhao Huang[1], Lele Zhang[1], Weitang Liu[2] and Jinxin Wang[3]

[1]Graduate Student, Key Laboratory of Pesticide Toxicology and Application Technique, College of Plant Protection, Shandong Agricultural University, Shandong Tai'an, China, [2]Lecturer, Key Laboratory of Pesticide Toxicology and Application Technique, College of Plant Protection, Shandong Agricultural University, Shandong Tai'an, China and [3]Professor, Key Laboratory of Pesticide Toxicology and Application Technique, College of Plant Protection, Shandong Agricultural University, Shandong Tai'an, China

Abstract

Little information is published related to seed germination and seedling emergence of Japanese foxtail, a troublesome annual grass weed widely distributed in winter wheat fields in China. Three Japanese foxtail populations were studied under laboratory and greenhouse conditions, to determine the effects of different environmental factors on seed germination or seedling emergence. Chemical control is absolutely necessary in integrated management, and efficacy of POST herbicides against different growth stages of Japanese foxtail was evaluated. Germination rate was 90% or more when temperature ranged from 5 to 25 C, with germination onset shortened as temperature increased. Light was not required for germination to occur. For pH values ranging from 5 to10 there was no effect on seed germination. Japanese foxtail seed germination was sensitive to osmotic stress and completely inhibited at an osmotic potential of -1.1 MPa. The '1513' population of Japanese foxtail demonstrated tolerance to soil salinity, with 98% germination at 80 mM NaCl compared with 25 and 40% germination for populations '1532' and '1544', respectively. High amounts of crop residue (10 t ha^{-1}) suppressed Japanese foxtail emergence 38 to 55%. Germination of seeds placed at 160 C for 5 min was completely inhibited for dry seeds, with a similar effect at 130 C for pre-soaked seeds. Seed burial in the soil from 0 to 4 cm had no effect on seedling emergence, but burial at 7 cm completely inhibited seedling emergence. POST herbicides mesosulfuron-methyl (13.5 g ai ha^{-1}), clodinafop-propargyl (67.5 g ai ha^{-1}), pyroxsulam (13.5 g ai ha^{-1}), pinoxaden (67.5 g ai ha^{-1}) and isoproturon (1125 g ai ha^{-1}) reduced plant dry weight 80% or more when applied at three- to seven-leaf stage, but control declined with application at later growth stages. The information from this study helps to develop an integrated approach to Japanese foxtail management.

Changes in cropping systems of intensive farming to mechanized farming and occurrence of resistant weeds owing to frequent application of single herbicides have led to shifts in weed flora, resulting in greater weed diversity (Ahmed et al. 2014; Chauhan and Johnson 2010; Singh et al. 2009; Tomita et al. 2003). This is true for Japanese foxtail, a troublesome annual grass weed that has become an increasing problem in winter wheat fields in China, Japan, Turkey, and other Asian countries (Yang et al. 2007). Japanese foxtail has been considered one of the worst grass weeds in China because it causes serious harm to wheat, reducing yield by more than 30% (Shen et al. 2000). In addition, Japanese foxtail is also a host of various crop pests such as small brown planthopper [*Laodelphax striatellus* (Fallén)] and rice thrip [*Chloethrips oryzae* (Wil.)] which have negative effects on crop growth and production.

Many environmental factors can influence seed germination and seedling emergence of a weed species, such as light, temperature, soil salinity, soil moisture, soil pH, seed burial depth in the soil through tillage, the amount of crop residue in the field, and heat shock. For example, although weed seeds that require light for germination cannot germinate when buried deeply, they are dominant in no-till or reduced-tillage systems that lead to seeds being close to soil surface (Chauhan and Johnson 2010). Temperature affects the occurrence and rate of seed germination (Evert et al. 2009). Seeds of some weed species can germinate over a broad soil pH range (Chauhan et al. 2006), but some others can only germinate between pH 6 and 7 (Wilson 1979). While soil moisture is needed for seeds to germinate, the amount of soil water needed for germination varies by species (Atia et al. 2011; Wu et al. 2016a). The ability of some weed seeds to germinate under high soil salinity conditions enables certain weed species to have advantage over crops in areas with high salinity (Geissler et al. 2009). In some dry rice–wheat rotation systems, farmers seldom practice tillage following dry rice harvest and wheat is sown after burning rice residue (Johnson and Kent 2002). The heat and exposure time generated by this burning may stimulate or inhibit weed seedling emergence (White and Boyd 2016). Presence of crop residue has also been shown to suppress emergence of several weed species (Teasdale and Mohler 1993).

Herbicides are widely used in modern agriculture for their high efficiency in killing weeds, becoming the fastest and most reliable method of farmland weed control. Generally, Japanese foxtail emerges later than wheat, and POST herbicides are used for the control of Japanese foxtail in China. Pinoxaden, fenoxaprop-P-ethyl, and mesosulfuron-methyl are the most commonly used herbicides for Japanese foxtail control in China, introduced in the 1970s, the 1990s, and 2003, respectively (Bi et al. 2016). The efficacy of POST herbicides varies according to the growth stage of the weed species (Chauhan and Abugho 2012; Singh and Singh 2004). In general, herbicide works less effectively when applied on bigger weeds due to faster herbicide degradation (Singh and Singh 2004). Consequently, farmers have to increase herbicide rates to achieve the same control effect (Chauhan and Abugho 2012). Therefore, the time of herbicide application is a very important factor in effectively controlling weeds. Although herbicides are an effective means to control weeds, it is unwise to have an overreliance on herbicides. The intensive use of herbicides not only causes harm to human health and the environment but also results in weeds evolving resistance to herbicides (Bi et al. 2016). For example, Japanese foxtail has evolved resistance to haloxyfop, fenoxaprop, pinoxaden, and mesosulfuron-methyl (Bi et al. 2016; White and Boyd 2016; Yang et al. 2007). Therefore, there is an urgent need for an integrated approach to weed management. Among the weed management tools, knowledge of weed seed biology is one of the most important. What is more, better understanding of the factors influencing Japanese foxtail seed germination and emergence help us to predict potential new areas where this species may spread to due to the changes of crop systems and climate. Meanwhile, chemical control is absolutely necessary in integrated management.

A previous study (Wu et al. 2016b) focused on the germination requirements for Japanese foxtail, including light, temperature, osmotic potential, salt stress, pH, and seed burial depth, comparing fenoxaprop-P-ethyl resistant and susceptible biotypes. However, seed dormancy, along with other factors affecting the germination and emergence of Japanese foxtail, such as heat shock and the amount of crop residue, and the response to other POST applied herbicides, have not been studied. Furthermore, some weed populations in different areas may respond differently to environmental factors, and using only one population in a study may lead to a bigger evaluation error. Therefore, the objectives of this study were to a) determine seed dormancy characteristics in Japanese foxtail and study the effects of temperature, light, osmotic potential, salt stress, pH, soil burial depth, heat shock, and rice residue mulch on seed germination or seedling emergence, and b) evaluate the influence of application timing on the efficacy of seven selected POST herbicides.

