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ORIGINAL ARTICLE / ORIGINALBEITRAG

Avena sterilis ssp. *ludoviciana* (Durieu) Control in Wheat Through Integration of Tillage, Seeding Rate, and Herbicide Application

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Abstract
Avena sterilis ssp. *ludoviciana* (Durieu) is a problematic weed in the wheat crop of Australia. Pinoxaden is an effective herbicide for the control of this weed. However, late cohorts of *A. ludoviciana* escape from the early application of pinoxaden and produce seeds. This research investigated the integrated effect of tillage systems (no-tillage and conventional tillage), seeding rates (100 and 200 seeds m^{-2}), and weed control treatments (nontreated control and pinoxaden application at Z12 and Z33 stages of wheat) on *Avena ludoviciana* control and wheat yield. The wheat yield remained similar in no-tillage and conventional tillage systems; however, the no-tillage system helped in reducing *A. ludoviciana* seed production by 28% compared with the conventional tillage system. In the nontreated control, the increased seeding rate of wheat reduced *A. ludoviciana* biomass and seed production by 33 and 66%, respectively, compared with the low seeding rate. These results suggest that a high seeding rate could be useful in the organic production of wheat. Application of pinoxaden at Z12 and Z33 stages of wheat resulted in an improvement in grain yield by 170 and 150%, respectively, compared with the nontreated control. At both seeding rates, the application of pinoxaden at the Z33 stage of wheat reduced weed seed production by 99% compared with the nontreated control. These results implied that the delayed application of pinoxaden at the Z33 stage of wheat effectively reduced weed biomass and seed production of *A. ludoviciana* without compromising grain yield as the yield in this treatment was similar to the pinoxaden application at the Z12 stage.

Keywords Competition · Growth stage · Pinoxaden · Post-emergent herbicides · Plant size · Weed biomass · Weed seed production

Introduction

Weeds in crops are an issue for improved crop productivity as they compete with crops for water and nutrients, causing biotic stress. In Australia, two *Avena* species namely, *A. fatua* L. (wild oats) and *A. sterilis* ssp. *ludoviciana* (Durieu), (hereafter, *A. ludoviciana*, sterile oats) are the dominant weed species that interfere in winter season crops. These two species, along with *A. barbata* Pott ex Link (slender oats), collectively cause a loss of about AU$ 28 million per annum to the Australian grain industry when estimated in terms of yield loss and control measures (Llewellyn et al. 2016). *Avena ludoviciana* is a dominant species in the winter crops of eastern Australia, while *A. fatua* is dominant in cropping regions of southern and western Australia (Nugent et al. 1999).

The infestation of *A. ludoviciana* in wheat (*Triticum aestivum* L.) fields, if left uncontrolled, could cause a yield loss of up to 80% (Martin et al. 1987; Storrie 2007). A recent study conducted in Australia predicted a 50% wheat yield loss at *A. ludoviciana* density of 16 plants m^{-2}, suggesting that this weed has a strong competitive ability in wheat (Mahajan and Chauhan 2021a). Therefore, control of *A. lu-*

Data Availability Statement All relevant data are within the manuscript.

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doviciana is important in improving wheat productivity in Australia.

In eastern Australia, the no-till wheat production system is common, especially in dryland regions, and has been adopted at a large scale (Llewellyn et al. 2012). The no-till production system helps in residual soil moisture utilization and improves nutrient uptake, as well as improve the soil structure through crop residue retention (Llewellyn et al. 2012). However, weeds remain a problem in no-till production systems due to weed emergence prior to crop emergence, and the low efficacy of pre-emergence herbicides as a result of residue crop cover (Chauhan et al. 2006; Walsh and Powles 2007; Triplett and Dick 2008, Nord et al. 2012). The expansion of the cotton (*Gossypium hirsutum* L.) industry in eastern Australia has increased the area of conventional tilled irrigated wheat in some pockets as it helps in breaking disease and pest cycles in cotton-based cropping systems (Sykes 2012). Weeds behave differently in response to varied tillage systems (Chauhan et al. 2006, 2012).

