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Interference of wild oat (*Avena fatua*) and sterile oat (*Avena sterilis* ssp. *ludoviciana*) in wheat

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Abstract

Prevalence of wild oat (*Avena fatua* L.) and sterile oat [*Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet & Magne; referred to as *A. sterilis* hereafter], winter-season weeds, is increasing in the eastern grain region of Australia. Biological attributes of these weeds enable them to survive in a wide range of environments and under different weed infestation levels. The interference of *A. fatua* and *A. sterilis* in a wheat (*Triticum aestivum* L.) crop was examined in southeast Queensland, Australia, through field studies in 2019 and 2020. Different infestation levels (0, 3, 6, 12, 24, and 48 plants m^{-2}) of *A. fatua* and *A. sterilis* were evaluated for their potential to cause yield losses in wheat. Based on a three-parameter logarithmic model, the *A. fatua* and *A. sterilis* infestation levels corresponding to 50% wheat yield loss were 15 and 16 plants m^{-2}, respectively. The yield reduction was due to a reduced spike number per unit area because of an increased weed infestation level. At the highest weed infestation level (48 plants m^{-2}), *A. fatua* and *A. sterilis* produced a maximum of 4,800 and 3,970 seeds m^{-2}, respectively. *Avena fatua* exhibited lower seed retention (17% to 39%) than *A. sterilis* (64% to 80%) at wheat harvest, as most of the seeds of *A. fatua* had shattered at crop maturity. Our results implied that there is a good opportunity for harvest weed seed control if the paddock is infested with *A. sterilis*. This study suggests that in the absence of an integrated weed management strategy (using both chemical and nonchemical options), a high infestation of these weeds could cause a severe crop yield loss, increase weed seed production, and replenish the weed seedbank in the soil.

Introduction

Wild oat (weedy *Avena* spp.) is a troublesome winter-season weed having wide distribution across 55 countries and causing an enormous yield loss in more than 20 crop species (Holm et al. 1977; Sharma and Vanden Born 1983). In Australia, three species, namely wild oat (*Avena fatua* L.), sterile oat [*Avena sterilis* ssp. *ludoviciana* (Durieu) Gillet & Magne; referred to as *A. sterilis* hereafter], and slender oat (*Avena barbata* Pott ex Link) occur. These three species altogether caused an annual revenue loss of A$28 million to Australian agriculture in terms of loss of crop yield and cost of control (Llewellyn et al. 2016). *Avena fatua* and *A. sterilis* are quite common in the cropping regions of Australia (Cousens 2002; Fernandez-Quintanilla et al. 1990; Storrie 2019). *Avena fatua* is mostly dominant in southern Australia; however, *A. sterilis* is mostly dominant in northern New South Wales and southern Queensland (Nugent et al. 1999). In the eastern region (Queensland and New South Wales) of Australia, wild oat (*Avena* spp.) holds the top ranking in the regional ranking of residual winter weeds in all crops when assessed in terms of infested area (Llewellyn et al. 2016).

Avena fatua and *A. sterilis* have prolific seed production (Storrie 2007, 2019). A recent field study conducted by Mahajan and Chauhan (2021a) in Australia showed that *A. sterilis* could produce around 2,500 seeds $plant^{-1}$ under a lack of competition when it emerged at the start of the winter season (May). However, plants that emerged in July were shorter than plants that emerged in May and yielded fewer seeds. In another pot study under well-watered conditions, *A. fatua* produced a higher seed number (480 seeds $plant^{-1}$) than *A. sterilis* (417 seeds $plant^{-1}$) (Sahil et al. 2020). These studies suggest that *A. fatua* and *A. sterilis* have different seed production potential and that seed production may vary with environmental conditions. There are no reports showing seed production of *A. fatua* and *A. sterilis* when they are grown in competition with wheat (*Triticum aestivum* L.) at different infestation levels.

A herbicide-resistance study on *Avena* spp. in Australia revealed that populations that have experienced repeated use of acetolactate synthase–inhibiting herbicides over the last 15 yr have a high risk for evolving resistance to these herbicides (Storrie 2007, 2019). In such a scenario, a better understanding of weeds, competitiveness, and interference in crops could provide important information for strengthening integrated weed management (IWM) strategies (Lemerle et al. 2014; Reiss et al. 2018).

