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RESEARCH ARTICLE

Seed-shattering phenology of *Phalaris minor* and *Avena ludoviciana* at wheat harvest in north-western India

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ABSTRACT

Weed infestations are primarily driven by the weed seedbank, making it essential to reduce seedbank replenishment for effective control. Seed shattering or retention is a weed plant-specific characteristics and can vary for different weed species, their cohorts or biotypes/populations and weather conditions. Seed shattering phenology of *Phalaris minor* and *Avena ludoviciana* and possible drivers (such as total number of seeds per panicle, plant height, number of tillers and plant biomass) for seed retention was studied at wheat harvest in a two-year study at Punjab Agricultural University, Ludhiana. The results suggested that 74% and 9% seed retention of *P. minor* and *A. ludoviciana*, respectively at wheat harvest. The plant biomass played a critical role in seed retention for *P. minor*, while none of the tested predictors significantly influenced retention in *A. ludoviciana*. This highlighted the weed species-specific differences in seed retention mechanisms, which could be essential for understanding their ecological and management implications. It is concluded that *P. minor* may be a suitable candidate (with 74% seed retention) for harvest weed seed control (HWSC) approaches while *A. ludoviciana* (with 9% seed retention) cannot be targeted with this approach.

Keywords: *Avena ludoviciana*, Harvest weed seed control, *Phalaris minor*, Plant height, Seed retention, Weed control

INTRODUCTION

Wheat [*Triticum aestivum* L. emend. Fiori et Paol.] is the most popular and staple food for human consumption in the world. It is the most significant crop in India in terms of area and production, after rice. Weeds are one of major biological constraints in wheat as crop is infested with complex weed flora. *Phalaris minor* Retz. and *Avena ludoviciana* L. are the dominant monocot weeds in the wheat crop. Both weeds are satellite weeds of wheat crop and mimics the crop. Their initial morphology and physiological similarities to wheat plant makes these grass weeds difficult to control with mechanical methods. Both weeds have similar ecological requirements to that of wheat. Recently, there are reports of evolution of herbicide resistance in *P. minor* and *A. ludoviciana* in northwest India (Kaur *et al.* 2022). *Phalaris minor* is a major weed of rice-wheat cropping system while *A. ludoviciana* is mainly observed in irrigated, well drained, lighter textured soils, and mainly in cotton/ maize-wheat cropping systems (Bhullar *et al.* 2017).

Phalaris minor typically germinates between November-January and reaches maturity during March-April. The plant features an erect stem with well-defined nodes and internodes, and at maturity, it grows taller than wheat. It sheds its seeds from mid-March till wheat harvest in early-April. Early in the 1990s, *P. minor* has evolved resistance against isoproturon in the rice-wheat cropping system. The resistance evolution was mainly observed in the wheat fields where isoproturon herbicide has continuously been used for 10-15 years (Malik and Singh 1993). Thereafter, *P. minor* also evolved resistance against fenoxaprop, clodinafop and sulfosulfuron and pinoxaden (Kaur *et al.* 2015). *Avena ludoviciana* is particularly serious where wheat is grown in rotation with traditional crops such as cotton, maize, groundnut or with direct-seeded rice (Balyan *et al.* 1991). It is one of the worst annual (winter) weed of temperate agricultural region in the world (Holm *et al.* 2000). The earlier shedding of seed and ability to remain dormant for several years are some features which contributes to its success.

Weeds tend to have variable shattering that enable the weeds to persist in the cropping system. Shattered seeds will add to the weed seed bank and will infest the cropped fields for years (Shivrain *et al.* 2010). Therefore, seedbank replenishment must be