Materials and Methods

Seed Sources

Even when populations experience similar climatic conditions, germination can vary within a species (Mulligan and Bailey 1975; Leon and Owen 2006; Leon et al. 2006). To decrease evaluation error, we selected seeds from three Japanese foxtail populations, ‘1544’, ‘1532’, and ‘1513’ (Table 1), from three remote wheat fields in different provinces where Japanese foxtail has caused significant yield losses. Seeds from each population were collected from more than 500 randomly selected plants in May, 2015. After collection, seeds were cleaned, sun-dried in open trays, and stored in paper bags at room temperature (20 ± 5 C). Except for seeds used for the dormancy test, all seeds had been stored in paper bags for at least five months before use.

Germination Testing

For all germination tests, the following procedures were used with exceptions for specific environmental conditions required by experiments that will be described further. Germination was evaluated by placing 20 seeds evenly in a 9-cm-diam petri dish containing two pieces of filter paper (Whatman No. 1, Maidstone, UK) moistened with 5 ml distilled water or solutions having different salt concentrations or osmotic potentials. The dishes were sealed with flexible, self-sealing film to prevent evaporation and were maintained in controlled-environment growth chambers at 20 C under a 12-h photoperiod. The photosynthetic photon flux density produced by fluorescent lamps was 200 μmol m^{-2} s^{-1}. The number of germinated seeds was counted daily unless otherwise stated. Final germination was calculated after 21 d. Seeds were considered germinated if the radicle was visible (Chauhan and Johnson 2008). Germination values were counted as the total number of seeds germinated divided by the total number of seeds in the petri dish.

To test for Japanese foxtail dormancy, a germination test was started every other day from 3 to 99 d after collection as previously described.

To determine the effect of temperature on germination, Japanese foxtail seeds were subjected to seven constant temperatures (5, 10, 15, 20, 25, 30, and 35 C) and five fluctuating temperatures (35/25, 30/20, 25/15, 20/10, and 15/5 C). These ranges of fluctuating temperatures reflect the temperature differences between day and night in the seed collection regions.

To determine the effect of light on the germination of Japanese foxtail seeds, seeds were exposed to different periods of light and

Table 1. Geographical information for the cities where the seeds of Japanese foxtail were collected.

Location	GPS coordinates	Climate	Annual average temperature	Annual rainfall	Soil pH[a]
			C[b]	mm[b]	
Suqian (‘1544’)	33.97°N, 118.28°E	Subtropical humid monsoon	14.3	1059	8.0-8.5
Tianchang (‘1532’)	32.70°N, 119.00°E	Subtropical monsoon	15.0	1073	7.3-8.3
Zhumadian (‘1513’)	32.98°N, 114.02°E	Subtropical humid monsoon	14.9	940	6.5-8.0

[a] Data from the China Soil Database (http://gis.soil.csdb.cn/)
[b] Data from the National Meteorological Information Center (http://www.nmic.cn/)

dark conditions as follows: dark (24/0 h dark/light), light (0/24 h dark/light), or alternating light and dark conditions (12/12 h dark/light). The dark treatment was accomplished by wrapping the dishes in two layers of aluminum foil immediately after sowing.

The effect of osmotic stress on seed germination was assessed by placing 20 seeds in solutions with osmotic potentials of 0, −0.1, −0.3, −0.5, −0.7, −0.9, −1.1, −1.3, and −1.5 MPa. The solution concentrations were prepared by dissolving polyethylene glycol 6000 in distilled water (Michel and Kaufmann 1973). The effect of salt stress on the germination of Japanese foxtail was determined by placing 20 seeds in petri dishes containing 5-ml solutions of 0-, 20-, 40-, 80-, 120-, 60-, 200-, 240-, 280-, 320-, 360-, and 400-mM sodium chloride. The solutions were prepared by dissolving NaCl in distilled water (Michel 1983).

To examine the effect of pH on germination, buffer solutions with pH values of 4, 5, 6, 7, 8, 9, and 10 were prepared as described by Chachalis and Reddy (2000). Deionized water (pH 6.8) was used as the control.

Effect of Seed Burial Depth on Emergence

Twenty seeds were sown at depths of 0, 1, 2, 3, 4, 5, 6, and 7 cm below the soil surface in plastic pots with a 16-cm diameter and 13-cm height to assess the effect of burial depth on seedling emergence. Pots without seeds deliberately sown confirmed that there was no background seed bank of Japanese foxtail in the soil used in the experiments. The loam soil (clay, 38%; silt, 26%; sand, 36%; pH, 7.1; organic matter, 1.7%) was autoclaved and passed through a 3-mm sieve. The soil bulk density after seed burial was 1.1 to 1.4 g cm^{-3}. The experiment was conducted in controlled environment growth chambers at 20 C under a 12-h photoperiod. The pots were watered as needed to maintain moisture. Seedlings were considered emerged when the coleoptiles were visible, and seedling emergence was counted 21 d after planting. At the end of the test, the soil in pots with nonemerged plants was poured out to examine whether seeds failed to germinate or the coleoptile failed to emerge.

Effect of Residue Amount on Seedling Emergence

Twenty seeds were broadcast on the soil surface inside plastic pots, and finely chopped rice straw (leaves and stems) was spread on the soil surface at rates equivalent to 0, 1, 2, 4, 6, 8, and 10 t ha^{-1}. The pots and soil used in this experiment were the same as those described in the seed burial depth experiment. Seedlings were considered as having emerged when the coleoptiles were visible, and seedling emergence was counted 21 d after planting. The experiment was conducted in controlled-environment growth chambers at 20 C under a 12-h photoperiod. After 21 days, seedling emergence was counted. At the end of test, the residue in pots with nonemerged plants was poured out to examine whether seeds failed to germinate or the coleoptile failed to emerge.

Effect of Heat Shock on Germination

The effect of heat shock on seed germination was tested in a factorial experimental design with six heat shock levels and two seed treatments. The seeds were either dry or submerged in sterilized water for 24 h (presoaked) before being used for the experiment. Twenty seeds were placed in each mesh bag, and the bag was placed into a container and covered with preheated soil at 20, 40, 70, 100, 130, and 160 C (Fernando et al. 2016). Then, the containers with seeds were placed in heat chambers with relevant temperatures mentioned above for 5 min, and seed bags were removed from the soil. Seeds were then placed in petri dishes with filter papers dampened with sterilized water and placed into controlled-environment growth chambers at 20 C under a 12-h photoperiod.

Effect of POST Herbicides on Weed Growth at Different Leaf Stages

Twenty seeds from populations ‘1544’, ‘1532’, and ‘1513’ were broadcast on the soil surface in small plastic pots that were filled with the same soil as described above. Seedlings were thinned to nine plants per pot on the eighth day. POST herbicides were sprayed at the three-, five-, and seven-leaf stages using a research track sprayer that delivered a 450 L ha^{-1} spray solution at a spray pressure of 275 kPa; flat-fan nozzles (TeeJet 903EVS, Greenman Machinery Company, Beijing, China) were used in the sprayer. The seven POST herbicides most commonly used in wheat fields in China were tested at different leaf stages in the experiment (Table 2). A nontreated control was included for comparison. The pots were placed in a greenhouse with day/night temperatures set at 25 ± 5/20 ± 5 C with natural illumination. At 21 d after the herbicide application, shoots were harvested and oven-dried at 70 C for 72 h and biomass was recorded.