Avena fatua and *A. sterilis* infestation may cause yield reductions (30% to 80%) in winter crops such as wheat, oat (*Avena sativa* L.), barley (*Hordeum vulgare* L.), rye (*Secale cereale* L.), pea (*Pisum sativum* L.), and canola (*Brassica napus* L.) (Beckie et al. 2012; Daugovish et al. 2002; Dew and Keys 1976; Torner et al. 1991; Walia et al. 2001). The magnitude of yield loss in these crops depends on the weed and crop density, species, and environmental conditions. Weeds vary in their potential to compete with crops (Korres et al. 2019; Soltani et al. 2018). A previous study in Australia showed that wild oat caused a 78% yield reduction in a wheat crop (Martin et al. 1987). This study was mainly focused on the prediction of wheat yield loss in response to *A. fatua* competition, and the weed seed production components were not evaluated.

Crop maturity time and seed production of weeds may vary under competition conditions at different weed densities and weather or environmental conditions. Such information may provide an opportunity for harvest weed seed control and timely weed management (Mahajan et al. 2020; Walsh and Powles 2014; Walsh et al. 2018). The quantity of weed seed production, maturity, and seed-shattering time of weeds in relation to the crop are major determinants affecting the success of harvest weed seed control such as row burning, the Harrington Seed Destructor, bale-direct systems, and other means of targeting the chaff during harvest (Schwartz et al. 2016; Walsh et al. 2012, 2013). The performance of the Harrington Seed Destructor can vary with weed species and with the maturity time (Walsh et al. 2012). For example, in a wheat crop, more than 90% control was observed with the Harrington Seed Destructor for rigid ryegrass (*Lolium rigidum* Gaudin) due to high seed retention, while less than 50% control was observed for common lambsquarters (*Chenopodium album* L.) due to poor seed retention (Walsh et al. 2012, 2013).

Information on seed-retention behavior of *A. fatua* and *A. sterilis* is very important when they compete with wheat, as seeds of *A. sterilis* shatter in pairs at plant maturity, while seeds of *A. fatua* shatter individually (Sahil et al. 2020). The shattering behavior of these weed species may cause their reinfestation and impose competition to the crop in the next season. In the eastern region of Australia, knowledge gaps exist concerning the effect of interference levels on wheat grain yield, weed seed production, and weed seed retention at crop maturity. Therefore, a study was carried out in the winter seasons of 2019 and 2020 to evaluate the seed production, seed retention, and interference of *A. fatua* and *A. sterilis* in wheat.

Materials and Methods

Experimental Site and Treatments

Field experiments were conducted in 2019 and 2020 (from May to October) at the Research Farm of the University of Queensland, Gatton (27.5514°S, 152.3428°E), Australia. The study was conducted in two separate fields for *A. fatua* and *A. sterilis*, with six plant density levels (0, 3, 6, 12, 24, and 48 plants m^{-2}) in wheat crops. All treatments were tested in a randomized complete block design, replicated three times. The soil type of the experimental site was clay with pH 7.1 and organic matter content of 1.12% (up to 10-cm depth). The field was cultivated twice before wheat planting using a rotary cultivator. The wheat cultivar 'Spitfire' was planted at 35-cm row spacing with a seeding rate of 100 kg ha^{-1}. The crop was sown on May 8, 2019, and May 7, 2020.

Planting of wheat was done using a cone planter, and seeds were sown at a soil depth of 5 cm. The size of the individual plot was 1.4 by 1.0 m. Seeds of *A. fatua* and *A. sterilis*, as per respective infestation levels, were sown manually in each plot at a 5-cm depth immediately after wheat planting. Weed seeds were planted randomly in between wheat rows. Plots were surface irrigated immediately after sowing using an overhead sprinkler system. All plots were fertilized with urea at a dose of 92 kg N ha^{-1}.

Seeds of *A. fatua* and *A. sterilis* used in this study were originally collected from Warialda (29.395°S, 50.620°E), NSW, with the permission of the property owner in October 2017, and multiplied in the field at the Research Farm of the University of Queensland, Gatton, in the winter season of 2018. Seeds were collected from 50 to 60 matured plants and stored in the laboratory at room temperature until used in the experiment. Seeds were 100% viable at the start of the experiment. For the viability test, 15 d before the start of the experiment, 20 seeds of *A. fatua* and *A. sterilis* were sown in pots replicated three times. All seeds germinated within 10 d of sowing.