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reduced for efficient weed control (Schwartz-Lazaro and Copes 2019). To prevent faster evolution of herbicide resistance and reduce the weed pressure in future, it is crucial to ensure that no individual weed plant produces seeds for the next generation (Pulambi 2001). Harvest weed seed control (HWSC) is a technique for capturing unshattered weed seeds while harvesting operation and thus, lowering the number of viable seed delivered to the soil. By restricting seed production and inhibiting the gradual emergence of resistant sub-populations in the soil seed bank, HWSC can have a detrimental effect on the dynamics of weed populations. The effectiveness of HWSC depends upon seed retention at maturity, its collection and further milling/processing (Walsh *et al.* 2018). The seeds retained on the panicle/spike can be targeted by HWSC approaches especially weed seed destruction through impact mills such as Harrington seed Destructor or Redekop Combines (Schwartz-Lazaro *et al.* 2021a, 2021b, 2022). Seed shattering is genetically controlled, but is largely regulated by environmental conditions and agronomic practices (Shirtliffe *et al.* 2000, Walsh and Powles 2014). There is a need to test the potential of HWSC approaches for controlling *P. minor* and *A. ludoviciana* in wheat. Therefore, an experiment was conducted to study the seed retention or shattering behavior of *P. minor* and *A. ludoviciana* at wheat harvest. Also, weed growth parameters along with seed retention at harvest were studied to investigate the relationship between these factors, if any.

MATERIALS AND METHODS

The field experiment was conducted during the winter/*rabi* season of 2022-23 and 2023-24 at Research Farm, Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab, India. The experimental site is situated at an altitude of 247m above mean sea level in the Trans-Gangetic agro-climatic zone at 30°542 N latitude, 75°482 E longitude. The field with population of 100-150 plants/m^2 of *Phalaris minor* and *Avena ludoviciana* during past years was selected for conducting field trial. The field was prepared through conventional practice of ploughing with tractor driven rotavator in all plots and wheat crop (cv. PBW 826 with 100 kg/ha seed rate) was sown using seed-cum-fertilizer drill during first week of November during both years of study.

About 40 plants of both weed species were tagged during first year while 75-80 plants were tagged for recording the data during the second year. Cohorts emerged along with crop and after first irrigation were tagged soon after their emergence. Tagged weed plants were allowed to grow in the field with normal agronomic practices as for wheat crop. Inflorescence of both weeds was covered with bags made of butter paper after the complete emergence. Bag paper of size 15 cm × 10 cm and 30 cm ×10 cm was used to cover inflorescence of *P. minor and A. ludoviciana*, respectively. Seeds were collected at interval of 4 days after 15 days of spike/panicle emergence till the harvest of wheat crop at physiological maturity. Seed collected just before harvest was counted as total seed retained by weed at crop harvest. The observations on total seeds/panicle, plant height, number of tillers and plant biomass were recorded at wheat harvest.

The descriptive statistics was performed on individual years and after pooling the data over the years. The pooled analysis was performed as experimental error for both years was homogeneous according to Bartlett's test of homogeneity of variance. The Pearson correlation coefficients were calculated for seed retention and individual plant growth parameters. Further, standard multiple regression analysis was performed on the pooled data with seed retention as outcome or dependent variable and plant growth parameters (total number of seeds per panicle, plant height, number of tillers and plant biomass) as independent variable or predictors. The assumptions for standard multiple regression analysis were tested before performing the analysis. Collinearity diagnostics was performed before fitting the regression model. The tolerance, variation inflation factor and cook's distance were evaluated for the data and outliers were removed before fitting the regression model as below:

$$\hat{y} = \alpha + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$$

where, w is seed retention; $\hat{y}$ is intercept and $\beta_1, \beta_2, \beta_3$ and β_4 that are unstandardized regression coefficients for x_1, x_2, x_3 and x_4, that are total number of seeds per panicle, plant height, number of tillers and plant biomass, respectively. The analysis of variance (ANOVA) to test the significance of predictor effect in multiple correlation-regression was performed using IBM SPSS Statistics 19.

RESULTS AND DISCUSSION

The success of HWSC method such as impact mills is dependent upon weed seed retention on panicle per spike. Seed retention percentage in *P. minor* was found much higher as compared to *A. ludoviciana* (**Table 1**). Seed retention of *P. minor* varied from 70.2±1.4% (2022-23) to 74.1±1.24%

(2023-24), with a pooled average of 73.7±0.8%. Further, seed production per panicle in *P. minor* at wheat harvest was 256.0±9.6 and 330.8±9.4 during 2022-23 and 2023-24, respectively with a pooled average of 309.1±7.5. On the other hand, seed retention of *A. ludoviciana* at wheat harvest was 11.2% and 10% during 2022-23 and 2023-24, respectively, and total number of seeds per panicle ranged from 52.0±1.9 to 61.4±0.9 during two years of study. It indicated that most of seeds of *A. ludoviciana* would have shed at the time of wheat harvest.