Avena ludoviciana could behave differently in no-till and conventional-till production systems due to varied emergence patterns in response to burial depth. It has been found that *A. ludoviciana* emergence was greater from 2 and 5-cm soil depths compared with that on the surface (Mahajan and Chauhan 2021b). These results suggest that the emergence of *A. ludoviciana* could be greater in conventional systems compared with the no-till system. Information on the growth behavior and seed reproduction potential of *A. ludoviciana* in response to the tillage system is limited in Australia. The ability of *A. ludoviciana* to produce seeds in a water-stress environment could increase the persistence of this weed in response to varied tillage systems (Sahil et al. 2020). The plants of *A. ludoviciana* are prolific in seed production. It was estimated that early cohorts (May) of *A. ludoviciana* could produce up to 4000 seeds plant^{-1} (Mahajan and Chauhan 2021c). The peak emergence time of *A. ludoviciana* coincides with the optimum sowing time of wheat (first fortnight of May) in Australia (Mahajan and Chauhan 2021b). These observations suggest that it is essential to control *A. ludoviciana* before it produces seeds to reduce the weed seed bank in the soil and for improving wheat yield.

In Australia, *A. ludoviciana* biotypes have evolved resistance to Group 1 and 2 herbicides (Heap 2023). Herbicides belonging to Groups 1 and 2, in general, are applied at a young seedling stage (2–3 leaf stage) for high efficacy and effective control (Beckie et al. 2002). However, growers wait for a greater number of weeds to emerge to obtain maximum weed control in the field. However, by that time weeds become large and difficult to control (Chauhan et al. 2021). This type of situation is very frequent when weeds have multiple cohorts and late emerging weeds escape from timely spray applications (personnel, communication). In Australia, multiple cohorts of *A. ludoviciana* appeared from March to October (Mahajan and Chauhan 2021b). The staggered emergence pattern of *A. ludoviciana* could lead to a decision-making process difficult for spraying post-emergent herbicide application.

Pinoxaden is a selective post-emergence herbicide used for controlling annual weeds in winter cereals (Anonymous 2022). It kills weeds by inhibiting acetyl-CoA carboxylase (ACCase) (Hofer 2006, Bitarafan and Andreasen 2020). Many weeds have evolved resistance to pinoxaden in more than 15 countries (Heap 2023). Large weed plants may build up resistance to herbicides with time, even when applied at an optimal rate, due to poor weed control (Botterman and Leemans 1988). Therefore, the stage of the plant is very critical for effective control during the spray application of herbicides. We hypothesized that late application of pinoxaden in wheat (Z33 stage: third node formation) may provide complete control of early and late cohorts of *A. ludoviciana*.

Exploring crop competition for weed suppression is found to be an effective cultural strategy for weed control in Australian cropping regions (Lemerle et al. 1996; Scott et al. 2013). Crop competitiveness against weeds can be increased by using a high seeding rate (Mahajan and Chauhan 2022). We hypothesized that the competitiveness of a crop in response to a tillage system can be increased by using a high seeding rate and that competitiveness can also be exploited for reducing the seed production of *A. ludoviciana* without using any herbicides. Increased crop competition using a high seeding rate in wheat may suppress weeds without using any herbicides and promote organic wheat.

This research aimed to answer two questions: (i) can an increase in seed rate of wheat in different tillage systems suppress *A. ludoviciana*, reduce its seed number, and improve wheat productivity; and (ii) can a late application of pinoxaden provide effective control of *A. ludoviciana* without compromising grain yield.

Materials and Methods

A 2-yr field study was conducted at the Research Farm of the University of Queensland, Gatton (27.5514° S and 152.3428° E), Australia. In each year (2020 and 2021), the experiment was conducted in the winter season (May-October). The experimental location belongs to the subtropical climatic region of Australia and has an average annual rainfall of 728 mm. The soil in the experimental field was clay with a pH of 6.9 and 1.4% organic matter. The experimental location was the same in both years. Experimental plots in conventional tillage treatments were tilled (12–15 cm deep) with a disc-harrow (two times) followed by a rotovator operation. The field was kept fallow after the first wheat crop.