Table 2. Details of the POST herbicides used in the efficacy test.

Herbicide common name	Commercial name	Dose	Herbicide formulation	Herbicide rate in active ingredient	Herbicide manufacturer
		g ai ha^{-1}			
Mesosulfuron-methyl	Shima	13.5	OD	30 g ai L^{-1}	Bayer Crop Science, Zhejiang, China
Clodinafop-propargyl	Maiji	67.5	WP	15%	Syngenta, Shanghai, China
Pyroxsulam	Youxian	13.5	WDG	7.5%	Dow Chemical Company, Shanghai, China
Fenoxaprop-P-ethyl	Biaoma	62.1	EW	69 g ai L^{-1}	Bayer Crop Science, Zhejiang, China
Pinoxaden	Aixiu	67.5	EC	50 g ai L^{-1}	Syngenta, Shanghai, China
Flucarbazone-sodium	Biaohu	31.5	WDG	70%	Arysta Life Science, Shanghai, China
Isoproturon	Yibinglong	1125	WP	50%	FMC, Shanghai, China

Statistical Analysis

Except for the heat shock experiment, all the other experiments were arranged in a randomized complete block design and were conducted at least two times with four replicates. Each replication was considered as a block and arranged on different benches or shelves in the incubators or greenhouse. The effect of heat shock on seed germination was tested in a factorial experimental design with two fixed factors (six heat shock levels and two seed treatments). Replicates were considered as a random factor in both analysis of variance (ANOVA) analyses. According to Bartlett's test, homogeneity of variance was not improved by arcsine square transformation, thus ANOVA was performed on nontransformed percent germination values (SPSS 19.0, IBM Corporation, Armonk, NY); because of the nonsignificant interaction with two repeated experiments, the data were pooled for analysis. Mean comparison was performed using Tukey's HSD test at $P \leq 0.05$. All regression analysis was conducted using SigmaPlot (version 12.5, Systat Software, Inc., Point Richmond, CA). To better understand the germination or emergence response of each population, three seed populations were evaluated separately rather than pooled together, even though nonsignificant interaction was observed with three populations in some tests.

Days required to reach 80% germination (t_{80}) under different temperature and germination rates (V) were estimated as shown:

$$t_{80} = (Hp - Lp)^{-1} + L, \text{ and} \qquad [1]$$

$$V = 1 / t_{80} \qquad [2]$$

where L is the last day before 80% germination was reached, Lp is the observed germination percentage on day L, and Hp is the observed germination percentage on the day when germination reached or exceeded 80% (Li et al. 2012).

Percent germination values at different osmotic potentials, salt concentrations, and heat shock treatments (dried seeds exposed to heat shock and presoaked seeds exposed to heat shock) were fitted to a functional three-parameter logistic model using SigmaPlot version 12.5. The model fitted was

$$G(\%) = G_{max} / [1 + (x / x_{50}) G_{rate}] \qquad [3]$$

In this equation, G represents the total percentage of germination (%) at NaCl concentration, osmotic potential, or temperature x, G_{max} is the maximum germination (%), x_{50} is the NaCl concentration, osmotic potential, or heat shock treatments for 50% inhibition of the maximum germination, and G_{rate} indicates the slope of the equation. The seedling emergence (%) rates obtained at different burial depths were fitted using SigmaPlot sigmoidal decay curve as follows:

$$E(\%) = E_{max} / \{1 + \exp[-E_{rate}(x - x_{50})]\}, \qquad [4]$$

where E is the total seedling emergence (%) at burial depth x, E_{max} is the maximum seedling emergence (%), x_{50} is the depth to reach 50% of maximum seedling emergence, and E_{rate} indicates the slope of the equation. A linear model of the form

$$E(\%) = E_{max} - bx \qquad [5]$$

was fitted to seedling emergence (%) obtained at different residue amounts, where E represents emergence (%) at residue amount x, E_{max} is the maximum seedling emergence and b represents the constant. r^2 values were used to determine the goodness of fit to all selected models.

Results and Discussion

Dormancy

Seed germination response in days was consistent among the three Japanese foxtail populations. For the first 29 d, the germination rate was 0% and there was a slow increase between 29 and 61 d. Subsequently, a rapid increase in germination rates occurred, with approximately 90% germination at 85 d and thereafter (Figure 1). It is generally recognized that seed dormancy results from 1) endogenic factors, such as embryo dormancy, a germination-inhibiting substance, and phytohormone imbalance, and 2) extrinsic factors, such as a seed coat barrier or pericarp (Wu 2016a). The dormancy of Japanese foxtail seed may result from endogenic factors because the Japanese foxtail seed coat is very thin. These results indicated that Japanese foxtail seed has a dormancy period of approximately 80 d. However, it is possible that this dormancy period of 80 d is an overestimation, because the germination test was conducted under stable temperature conditions, unlike those seen in nature. The results from temperature tests indicated that fluctuating temperatures were more suitable for seed germination of Japanese foxtail.

Impact of Temperature on Germination

When exposed to a constant temperature, Japanese foxtail germinated over a wide temperature range, from 10 to 25 C, with germination always exceeding 85% with the exception of population '1532' at 25 C (13%) (Table 3). The low germination rate observed in population '1532' at 25 C may be because population '1532' was collected from an area with a cooler climate. A sharp decrease in germination occurred when the temperature was greater than 25 C, with almost no germination at 30 C or 35 C. Japanese foxtail also failed to germinate at 5C. Overall, considering germination rate, optimum germination occurred at 20 C. When temperature increased from 10 to 20 C, it did not influence the germination value; however, it reduced the time to the onset of germination and T_{80} (Table 3). Haferkamp (1994) and Li (2015) reported that a low-temperature environment did not affect the total germination but did reduce the time to onset of germination of Japanese brome (*Bromus japonicus* Thunb. ex Murr.) seeds.

Compared with constant temperature, alternating between the same two mean temperatures significantly improved the germination values. For instance, the germination value of population

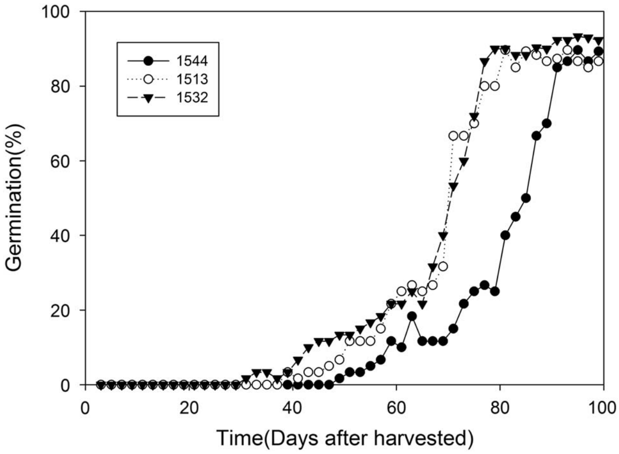

Figure 1. Germination of three Japanese foxtail populations ('1544', '1513', and '1532') in days. The values (mean) are calculated to four replicates.