The data in **Table 2** and **3** presented the Pearson correlation coefficients among various agronomic traits, including retention percentage, total seeds per panicle, plant height, tillers per plant, and biomass. In *P. minor*, seed retention percentage had a significant positive correlation with total seeds per panicle, plant height and biomass (**Table 2**). Total seeds/panicle demonstrated a strong positive correlation with plant height, a weak positive correlation with biomass, and a negligible correlation with tillers. These findings in *P. minor* indicated presence of significant associations among some traits in *P. minor* where the correlation coefficients exceed the critical value of 0.183, emphasizing the interdependence of these agronomic parameters. Seed shattering (or pod dehiscence, or fruit shedding) is an essential process for the propagation and the evolutionary success of wild plant species. In the cropped environment, weeds are under strong selective pressures and fruit morphology and associated dispersal strategies are of significant adaptive importance. There is molecular and hormonal regulation of tissues that are necessary for seed shattering and fruit shedding (Dong and Wang 2015).

Seed retention percentage in *A. ludoviciana* had a significant negative correlation with total seeds per panicle (**Table 3**). Total seeds per panicle exhibited a strong positive correlation with plant height and biomass but shows minimal correlation with tillers. Plant height was positively correlated with biomass and negatively correlated with tillers. These values highlighted the relationships among the traits, indicating significant associations where the absolute correlation coefficients exceed the critical value of

Table 1. Descriptive statistics of seed retention and growth characteristics of *Phalaris minor* and *Avena ludoviciana* during 2022-23 and 2023-24

Parameters	*Phalaris minor*			*Avena ludoviciana*		
	2022-23 (n=39)*	2023-24 (n=77)	Pooled (n=116)	2022-23 (n=35)	2023-24 (n=76)	Pooled (n=111)
Retention (%)	70.2±1.4 (46.7-84.8)	74.1±1.24 (14.0-91.4)	73.7±0.8 (54.4-91.4)	11.2±1.0 (0-30.4)	10.0±0.9 (0-50)	9.4±0.5 (0-25)
Total seeds/ panicle (no.)	256.0±9.6 (120-362)	(330.8±9.4) (106-536)	309.1±7.5 (145-536)	52.0±1.9 (23-75)	61.4±0.9 (0-30.4)	58.9±1.5 (23-119)
Plant height (cm)	103.0±3.5 (59-145)	113.9-1.8 (76-149)	110.1±1.8 (59-149)	119.6±2.7 (88-145)	130.5±1.6 (98-164)	127.6±1.4 (96-164)
Tillers/plant (no.)	3.0±0.2 (1-6)	3.2±0.1 (1-7)	3.2±0.1 (1-7)	3.9±0.3 (2-7)	3.184±0.14 (2-7)	3.4±0.1 (2-7)
Biomass/plant (g)	2.0±0.2 (0.6-5.1)	2.5±0.1 (0.9-5.8)	2.4±0.1 (0.6-5.8)	2.2±0.1 (0.9-4.4)	2.9±0.1 (1.4-6.8)	2.7±0.1 (0.9-6.8)

*Indicated the sample size (n) in a year. Results are presented as mean ± standard error. Figures in parentheses indicated the range from minimum to maximum

Table 2. Correlation matrix of seed retention and growth characteristics of *Phalaris minor*

Parameters	Seed retention (%)	Total Seeds/panicle (no.)	Plant height (cm)	Tillers (no.)
Total Seeds/panicle (no.)	0.303			
Plant height (cm)	0.183	0.512		
Tillers/plant (no.)	-0.002	0.018	-0.186	
Biomass/plant (g)	0.276	0.143	0.167	0.118
r (p=0.05)		0.183		

Table 3. Correlation matrix of seed retention and growth characteristics of *Avena ludoviciana* at wheat harvest

Parameters	Seed retention (%)	Total Seeds/panicle (no.)	Plant height (cm)	Tillers (no.)
Total Seeds/panicle (no.)	-0.192			
Plant height (cm)	-0.111	0.444		
Tillers/plant (no.)	0.142	0.034	-0.122	
Biomass/plant (g)	-0.011	0.348	0.463	-0.134
r (p=0.05)		0.187		

0.187.