Experiment Design and Herbicide Treatments

The experiment was arranged in a split-split plot design with two tillage regimes (no and conventional tillage) in main plots, two seeding rates (100 and 200 seeds m^{-2}) in sub-plots, and three weed control treatments (nontreated control, pinoxaden application at Z12 (two-leaf stage), and Z33 stage (third node formation) of wheat) in sub-sub plots. Wheat (variety Spitfire) was sown using a cone planter (six rows) at a row spacing of 35 cm in both years. The crop was sown on 7th May in both years.

All treatments were replicated thrice each year, and the size of each plot was 4.0 m (length) × 1.4 m (width). *Avena ludoviciana* seeds at a rate of 40 kg ha^{-1} were mixed with sand and broadcasted before wheat planting and tillage operation for ensuring uniform weed infestation across the field each year. Pinoxaden spray was done with a CO_2 backpack sprayer equipped with four flat-fan nozzles (Airmix 110015 TeeJet nozzles, Model 25611) spaced at 50 cm and using a volume of 100 L of water ha^{-1} at 200 kPa. Pinoxaden 100 EC (Axial = active constituent; 100 g L^{-1} pinoxaden +25 g L^{-1} cloquintocet-mexyl; Syngenta, Australia) was applied at a rate of 20 g ai ha^{-1}. To create the herbicide solution, pinoxaden was mixed with Adigor adjuvant at 500 ml per 100 L water.

The crop was harvested on 14th and 7th October in 2020 and 2021, respectively. At crop harvest, *A. ludoviciana* density, biomass, and seed number m^{-2} were determined using a quadrat (50 cm × 50 cm) placed randomly in each plot at two places. Weeds from the quadrat area in each plot were counted and converted into plants m^{-2}. For biomass sampling, weeds were removed from the base level in each plot, placed in paper bags, and then dried in an oven at 70 °C for 72 h. After oven drying, weed samples were weighed for biomass. For weed seed count, florets (empty and nonempty) of each *A. ludoviciana*'s panicle were counted that occurred in the quadrat area. In both years, the crop was harvested when it attained maturity using a combine harvester. For effective tillers, tillers bearing earheads were counted from two places in each plot by placing a ruler of 1 m length randomly and converted into plants m^{-2}. Grain yield was recorded from a net area of 4.2 m^2 (3.0 m × 1.4 m) per plot and converted to t ha^{-1} at a 12% moisture content.

Table 1 Analysis of variance (ANOVA) for different parameters of *Avena ludoviciana* and wheat yield

Source of variation	Degree of freedom	Mean square			
		Avena ludoviciana		Wheat	
		Biomass	Seed production	Effective tiller	Grain yield
		g m^{-2}	No. m^{-2}	No. m^{-2}	t ha^{-1}
Replication	2	7,536	368,405	478	0.65
Year (Y)	1	45,064	2,245,785	99,313	3.2
Error (Y)	2	3,086	194,123	4,323	2.6
Tillage (T)	1	42,224	2,403,893*	1,152	2.2
Y × T	1	5,810	799,690	4,737	0.72
Error (T)	4	8,732	160,379	3,973	2.1
Seeding rate (SR)	1	85,781*	4,478,027*	3,310	2.98
Y × SR	1	1,601	63,605	698	0.12
PD × SR	1	10,981	1,058,998	170	0.40
Y × T × SR	1	913	45,606	10,260	1.5
Error (SR)	8	11,330	290,506	2,016	1.1
Weed control (WC)	2	1,317,997*	61,973,810*	405,915	83.1*
Y × WC	2	23,703	458,336	4,721	2.7
T × WC	2	11,901	699,460	21.5	0.04
Y × T × WC	2	6,911	243,196	311	0.81
SR × WC	2	46,415*	2,594,448*	3,483	0.14
Y × SR × WC	2	17,461	728,864	442	0.50
T × SR × WC	2	3,447	448,052	3,988	0.05
Y × T × SR × WC	2	5,734	575,180	375	0.27
Error (WC)	32	11,353	347,564	2245	0.80

*indicates significance at a 5% level of significance

Statistical Analyses

The results of the analysis of variance (ANOVA) for each parameter presented an overall picture of the relative effects of years, tillage, seeding rates, weed control treatments, and all possible interactions on *A. ludoviciana* and wheat (Table 1). In a combined analysis of data, parameters where the interactions of years × treatments were nonsignificant, data were pooled over the years.