Table 3. Germination percentage[a] and days required to reach 80% germination (t_{80}) for Japanese foxtail seeds exposed to 12 temperature treatments.

	Onset of germination			Germination			T_{80}[c]		
Temperature[b]	'1544'	'1513'	'1532'	'1544'	'1513'	'1532'	'1544'	'1513'	'1532'
	------------------d------------------			------------------%------------------			-----------d-----------		
5	NE[d]	NE	NE	0 f	0 f	0 f	NE	NE	NE
10	14	14	13	93 ± 1.5 ab	98 ± 0.6 b	98 ± 0.6 a	16	16	15
15	10	9	10	85 ± 1.7 cd	100 a	100 a	20	11	12
20	6	8	8	90 ± 1.2 bc	100 a	100 a	9	9	10
25	8	8	8	82 ± 1.5 de	93 ± 0.6 d	13 ± 0.6 e	10	11	NE
30	NE	NE	6	0 f	0 f	2 ± 1.0 f	NE	NE	NE
35	NE	NE	NE	0 f	0 f	0 f	NE	NE	NE
15/5	14	12	14	88 ± 0.6 c	97 ± 0.6 c	83 ± 2.3 c	NE	15	18
20/10	12	10	12	78 ± 4.0 e	97 ± 0.6 c	100 a	NE	11	13
25/15	7	7	7	97 ± 1.2 a	93 ± 0.6 d	93 ± 2.1 b	9	9	9
30/20	5	4	4	93 ± 0.6 ab	92 ± 1.2 d	90 ± 3.2 b	7	6	6
35/25	4	4	4	87 ± 0.6 bc	90 ± 1.0 e	52 ± 2.2 d	8	6	NE

[a] The values (mean ± SE) are calculated from eight replicates. Three populations were evaluated separately. Different letters indicate significant difference at the $P < 0.05$ level according to Tukey's HSD test.

[b] Temperature was either 24 h or alternating 12/12 h.

[c] Calculated as described in formula: $t_{80} = (Hp - Lp)^{-1} + L$, where L is the last day before 80% germination was reached, Lp is the observed germination percentage on day L, and Hp is the observed germination percentage on the day when germination reached or exceeded 80%.

[d] Abbreviation: NE, not estimated because germination did not reach 80% in all replications.

'1532' under alternating temperatures of 30/20 C was 90%, whereas, at the constant temperature of 25 C, germination was only 13%. These results suggest that the alternating temperature may be more suitable for seed germination of Japanese foxtail, possibly because alternating temperature can simulate the temperature changes between day and night in the natural environment (Leon et al. 2004; Thompson et al. 1977).

In China, over 70% of land area has tropical, subtropical, or temperate climate, where the annual average temperature is about 8 to 10 C. Japanese foxtail has the ability to spread into most areas of China due to its ability to germinate at 10 C. However, the areas where the average temperature in early autumn is 15 to 16 C, at 27° to 33° N (Ding et al. 2006), are most favorable for germination of Japanese foxtail seeds. In the future, Japanese foxtail is likely to be a troublesome weed in wheat fields of these areas, such as Yun-Gui plateau and Sichuan Basin, where it has not yet become a serious problem.

Impact of Light on Germination

Light was not a limiting factor for Japanese foxtail germination. When exposed to continuous light, alternating light and dark (12/12 h), and completely dark conditions, the germination rates of Japanese foxtail populations were all greater than 87% (data not shown). Japanese foxtail seed will germinate below the soil surface, even if early-planted wheat has already shaded the ground.

Effect of Osmotic Potential on Seed Germination

As shown in Figure 2, the germination values of each population's seeds exposed to 0 (no-stress) and − 0.1 MPa osmotic potentials all exceeded 83%, and seed germination declined sharply with a further reduction in osmotic potential. When exposed to −0.3 MPa, seed germination values fell below 25%. Almost no germination occurred when water potential was less than −0.7 MPa. From the fitted model, estimates show that an osmotic potential of −0.2 MPa would reduce germinations to 50% in all populations. Annual rabbitsfoot grass (*Polypogon maritimus* Willd.) had a high germination rate even at an osmotic potential of −1.6 MPa (Atia et al. 2011).

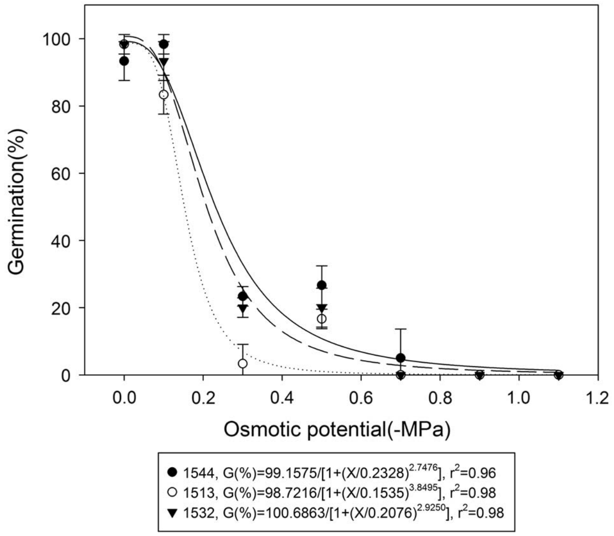

Figure 2. Effect of osmotic potential on germination of three populations ('1544', '1513', and '1532') of Japanese foxtail seed incubated at 20 C for 21 d in an incubator. Data represent the mean plus or minus standard error of the mean ($n = 8$).

Compared with annual rabbitsfoot grass, Japanese foxtail is highly sensitive to osmotic stress. However, the appropriate soil water potential for seedling emergence of wheat is from −0.05 to −0.02 MPa (Liu and Chen 1988). Therefore, the soil will provide sufficient moisture for germination of Japanese foxtail when wheat seedlings are able to emerge. In our study, germination values were over 90% when seeds were exposed to −1.5 MPa, rinsed, and placed in distilled water (data not shown). The results above indicate that Japanese foxtail seeds will germinate in moist conditions, whereas seeds in dry conditions may remain dormant until moisture conditions are favorable.

Rice–wheat rotation systems account for a large proportion of fields in the Yangtze Delta region, where the annual precipitation is 1,000 to 1,500 mm (Rao et al. 2008). The fields that previously supported rice crops have high soil moisture, which provides high soil moisture for germination of Japanese foxtail seeds. Therefore, it is not surprising that Japanese foxtail has become a troublesome weed in this area.

Effect of Salt Stress on Germination

Germination response to salt concentration was different among the three populations. The germination rate of population ‘1513’ at 80 mM was 98%; however, populations ‘1544’ and ‘1532’ had germination rates of 40% and 25% ($P=0.0001$), respectively. Meanwhile, the germination of population ‘1513’ at 160 mM was 41%, with no germination in populations ‘1544’ and ‘1532’ at this level.