Measurements and Data Collection

Seed production and biomass of *A. fatua* and *A. sterilis* were assessed at the wheat harvest. To estimate seed production of *A. fatua* and *A. sterilis*, seeds of all panicles from 1 m^2 (center of the plot) were counted. Shattered seeds of *A. fatua* and *A. sterilis* were determined by counting empty florets on each panicle from 1 m^2. Whole-plant samples were collected by cutting all *A. fatua* and *A. sterilis* plants at the ground level in each plot (1 m^2). Then, each plant sample was oven-dried at 70 C for 72 h and weighed to determine weed dry matter.

At crop harvest, five wheat plants were selected randomly from each plot for height measurements and then averaged. Height was measured from the base of the plant to the tip of the plant. The number of wheat spikes per square meter was determined by counting the number of wheat spikes in a 1-m length of two center rows in each plot. Wheat grains per spike at crop maturity were recorded from five randomly selected plants from each plot. A 1,000-grain weight was obtained after threshing from a random sample of the bulk produce of each plot. The wheat crop was harvested manually, and grain yield was recorded from a harvested area of 1 m^2 per plot. Grain yield was converted to kilograms per hectare and then adjusted to 12% moisture content.

Statistical Analyses

The 2-yr data were subjected to ANOVA using the software Elementary Designs Application (1.0 Beta; www.agristudy.com, published by Free Software Foundation; verified with Genstat 16th ed.; VSN International, Hemel Hempstead, UK) (see Supplementary Tables 1 and 2). No significant interaction was found between year and weed infestation level. Therefore, data were pooled across years. Treatment means were separated using Fischer's protected LSD at the 5% level of significance. Before ANOVA, data were also validated for meeting the assumptions of normality. A three-parameter logarithm regression model was fit (as it was the best fit) to weed infestation level/weed biomass and weed seed production/wheat yield reduction (%) data (SigmaPlot v. 14.0, Systat Software, San Jose, CA, USA):

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Table 1. Effect of *Avena fatua* infestation levels on the weed and yield parameters in wheat.

A. fatua infestation level	Weed panicles	Weed biomass	Weed seed retention	Wheat spike	Wheat grains per spike	1,000-wheat grain weight	Wheat yield
plants m^{-2}	no. m^{-2}	g m^{-2}	%	no. m^{-2}	no. spike^{-1}	g	kg ha^{-1}
0	—	—	—	417	36	40.4	6,600
3	9	54.3	38	411	35	39.0	6,000
6	14	122.7	38	323	32	38.7	4,100
12	38	230.5	39	293	31	37.5	3,400
24	57	320.7	27	240	30	35.9	2,400
48	76	367.8	17	174	28	34.7	1,600
LSD (0.05)	25	73.3	15	72	3.4	2.7	1,200

$$y = y_0 + a^* ln(x - x_0) \qquad [1]$$

where y is the wheat yield reduction/weed seed production, x is weed infestation/weed biomass level, y_0 is maximum crop yield, and a is a constant.

Results and Discussion

Wheat and weeds emerged 8 d after seeding in both years. *Avena fatua* and *A. sterilis* flowered 97 and 99 d after seeding in 2019 and 2020, respectively. The crop reached the final maturity stage at 132 and 135 d after seeding in 2019 and 2020, respectively.

Avena fatua Interference in Wheat

Avena fatua panicles per square meter increased from 9 to 57, with an increase in the infestation level from 3 to 24 plants m^{-2}, respectively (Table 1). A similar trend was observed for biomass and seed production of *A. fatua* (Table 1). *Avena fatua* biomass reached 54 and 321 g m^{-2} at densities of 3 and 24 plants m^{-2}, respectively. *Avena fatua* seed production reached 706 and 4,079 seeds m^{-2} at densities of 3 and 24 plants m^{-2}, respectively. *Avena fatua* panicles, biomass, and seed production per square meter remained similar at infestation levels of 24 and 48 plants m^{-2}. Seed retention of *A. fatua* varied from 17% to 38%, depending on the infestation level; it was the highest at the 3 plants m^{-2} infestation and lowest at 48 plants m^{-2}.

In the weed-free environment, wheat plants produced 417 spikes m^{-2}, which decreased by 22% and 42% at *A. fatua* infestation levels of 6 and 24 plants m^{-2}, respectively (Table 1). Wheat grain number per spike in the weed-free environment was 36, which decreased by 11% and 22% at *A. fatua* infestation levels of 6 and 48 plants m^{-2}, respectively (Table 1). The 1,000-grain weight of wheat in the weed-free environment was 40 g, which decreased by7% and 14% at *A. fatua* infestation levels of 12 and 48 plants m^{-2}, respectively (Table 1). Likewise, a reduction trend similar to that of spikes per square meter was observed for grain yield. Grain yield in the weed-free environment was 6,600 kg ha^{-1}, and it was reduced by 38% and 63% at weed infestation levels of 6 and 24 plants m^{-2}, respectively (Table 1). Grain yield and spikes per square meter of wheat remained similar at *A. fatua* infestation levels of 24 and 48 plants m^{-2}.