Data were analyzed using the software CPCS1 developed by Punjab Agricultural University (www.pau.edu), Ludhiana, India (Mahajan and Chauhan 2022) and verified with GenStat 21st edition (VSN International, Hemel Hempstead, UK). Before ANOVA, data were also validated for meeting the assumptions of normality and equal variance. Treatment means were separated with the use of Fisher's Protected LSD test. Unless indicated otherwise, after ANOVA, means were separated using LSD at $P = 0.05$.

Results

Weather Conditions

The crop received a higher amount of rainfall in May and July of 2021 (May: 90 mm and June: 82.6 mm) compared with 2020 (Fig. 1; Mahajan and Chauhan 2022,). In both years, July had the lowest mean monthly maximum temperature (21.7 °C for 2020 and 20.5 °C for 2021). The mean monthly minimum temperature for June and July 2021 was lower than in 2020. In 2020, the mean monthly minimum temperature was lowest in August (6.8 °C); however, in 2021, it was lowest in July (7.1 °C). These observations suggest that the early season of 2021 (July) was more congenial for the emergence of *A. ludoviciana* than in 2020 due to the occurrence of higher rainfall and more favorable temperatures, as supported by a recent study conducted in Australia revealed that those conditions in the winter season proved to be a catalyst for the emergence of *A. ludoviciana* (Mahajan and Chauhan 2021b).

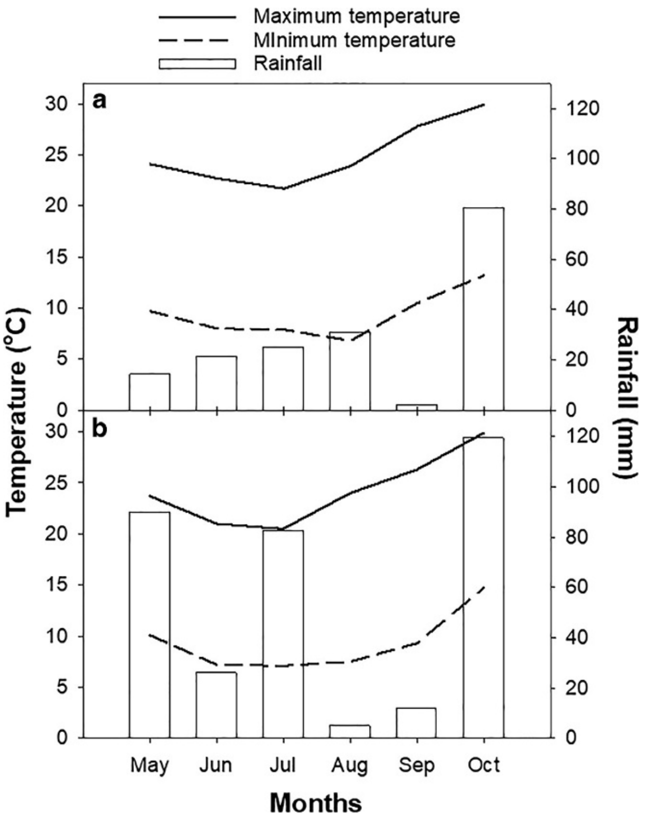

Fig. 1 Weather parameters (mean monthly maximum and minimum temperature, and rainfall) recorded at Gatton, Queensland, in 2020 (**a**) and 2021 (**b**) during the growth duration of wheat crops (Mahajan and Chauhan 2022)