Response of all three populations was inversely related to salt concentration, and the maximum germination (100%) occurred between 0 and 20 mM. Some seeds germinated at 160 mM NaCl (1,513, 41%) and 200 mM NaCl (1,544, 4.5%), but germination was completely inhibited at 240 mM NaCl (Figure 3). In our study, germination values were over 90% when seeds were exposed to 240 mM NaCl, rinsed, and placed in distilled water (data not shown). In China, the Yellow River and Yangtze River estuaries have salt contents of 1.0% (the NaCl concentration is 173.8 mM) and 0.8%, respectively. Water from these rivers is used to irrigate rice, wheat, or other crops in the regions, which may explain why population ‘1513’ (located in the Yellow River Basin) has a higher tolerance to salt stress than populations ‘1532’ and ‘1544’ (located in the Yangtze River Basin) (Ba and Zhao 1997). These results suggest that some ecotypes of Japanese foxtail have a high tolerance to salt stress, and such soil types are common in many parts of China.

Effect of pH on Germination

Compared to deionized water, germination of Japanese foxtail seed was not significantly influenced by pHs ranging from 5 to 10, and the germination rate of each population was over 90%. When exposed to solutions with pH values of 3 and 4, seed germination was completely inhibited (data not shown). In China, the pH of most soils range from 4.5 to 9.0 (Dai et al. 2009). Hence, soil pH may not be a limiting factor for Japanese foxtail germination.

Effect of Seed Burial Depth on Emergence

Estimates from the three-parameter sigmoid model indicate that 50% seedling emergence inhibition was achieved at 4.6 cm for population ‘1544’, and 5.3 cm for populations ‘1513’ and ‘1532’ (Figure 4). Benvenuti (1995) reported that very little light could reach a depth greater than 4 mm under the soil surface. Japanese foxtail seeds buried from 0 to 3 cm in soil have a high germination rate (over 90%), which is consistent with the concept that light is not a limiting factor for germination. Emergence values for the three populations rapidly declined when burial depth was more than 4 cm. Almost no emergence occurred when seeds were buried at a depth of 7 cm. This study found that failed emergence of Japanese foxtail seeds mainly resulted from fatal germination. The Japanese foxtail seeds could germinate at the depth of 7 cm because light is not a limiting factor. However, seedlings failed to emerge because seeds planted at deep depths could not provide enough nutrition for the coleoptiles to reach the soil surface (Baskin and Baskin 1998). Generally, larger seeds have more energy reserves and can emerge from deeper burial depths (Baskin and Baskin 1998); however, small-seeded species, such as smallflower umbrella sedge (*Cyperus difformis* L.) and globe

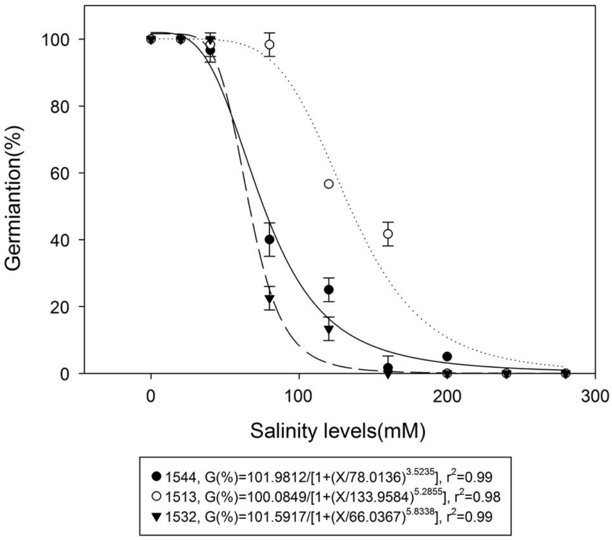

Figure 3. Effect of salt concentration on germination of three populations (‘1544’, ‘1513’, and ‘1532’) of Japanese foxtail seed incubated at 20 C for 21 d in an incubator. Data represent the mean plus or minus standard error of the mean (n = 8).

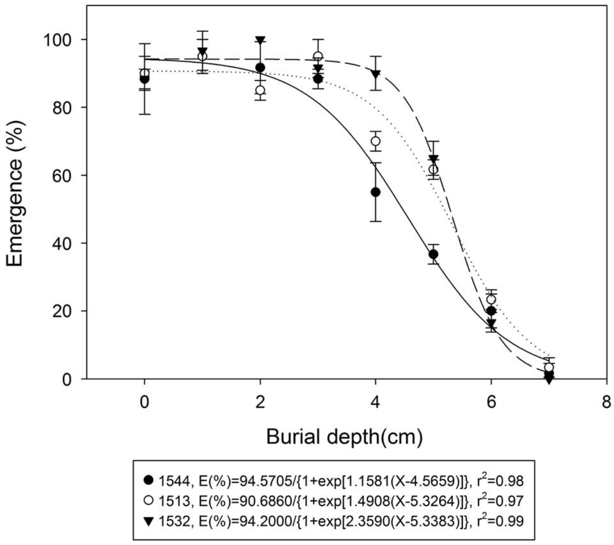

Figure 4. Effect of burial depth on seedling emergence of three populations (‘1544’, ‘1513’, and ‘1532’) of Japanese foxtail seeds incubated in a greenhouse for 21 d. Data represent the mean plus or minus standard error of the mean (n = 8).

fringerush [*Fimbristylis miliacea* (L.) Vahl], do not have sufficient nutrient reserves to support seedling emergence from deep depths (Chauhan and Johnson 2010). There is less temperature fluctuation at deeper soil layers, which also decreased germination. Further, hypoxia and low rates of gaseous diffusion at deeper depths may also be reasons that seed emergence was reduced with increasing soil depth (Benvenuti 2003).

Therefore, burying Japanese foxtail seeds at a depth below 7 cm by deep plowing could be an effective method for managing Japanese foxtail. However, farmers tend to sow wheat without plowing in the south of China, especially in areas of rice–wheat rotation, which may cause weed seed bank accumulation on the surface of the soil and aggravate the occurrence of Japanese foxtail.

Effect of Rice Residue Amount on Seedling Emergence

Seedling emergence in all populations decreased with an increasing rate of residues (Figure 5). Seedling emergence was 80% in population ‘1544’, 90% in population ‘1513’, and 91% in population ‘1532’ when no residues were applied, while the application of 10 t ha^{-1} of residue reduced emergence in ‘1544’ by 38%, in ‘1513’ by 48%, and in ‘1532’ by 55%. This study found that failed emergence of Japanese foxtail seeds also mainly resulted from fatal germination.

Weed suppression with the addition of surface residue could be attributed to lower soil temperatures, shading, and physical obstruction provided by the mulch itself (Crutchfield et al. 1986; Facelli et al. 1991). Similar reductions in seedling emergence have been reported for several other weed species such as feather lovegrass [*Eragrostis tenella* (L.) Beauv. ex Roemer & J.A. Schultes] (Chauhan 2013), *Echinochloa glabrescens* (Opeña et al. 2014), and itchgrass [*Rottboellia cochinchinensis* (Lour.) W.D. Clayton] (Bolfrey-Arku et al. 2011). While high amounts of residue may suppress Japanese foxtail emergence, using this as a management strategy may be difficult if straw is used as fodder or where there is a shortage in the farm labor force. However, in areas with depleted soil organic matter, or where rice hull burning is banned because of air pollution concerns, such as India and the north of China, the addition of high amounts of rice residue mulch may be considered.