Avena sterilis Interference in Wheat

Avena sterilis panicles per square meter increased from 13 to 80 as the infestation level increased from 3 to 48 plants m^{-2} (Table 2). *Avena sterilis* biomass reached 83 and 302 g m^{-2} at densities of 3 and 24 plants m^{-2}, respectively. *Avena sterilis* seed production reached 766 and 3,967 seeds m^{-2} at densities of 3 and 24 plants m^{-2}, respectively. (Table 2). *Avena sterilis* biomass remained similar at infestation levels of 24 and 48 plants m^{-2}. Seed retention of *A. sterilis* varied from 64% to 80%, depending on the infestation level; the lowest was at 3 plants m^{-2} and the highest at 48 plants m^{-2}.

Wheat height was not influenced by *A. sterilis* infestation levels (Table 2). In the weed-free plots, wheat plants produced 398 spikes m^{-2}, which were decreased by 27% and 48% at infestation levels of 6 and 24 plants m^{-2}, respectively (Table 2). A similar trend was observed for grain yield. Grain yield in a weed-free environment was 5,600 kg ha^{-1}, and it was reduced by 36% and 60% at *A. sterilis* infestation levels of 6 and 24 plants m^{-2}, respectively. Grain yield and spikes per square meter of wheat remained similar at *A. sterilis* infestation levels of 24 and 48 plants m^{-2} (Table 2). Wheat grain numbers per spike were not influenced by *A. sterilis* infestation levels. However, the 1,000-grain weight of wheat was 40 g in the weed-free environment, reduced by 7% and 21% at *A. sterilis* infestation levels of 6 and 48 plants m^{-2} (Table 2).

This study reports the interference of *A. fatua* and *A. sterilis* in wheat at various infestation levels. Results revealed that both *A. fatua* and *A. sterilis* behaved similarly for yield reduction in wheat (Figure 1). Grain yield of the weed-free plot in the *A. sterilis* experiment was lower than in the *A. fatua* experiment, due to site difference. Based on the three-parameter logarithmic model, *A. fatua* and *A. sterilis* densities corresponding to 50% yield reduction were 15 and 16 plants m^{-2}, respectively (Figure 1). *Avena fatua* and *A. sterilis* caused yield reductions of 75% and 71%, respectively, at the infestation level of 48 plants m^{-2}. The yield reduction in wheat was primarily due to a lower number of spikes per unit area and reduced 1,000-grain weight because of weed–crop competition. This suggests that early competition of *A. fatua* and *A. sterilis* reduced wheat spikes per unit area and late competition reduced the 1,000-grain weight.

Based on the logarithmic model, *A. fatua* and *A. sterilis* biomass values corresponding to the 50% yield reduction were 221 and 237 g m^{-2}, respectively (Figure 2). The logarithmic model also indicated that *A. fatua* and *A. sterilis* produced 3,671 and 3,021 seeds m^{-2} at the weed infestation level of 24 plants m^{-2}, and seed production of *A. fatua* and *A. sterilis* further increased to 5,065 and 3,938 seeds m^{-2}, respectively, at the 48 plants m^{-2} density (Figure 1). The high level of seed production of *A. fatua* and *A. sterilis* enhances their adaptive potential to become dominant weeds. This study revealed that seed retention was higher in *A. sterilis* (64% to 80%) than *A. fatua* (17% to 38%), suggesting a better opportunity for harvest weed seed control for managing

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Table 2. Effect of *Avena sterilis* infestation levels on the weed and yield parameters in wheat.

A. sterilis infestation level	Weed panicles	Weed biomass	Weed seed retention	Wheat spike	Wheat grains per spike	1,000-wheat grain weight	Wheat yield
plants m^{-2}	no. m^{-2}	g m^{-2}	%	no. m^{-2}	no. spike^{-1}	g	kg ha^{-1}
0	—	—	—	398	34	39.7	5,600
3	13	83.3	80	386	33	36.7	4,800
6	21	117.8	75	291	34	36.7	3,500
12	44	220.2	72	276	34	35.0	3,000
24	55	302.0	67	207	31	34.3	2,200
48	80	376.7	64	174	32	31.4	1,600
LSD (0.05)	14	82.0	9	70	NS[a]	2.5	900

[a]NS, nonsignificant.