Weed Biomass and Weed Seed Production

For weed (*A. ludoviciana*) biomass, the interaction between the seeding rate and the weed control treatment was found to be significant and all other interactions were found to be nonsignificant (Table 1). In the nontreated control, the high seeding rate reduced the biomass of *A. ludoviciana* by 33% compared with the low seeding rate (Table 2). In herbicide-treated plots, the seeding rate did not influence weed biomass. Averaged over tillage treatments, at the low seeding rate, weed biomass in the nontreated plot was 508 g m^{-2}, and this biomass was reduced by 89 and 99% with pinoxaden application at Z12 and Z33 stages, respectively (Table 2). Averaged over tillage treatments, at the high seeding rate, weed biomass in the nontreated plot was 340 g m^{-2}, and this weed biomass was reduced by 95 and 99% with pinoxaden application at Z12 and Z33 stages, respectively (Table 2).

Seed production of *A. ludoviciana* followed a similar trend to biomass as the interaction between seeding rate and weed control treatment was significant (Table 2). In the nontreated control, the use of the high seeding rate reduced weed seed production by 66% compared with the low seeding rate (Table 2). Application of pinoxaden at Z12 and Z33 stages of wheat grown at the low seeding rate reduced weed seed production by 89 and 99%, respectively, compared with nontreated control (3500 seeds m^{-2}) (Table 2). Similarly, at the high seeding rate, application of pinoxaden at Z12 and Z33 stages of wheat reduced weed seed production by 88 and 98%, respectively, compared with the nontreated control (1200 seeds m^{-2}) (Table 2).

Averaged over seeding rate and weed control treatments, weed biomass was similar in both tillage systems. However, seed production of *A. ludoviciana* was reduced by 28% in

Table 2 Interaction effect of seeding rate and weed control treatments on biomass and seed production of *Avena ludoviciana* (Averaged over tillage treatments)

Weed control treatments	Seeding rate	
	100 seeds m^{-2}	200 seeds m^{-2}
Weed biomass ($g\,m^{-2}$)		
Nontreated control	508	340
Pinoxaden at Z12	55.9	16.6
Pinoxaden at Z33	1.9	2.1
LSD (0.05)	89	
Weed seed production (number m^{-2})		
Nontreated control	3,538	1,196
Pinoxaden at Z12	396	137
Pinoxaden at Z33	15	20
LSD (0.05)	490	

Z12 (two-leaf stage), and Z33 stage (third node formation) of wheat; *LSD* Least significant differences at 5% level of significance

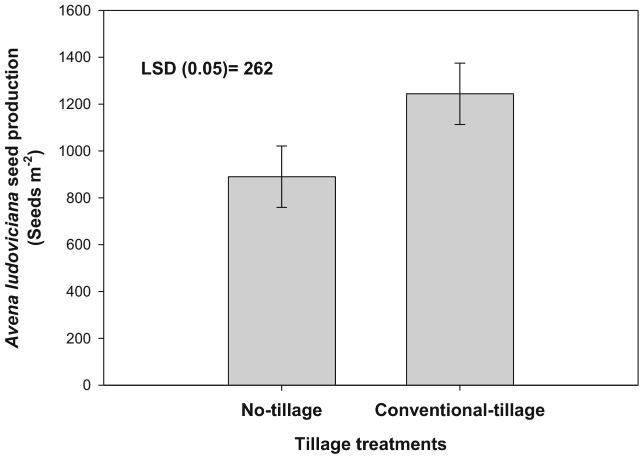

Fig. 2 *Avena ludoviciana* seed production (number m^{-2}) in response to tillage treatments (Averaged over seeding rate and weed control treatments). Error bars indicate the least significant differences (LSD) at a 5% level of significance

the no-tillage system compared with the conventional tillage system (Fig. 2).