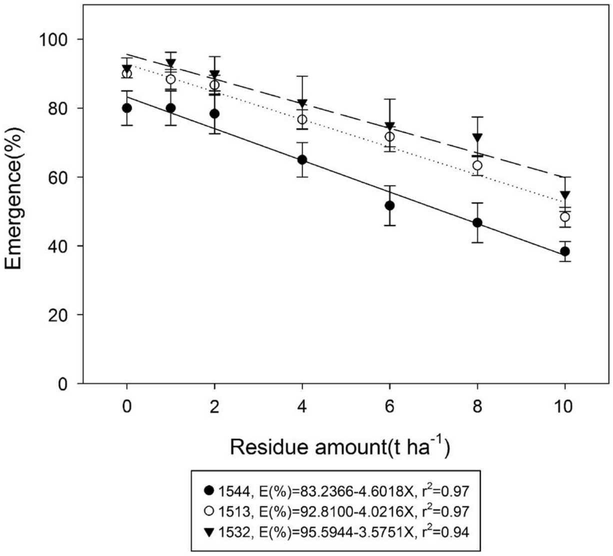

Figure 5. Emergence of three populations (1544, 1513, and 1532) of Japanese foxtail seeds, in response to residue amount (t ha^{-1}) when grown in greenhouse for 21 d. Data represent the mean plus or minus standard error of the mean (n = 8).

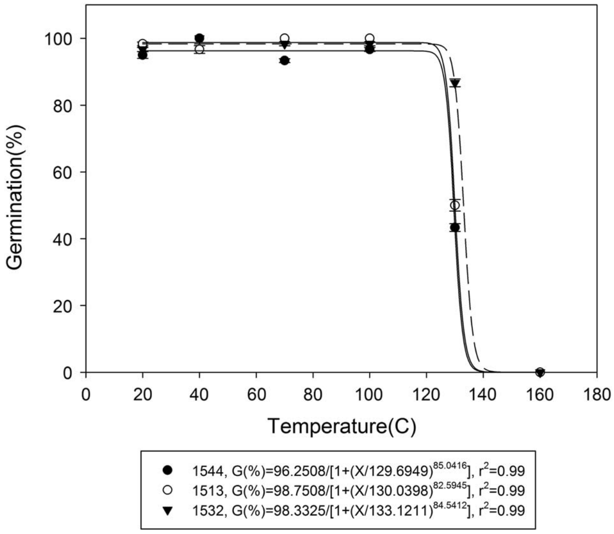

Figure 6. Effect of heat shock of dry seeds on the germination of three populations (‘1544’, ‘1513’, and ‘1532’) of Japanese foxtail at 20 C for 21 d. Data represent the mean plus or minus standard error of the mean (n = 8).

Effect of Heat Shock on Germination

Seed germination was reduced when dry seeds were exposed to heat shock (Figure 6). Maximum germination of the three populations was over 90% when exposed to 20, 40, 70, and 100 C. However, seed germination of populations ‘1544’ and ‘1513’ sharply declined to 43% and 50%, respectively, when the temperature was increased to 130 C, though that of population ‘1532’ did not decline (86%). Germination was inhibited in all populations at 160 C (Figure 6). Seed germination was also reduced when presoaked seeds were exposed to heat shock (Figure 7). However, population ‘1513’ was able to withstand heat shock better than the other two populations. For instance, the

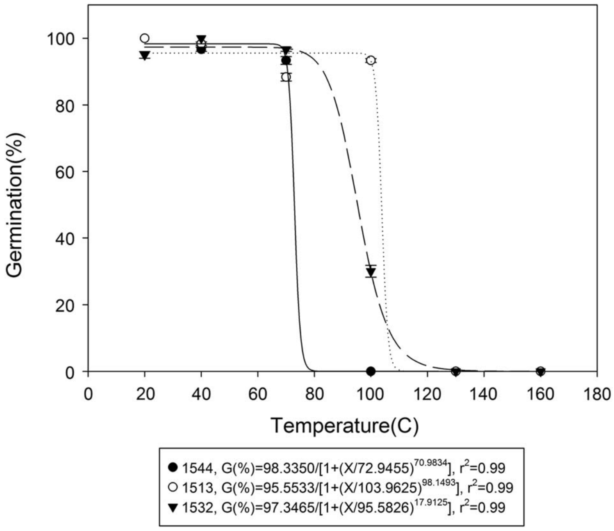

Figure 7. Effect of heat shock of presoaked seeds on the germination of three populations (‘1544’, ‘1513’, and ‘1532’) of Japanese foxtail at 20 C for 21 d. Data represent the mean plus or minus standard error of the mean (n = 8).

germination value of seeds in population ‘1513’ was 93% at 100 C, while the germination values of seeds in populations ‘1544’ and ‘1532’ were 0% and 12%, respectively (Figure 7). The temperature where germination was inhibited by 50% was estimated from the fitted models. For dry seeds, this temperature was approximately 130 C for all three populations (Figure 6). For presoaked seeds, this temperature was 72 C for population ‘1544’, 104 C for population ‘1513’, and 95 C for population ‘1532’ (Figure 7). These results demonstrate that the heat shock temperature required to reduce viability of dry Japanese foxtail seed is relatively consistent in the different populations tested.

Previous studies have shown that to guarantee the death of itchgrass seeds (a weed of many crops throughout the tropics and one of the most important grass weeds of rice), temperatures are required to be in excess of 160 C for 5 min (Bolfrey-Arku et al. 2011). In the Philippines, the majority (95%) of farmers burn rice straw after the harvest (Gadde et al. 2009). In Australia, a narrow windrow burning technique is currently the most widely adopted harvest weed seed control system, as it is a simple and effective mechanism (Walsh et al. 2013). In experimental weed control fires, soil surface temperatures reached above 500 C (Bebawi and Campbell 2003). Our study showed that germination of Japanese foxtail seeds is completely inhibited at 160 C, and thus seeds on or close to soil surface should be easily destroyed by either burning straw or narrow windrow burning. Therefore, burning should be considered as a tool for managing the soil surface seed bank. However, studies have shown that soil temperatures decrease at a rate of 100 C cm^{-1} within 5 cm below soil surface (Sanchez 1976). Considering these values, Japanese foxtail seeds buried below 4 cm may not be destroyed by burning straw.

Effect of POST Herbicides on Weed Growth at Different Leaf Stages

Efficacy of Japanese foxtail control, presented as inhibition rate, was 80% or more for mesosulfuron-methyl, clodinafop-propargyl, pyroxsulam, pinoxaden, and isoproturon. Control with these herbicides was greater than that with fenoxaprop-P-ethyl and flucarbazone-sodium at all growth stages tested (Table 4). The inhibition rate for fenoxaprop-P-ethyl was less than 70% when applied at all leaf stages, except in population ‘1513’ at the three- and five-leaf stages (84.6% and 80.3%, respectively) (Table 4). The efficacy of flucarbazone-sodium was the least, and its dry weight inhibition rate was approximately 60% when applied at the three- and five-leaf stages. Furthermore, the dry weight inhibition rate of flucarbazone-sodium was only approximately 45% when applied at the seven-leaf stage (Table 4). The efficacy of almost all herbicides was reduced with the increased growth stage of Japanese foxtail, thus the herbicides should be used early in wheat fields.