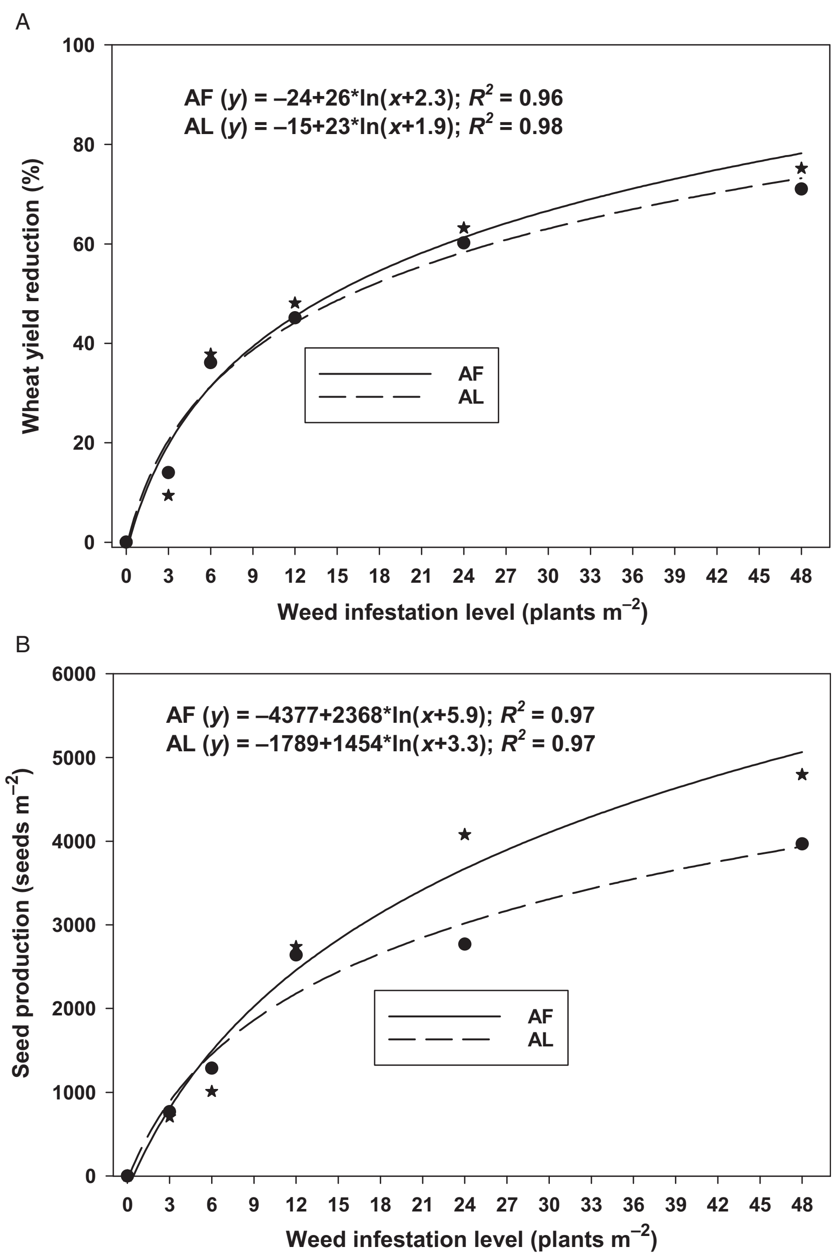

Figure 1. (A) Wheat yield reduction (%) and (B) weed seed production as influenced by weed infestation level. AF, *Avena fatua*; AL, *Avena sterilis*. Lines represent a three-parameter logarithm regression model.