Grain Yield

All interactions (two-way and three-way) between tillage, seeding rate, and weed control treatments for grain yield were found to be non-significant. Averaged over seeding rate and weed control treatments, grain yield was similar (4.7–5.1 t ha^{-1}) in both tillage systems (data not shown). Averaged over tillage and weed control treatments, the grain yield at both seeding rates was also similar (4.7–5.1 t ha^{-1}, data not shown). Averaged over tillage and seeding rate, wheat yield in the nontreated control plot was 2.1 t ha^{-1} and it increased by 171 and 148% with pinoxaden application at Z12 and Z33 stages, respectively, compared with nontreated control (Fig. 3).

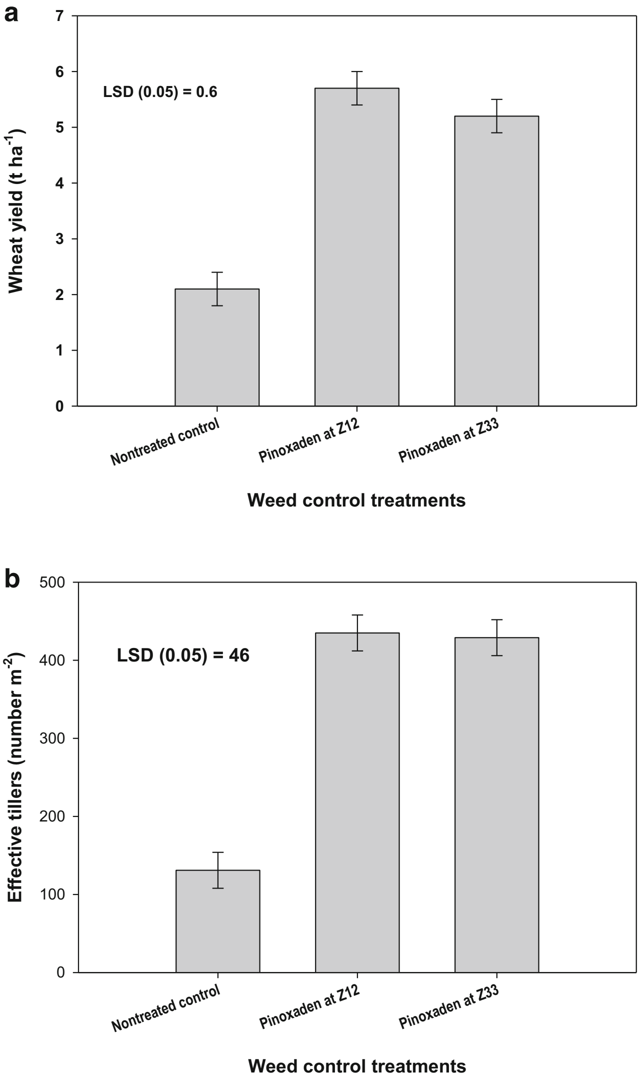

Fig. 3 **a** Grain yield (t ha^{-1}) and **b** effective tillers (number m^{-2}) and of wheat in response to weed control treatments (Averaged over tillage treatments). Error bars indicate the least significant (LSD) differences at a 5% level of significance. Z12 (two-leaf stage), and Z33 stage (third node formation) of wheat

A similar trend was also observed for effective tillers m^{-2} (Fig. 3). Averaged over tillage and seeding rate, effective tillers m^{-2} in the nontreated control plot were found to be 131 and it increased by 232 and 227% with pinoxaden application at Z12 and Z33 stages, respectively, compared with nontreated control (Fig. 3).

Discussion

This research demonstrated that wheat yield did not increase with an increased seeding rate, irrespective of tillage systems. However, an increased seeding rate helped in reducing weed biomass and weed seed production, especially in the nontreated control treatment. This information could be useful in making strategies for weed control in the organic production of wheat. Effective weed control through increasing seeding rate is a proven cultural weed management practice and is exploited in many crops (Gill and Holmes 1997; Lemerle et al. 2004). The concept behind the increased seeding rate in different crops is to increase the competitive ability of crops against weeds by attaining an early canopy closure (Lemerle et al. 1995; Mahajan and Chauhan 2022). The manipulation of this cultural practice is very useful where weeds look phenotypically similar (Lemerle et al. 2001, Cousens 1996). Thickening of a crop canopy through increased seeding rates was traditionally practiced to control weeds when high tillering varieties and herbicides were not available (Downing 1921).