The seeds from the three populations used in our study should have been grown in a common garden with controlled conditions to minimize environmental effects. This was not done, so we cannot know for sure whether the similarities or differences are due to genetic components or just differences in environmental conditions of the maternal plant.

Table 4. Inhibition rates of Japanese foxtail when herbicide was applied at the three-, five-, and seven-leaf growth stages.[a]

Herbicide	Dose	Three-leaf stage	Five-leaf stage	Seven-leaf stage
	g ai ha^{-1}	----------Inhibition rate (%)------------		
Population ‘1532’				
Mesosulfuron-methyl	13.5	92.6 ± 0.6 ab	92.9 ± 0.7 ab	81.2 ± 2.8 bcd
Clodinafop-propargyl	67.5	90.9 ± 1.2 ab	83.3 ± 1.8 abc	80.8 ± 5.4 bcd
Pyroxsulam	13.5	94.8 ± 1.1 ab	90.8 ± 2.3 ab	87.4 ± 1.5 ab
Fenoxaprop-P-ethyl	62.1	65.0 ± 6.4 de	69.2 ± 1.9 cde	68.5 ± 5.2 cde
Pinoxaden	67.5	82.2 ± 0.7 bcd	88.9 ± 0.8 ab	86.1 ± 3.1 abc
Flucarbazone-sodium	31.5	61.8 ± 8.5 ef	64.7 ± 3.2 de	40.3 ± 5.8 f
Isoproturon	1125	95.6 ± 0.4 a	86.7 ± 4.7 abc	84.9 ± 1.9 abc
Population ‘1513’				
Mesosulfuron-methyl	13.5	90.8 ± 0.7 de	89.6 ± 1.6 ef	85.3 ± 3.1 h
Clodinafop-propargyl	67.5	92.6 ± 1.2 c	88.2 ± 2.3 g	84.3 ± 2.2 hi
Pyroxsulam	13.5	96.9 ± 0.8 b	90.9 ± 1.1 de	83.2 ± 0.8 i
Fenoxaprop-P-ethyl	62.1	84.6 ± 2.6 hi	80.3 ± 3.4 j	69.4 ± 4.1 k
Pinoxaden	67.5	90.2 ± 1.7 ef	92.3 ± 0.9 c	84.8 ± 3.8 h
Flucarbazone-sodium	31.5	70.8 ± 3.3 k	62.1 ± 4.5 cd	45.6 ± 2.5 l
Isoproturon	1125	97.7 ± 0.3 a	92.3 ± 0.4 c	88.6 ± 1.1 fg
Population ‘1544’				
Mesosulfuron-methyl	13.5	93.6 ± 0.9 b	90.2 ± 1.2 d	83.1 ± 1.3 g
Clodinafop-propargyl	67.5	94.3 ± 1.2 b	92.1 ± 1.1 c	85.6 ± 2.1 f
Pyroxsulam	13.5	94.6 ± 0.6 b	89.6 ± 3.3 de	88.7 ± 0.9 e
Fenoxaprop-P-ethyl	62.1	73.1 ± 2.5 i	66.5 ± 3.9 j	65.6 ± 3.2 j
Pinoxaden	67.5	88.6 ± 1.9 e	85.7 ± 1.2 f	80.3 ± 2.3 h
Flucarbazone-sodium	31.5	65.9 ± 4.6 j	64.9 ± 4.1 i	50.3 ± 1.3 k
Isoproturon	1125	98.6 ± 0.3 a	89.7 ± 1.3 de	88.6 ± 1.3 e

[a] The values (mean ± SE) are calculated from eight replicates. Three populations were evaluated separately. Different letters indicate significant difference at the $P < 0.05$ level according to Tukey’s HSD test.

In summary, Japanese foxtail seed was shown to have a dormancy period of approximately 80 days. The seeds can germinate under a wide range of environmental conditions commonly found in the Yangtze Delta region, which may partially explain why it is a serious problem in this region. As Japanese foxtail seeds did not remain viable at temperatures over 160 C, fire and/or narrow windrow burning, with enough stubble to increase the top soil temperature higher than 160 C, may be an effective mechanism for destruction of seeds on the soil surface. Seeds buried between 0 and 4 cm in the soil are suitable for seedling emergence, and emergence is greatly reduced with an increase in burial depth. Therefore, tillage operations that bury seeds deeper than 6 cm may be possible management options. High amounts of rice residue (over 10 t ha^{-1}), used as mulch, suppressed seedling emergence of Japanese foxtail and may be combined with deep ploughing to discourage emergence of Japanese foxtail. The herbicides mesosulfuron-methyl, clodinafop-propargyl, pyroxsulam, pinoxaden, and isoproturon provided excellent control of this weed when applied at the three- and five-leaf stages.

Acknowledgments. This work was financially supported by the Special Fund for Agroscientific Research in the Public Interest of China (201303022), the Ph.D Programs Foundation of Ministry of Education of China (20133702110017), and the National Natural Science Foundation of China (31171866, 31601653). The authors thank all the workers for assistance in conducting this research.

References

Ahmed S, Salim M, Chauhan BS (2014) Effect of weed management and seed rate on crop growth under direct dry seeded rice systems in Bangladesh. PLOS ONE 9:e101919

Atia A, Smaoui A, Barhoumi Z, Abdelly C, Debez Z (2011) Differential response to salinity and water deficit stress in Polypogon monspeliensis (L.) Desf. provenances during germination). Plant Biol 13:541–545

Ba FC, Zhao Y (1997) Soil resources of tideland in China. Chin J Soil Sci 28:49–51 [In Chinese]

Baskin CC, Baskin JM (1998) Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination. New York: Academic. Pp 12–13

Bebawi FF, Campbell SD (2003) Effects of fire on germination and viability of bellyache bush (*Jatropha gossypiifolia*) seeds. Anim Prod Sci 42:1063–1069

Benvenuti S (1995) Soil light penetration and dormancy of jimsonweed (*Datura stramonium*) seeds. Weed Sci 43:389–393

Benvenuti S (2003) Soil texture involvement in germination and emergence of buried weed seeds. Agron J 95:191–198

Bi YL, Liu WT, Guo WL (2016) Molecular basis of multiple resistance to ACCase-and ALS-inhibiting herbicides in *Alopecurus japonicus* from China. Pestic Biochem Phys 126:22–27

Bolfrey-Arku GEK, Chauhan BS, Johnson DE (2011) Seed germination ecology of itchgrass (*Rottboellia cochinchinensis*). Weed Sci 59:182–187

Chachalis D, Reddy KN (2000) Factors affecting *Campsis radicans* seed germination and seedling emergence. Weed Sci 48:212–216