The multiple regression analysis for estimating seed retention in *P. minor* and *A. ludoviciana* using four predictors (seeds per panicle, plant height, tillers per plant, and plant biomass) revealed notable differences in model performance and predictor influence (**Table 4**). The model for *P. minor* demonstrated a better fit, with multiple correlation coefficient, R = 0.362 and coefficient of determination, R^2 = 0.131 that 13.1% of the variance in seed retention is explained due to these four predictors. The adjusted R^2 (0.099) and a statistically significant ANOVA value (p = 0.004) indicated a modest but meaningful relationship between the predictors and the dependent variable. Among the predictors, plant biomass emerged as the most significant factor (β = 2.174, p = 0.004), positively influencing seed retention, while seeds per panicle, plant height, and tillers per plant had minimal or insignificant effects ($p > 0.05$).

In contrast, the model yielded a low multiple correlation coefficient (R = 0.160) and an R^2 value of 0.026 for *A. ludoviciana*, indicating minimal explanatory power of the predictors (**Table 4**). The adjusted R^2 was negative (-0.012), further suggesting a poor model fit. The ANOVA significance value (0.612) was not statistically significant, and none of the predictors showed significant effects, as reflected by their p-values (e.g., plant biomass: p = 0.283). Among the predictors, plant biomass had the largest regression coefficient (β = -0.743), indicating its relative influence, albeit non-significant.

In wheat cropped fields, these two grass weeds may emerge with or after the crop emergence with every irrigation or rainfall event. It was observed by Franke *et al.* (2007) that all *P. minor* plants were able to produce seeds. Smaller plants with lower aboveground biomass produced a smaller number of seeds with the similar individual seed weight as that of seeds produced by the larger plants. This was established that seed size or weight was unaffected by the above ground biomass of the mother plant. The cohorts that emerged late in the cropping season produced only 1.1 g shoot biomass but resulted in the production of 205 seeds/plant. There are multiple cohorts of these weeds present in a field at one time which result in variable maturity and thus, longer period of seed shattering. This adaptive behaviour of weeds allowed them to manage seed bank. Therefore, early crop harvest may maximize the weed seed export from the field (into the combine) and could prevent significant long-distance dispersal if clubbed with sanitation, cleaning of farm machinery and narrow windrow burning. However, under late crop harvest scenario, both *P. minor* and *Avena* spp. will have less seed retention on spike/panicle *i.e.* more of seed shed.

Residue burning may have detrimental effect on mortality of weed seeds lying on soil surface depending upon the residue load (Kaur *et al.* 2021). Moreover, most weeds are prolific seed producers and can distribute seeds in the vicinity areas through shattering over a long duration following physiological maturity. Seed shattering has also been recognized as an essential adaptive trait that favours seed dispersal, seedbank establishment and weediness in many species (Delouche *et al.* 2007, Burton *et al.* 2017). The retained seeds on the spike per panicles can be harvested and spread across the field by the combine harvester for long-distance dispersal through contamination of harvested crop

Table 4. Multiple regression model estimates for estimating retention (dependent variable) of seeds of *Phalaris minor* and *Avena ludoviciana* from four predictors (seeds/panicle, plant height, tillers, biomass)

Model estimates		*Phalaris minor*	*Avena ludoviciana*
Multiple correlation, R		0.362	0.160
R square		0.131	0.026
Adjusted R square		0.099	-0.012
df		112	106
ANOVA significance		0.004	0.612
α		59.140	8.941
β	Seeds/panicle	0.004	-0.035
	Plant height	0.077	0.033
	Tillers/plant	-0.098	0.095
	Plant biomass	2.174	-0.743
Sig.	Seeds/panicle	0.697	0.357
	Plant height	0.117	0.445
	Tillers/plant	0.876	0.801
	Plant biomass	0.004	0.283

seed. Weeds are very adaptive to crop production practices. HWSC is widely adopted in Australia and USA, and there is a need to study if weeds retain only some seeds and shatter most of their seed before the harvest of crop as an evolutionary adaptation to avoid HWSC methods (Walsh *et al.* 2013, Walsh and Powles 2014, Walsh *et al.* 2018).

Based on two-year study, plant biomass has a significant positive effect on seed retention in *P. minor*. Further, it is concluded that *P. minor* may be a suitable target candidate (with 74% seed retention) for HWSC approaches while *A. ludoviciana* (with 9% seed retention) cannot be targeted for this approach.

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