Previous studies in Australia also reported the effect of increased wheat planting density on the suppression of *A. ludoviciana* (Radford et al. 1980). The authors found a negative correlation between wheat density and *A. ludoviciana* biomass (Radford et al. 1980). Reduced biomass of *Lolium rigidum* Gaudin (rigid ryegrass) was observed when the density of lupin was increased (*Lupinus* spp.), which resulted in an increase in yield (Allen 1977; Medd et al. 1985). Similarly, the effect of increased wheat density on *L. rigidum* suppression and improved wheat yield was also observed in Western Australia (Hashem et al. 1998). In the current study, weed seed production decreased with an increased seeding rate. Likewise, previous workers also reported that increasing the seeding rate of wheat from 50 to 200 kg ha^{-1} helped in reducing the seed production of *L. rigidum* (Fee and Anderson 1997).

The current study also demonstrated that yield remained similar when pinoxaden was applied at the Z12 and Z33 stages of wheat. However, the reduction in magnitude for weed biomass and weed seed production was higher when pinoxaden was applied at the Z33 stage compared with the nontreated control. These observations suggest that pinoxaden may be applied at a late stage (Z33) of the crop and could effectively reduce weed seed reduction without compromising grain yield. Late application of pinoxaden could help in controlling early and late cohorts of weeds as *A. ludoviciana* emerges in multiple cohorts. In addition to this, a delayed application of pinoxaden in wheat (ZCK31-32) caused a biomass reduction (60%) of *Alopecurus myosuroides* Huds (Pintar et al. 2021).

It is well-known fact that younger weeds are more sensitive to herbicides than those in more advanced stages (Kudsk 2017). However, this phenomenon depends on many factors, such as weed growth rate, type of weeds, herbicides, and environmental conditions. Pinoxaden causes inhibition of ACCase enzyme and results in chlorosis of leaves within a week after application followed by necrosis and death of rapidly growing meristematic tissue. Pinoxaden kills the susceptible plants (*Avena* spp., *Phalaris* spp., *Lolium* spp., etc.) completely within two to three weeks after application (Hofer 2006; Bitarafan and Andreasen 2020; Anonymous 2022).

Weed control strategies that prevent flowering and reduce the seed production potential of weeds may help in reducing the soil weed seed bank and enable fewer weed problems in the future. *Avena ludoviciana* plants have high seed-shattering ability (Mahajan and Chauhan 2021a), therefore, late application of pinoxaden may provide effective control of early and late cohorts before producing seeds. The current study also suggested that the no-till system helps in reducing weed seeds per unit area. A previous study revealed that *A. ludoviciana* seeds decayed fast on the soil surface and its emergence was lower on the soil surface (Mahajan and Chauhan 2021b). This could be the reason for reduced weed infestation in no-till plots compared with the conventional tilled plots, and ultimately lower weed seed production per unit area. Several studies reported a faster decline in the seed bank of *Avena* spp. in no-till compared with the conventional till system (McGillion and Storrie 2006; Nugent et al. 1999; Osten et al. 2007). It was postulated that the germination of *Avena* spp. was promoted with tillage operations (Chancellor 1976).

Conclusions

An increased seeding rate of wheat under weedy situations helped in reducing *A. ludoviciana* biomass and weed seed production, which resulted in a significant improvement in the yield. This information could be useful in the organic production of wheat. Wheat yield under no-till and conventional tilled systems remained similar; however, the no-till production system helped in reducing weed seed production. This information suggests that the no-till system had an added advantage of weed control. The application of pinoxaden at the Z33 stage (third node formation) helped in controlling early and late cohorts of *A. ludoviciana* without compromising the grain yield.

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Conflict of interest G. Mahajan and B.S. Chauhan declare that they have no competing interests.

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