Chauhan BS (2013) Seed germination ecology of feather lovegrass [*Eragrostis tenella* (L.) Beauv. Ex Roemer & JA Schultes]. PLOS ONE 8:e79398

Chauhan BS, Abugho SB (2012) Effect of growth stage on the efficacy of postemergence herbicides on four weed species of direct-seeded rice. Sci World J 2012:123071

Chauhan BS, Gill G, Preston C (2006) Factors affecting seed germination of annual sowthistle (*Sonchus oleraceus*) in southern Australia. Weed Sci 54:854–860

Chauhan BS, Johnson DE (2008) Germination ecology of goosegrass (*Eleusine indica*): an important grass weed of rainfed rice. Weed Sci 56:699–706

Chauhan BS, Johnson DE (2010) The role of seed ecology in improving weed management strategies in the tropics. Advs Agron 105:221–262

Crutchfield DA, Wicks GA, Burnside OC (1986) Effect of winter wheat (*Triticum aestivum*) straw mulch level on weed control. Weed Sci 34: 110–114

Dai WH, Huang Y, Wu L, Yu J (2009) Relationship between soil organic matter and pH in China. Acta Pedol Sin 46:851–861 [In Chinese]

Ding B, Gu XY, Miao QL (2006) Characteristics in the variation of temperature over the Yangtze River Valley over last 50 years. Resour Environ Yangtze Basin 15:531–536

Evert S, Staggenborg S, Olson BLS (2009) Soil temperature and planting depth effects on tef emergence. J Agron Crop Sci 195:232–236

Facelli JM, Pickett STA (1991) Plant litter: its dynamics and effects on plant community structure. Bot Rev 57:1–32

Fernando N, Humphries T, Florentine SK, Chauhan BS (2016) Factors affecting seed germination of feather fingergrass (*Chloris virgata*). Weed Sci 64:605–612

Gadde B, Bonnet S, Menke C, Garivait S (2009) Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ Pollut 157:1554–1558

Geissler N, Hussin S, Koyro HW (2009) Interactive effects of NaCl salinity and elevated atmospheric CO2 concentration on growth, photosynthesis, water relations and chemical composition of the potential cash crop halophyte *Aster tripolium* L. Environ Exp Bot 65:220–231

Haferkamp MR, Karl MG, MacNeil MD (1994) Influence of storage, temperature, and light on germination of Japanese brome seed. J Range Manag 47:140–144

Johnson DE, Kent RJ (2002) The impact of cropping on weed species composition in rice after fallow across a hydrological gradient in West Africa. Weed Res 42:89–99

Leon RG, Bassham DC, Owen MDK (2006) Germination and proteome analyses reveal intraspecific variation in seed dormancy regulation in common waterhemp (*Amaranthus tuberculatus*). Weed Sci 54: 305–315

Leon RG, Knapp AD, Owen MDK (2004) Effect of temperature on the germination of common waterhemp (*Amaranthus tuberculatus*), giant foxtail (*Setaria faberi*), and velvetleaf (*Abutilon theophrasti*). Weed Sci 52:67–73

Leon RG, Owen MDK (2006) Tillage systems and seed dormancy effects on common waterhemp (*Amaranthus tuberculatus*) seedling emergence. Weed Sci 54:1037–1044

Li Q, Tan J, Li W, Yuan GH, Du L, Wang JX (2015) Effects of environmental factors on seed germination and emergence of Japanese brome (*Bromus japonicus*). Weed Sci 63:641–646

Li XJ, Zhang M, Wei SH, Cui HL (2012) Influence of environmental factors on seed germination and seedling emergence of yellowtop (*Flaveria bidentis*). Pak J Weed Sci Res 18 (Special Issue):317–325

Liu MY, Chen PY (1988) Changes in emergence of wheat seedling, seedling growth and leaf photosynthesis under different soil water conditions. Mem NISWC Acad Sin 8:76–82 [In Chinese]

Michel BE (1983) Evaluation of the water potentials of solutions of polyethylene glycol 8000 both in the absence and presence of other solutes. Plant Physiol 72:66–70

Michel BE, Kaufmann MR (1973) The osmotic potential of polyethylene glycol 6000. Plant Physiol 51:914–916

Mohamed IA, Li R, You Z, Li Z (2012) Japanese foxtail (*Alopecurus japonicus*) resistance to fenoxaprop and pinoxaden in China. Weed Sci 60:167–171

Mulligan GA, Bailey LG (1975) The biology of Canadian weeds: 8. Sinapis arvensis L. Can J Plant Sci 55:171–183

Opeña JL, Chauhan BS, Baltazar AM (2014) Seed germination ecology of *Echinochloa glabrescens* and its implication for management in rice (*Oryza sativa* L.). PLOS ONE 9:e92261

Rao N, Dong L, Li J, Zhang H (2008) Influence of environmental factors on seed germination and seedling emergence of American sloughgrass (*Beckmannia syzigachne*). Weed Sci 56:529–533

Sanchez PA (1976) Soil management in shifting cultivation areas. In Properties and Management of Soils in the Tropics. Raleigh, NC: J. Wiley. Pp 346–412

Shen GH, Guan LQ, Shi X, Lu SQ (2000) Study on biological and ecological characteristics of *Alopecurus japonicus* in Shanghai region. Acta Agriculturae Shanghai 16:37–40 [In Chinese]

Singh S, Singh M (2004) Effect of growth stage on trifloxysulfuron and glyphosate efficacy in twelve weed species of citrus groves. Weed Technol 18:1031–1036

Singh SK, Bharadwaj V, Thakur TC, Pachauri SP, Singh PP, Mishra AK (2009) Influence of crop establishment methods on methane emission from rice fields. Curr Sci 97:84–89

Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85: 673–680

Thompson K, Grime JP, Mason G (1977) Seed germination in response to diurnal fluctuations of temperature. Nature 267:147–149

Tomita S, Nawata E, Kono Y, Nagata Y, Noichana C, Sributta A, Inamura T (2003) Differences in weed vegetation in response to cultivating methods and water conditions in rainfed paddy fields in northeast Thailand. Weed Biol Manag 3:117–127

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27: 431–436

White SN, Boyd NS (2016) Effect of dry heat, direct flame, and straw burning on seed germination of weed species found in lowbush blueberry fields. Weed Technol 30:263–270

Wilson RG Jr (1979) Germination and seedling development of Canada thistle (*Cirsium arvense*). Weed Sci 27:146–15

Wu X, Li J, Xu H, Dong L (2016a) Factors affecting seed germination and seedling emergence of Asia minor bluegrass (*Polypogon fugax*). Weed Sci 63:440–447

Wu X, Zhang T, Pan L, Wang L, Xu H, Dong L (2016b) Germination requirements differ between fenoxaprop-p-ethyl resistant and susceptible Japanese foxtail (*Alopecurus japonicus*) biotypes. Weed Sci 64: 653–663

Yang C, Dong L, Li J, Moss SR (2007) Identification of Japanese foxtail (*Alopecurus japonicus*) resistant to haloxyfop using three different assay techniques. Weed Sci 55:537–540