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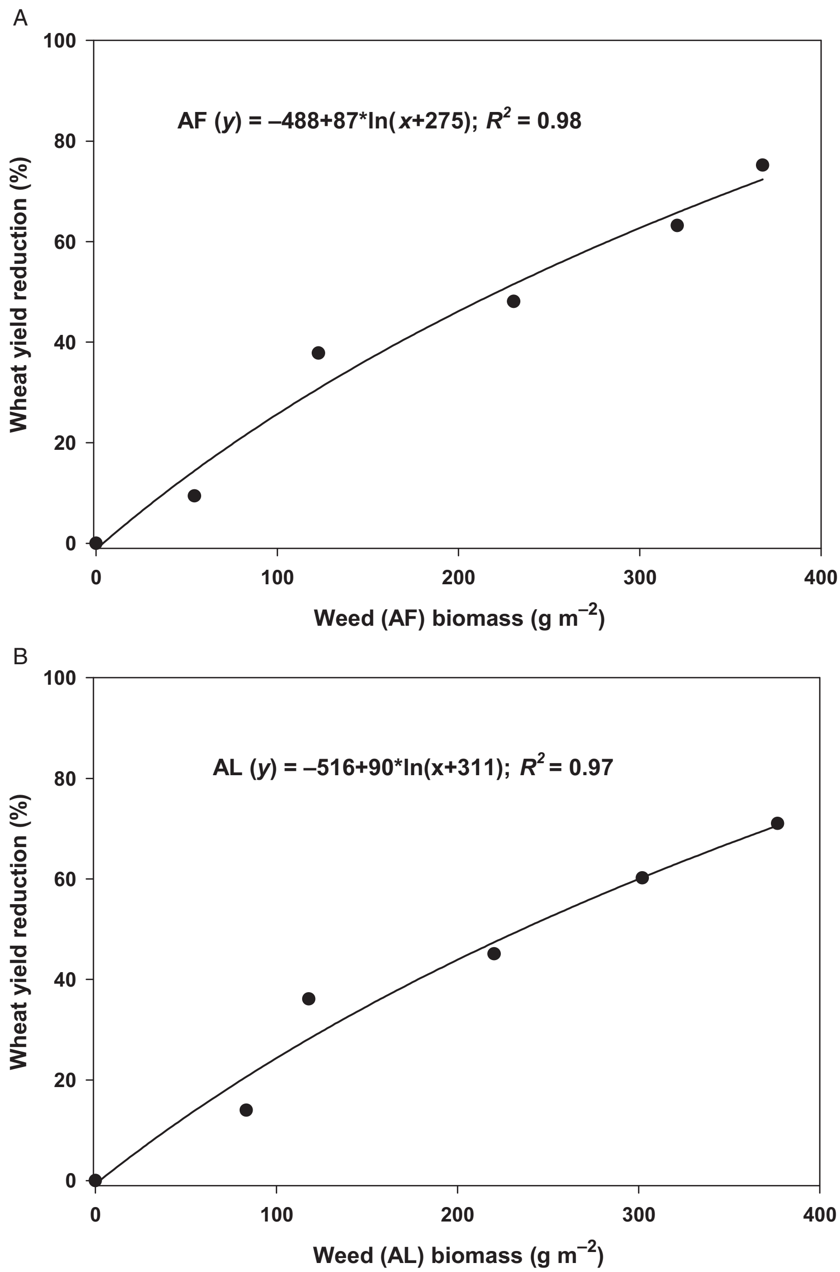

Figure 2. Relationship of wheat yield reduction (%) and weed biomass. (A) *Avena fatua* (AF) and (B) *Avena sterilis* (AL). Lines represent a three-parameter logarithm regression model.

A. sterilis. Further, lower seed retention of *A. fatua* and *A. sterilis* at 48 and 24 plants m^{-2}, respectively, suggests that a very high infestation level of *A. fatua* and *A. sterilis* in the wheat field could change the impact of seed destruction, as the high density of weeds increased their seed-shattering tendency.

Weeds compete with crop plants for growth resources; therefore, the reduction in grain yield of wheat due to infestation of *A. fatua* and *A. sterilis* is logical. Overall, our results are in close conformity with previous weed interference studies, which revealed that with the increasing density of *A. fatua* and *A. sterilis*, the grain yield of wheat was decreased (Balyan et al. 1991; Martin et al. 1987; Walia and Brar 2001).

Previous studies suggested that biological attributes of *A. fatua* and *A. sterilis* enabled these weeds to survive harsh conditions, which aided in the successful completion of life cycles in a wide range of environments and water-stress conditions (Mahajan and Chauhan 2021a; Sahil et al. 2020). These studies also suggested that *A. fatua* and *A. sterilis* tend to produce enough seeds to replenish the soil seedbank, leading to their persistence in the agroecosystems. In another study in Australia, it was found that *A. fatua* and *A. sterilis* tend to produce multiple cohorts under a wide range of climatic conditions (Mahajan and Chauhan 2021b). These studies suggest *A. fatua* and *A. sterilis* can infest a wheat crop at varied planting times and cause substantial yield losses in wheat if not managed in a timely way. Sole reliance on chemical weed control may not provide effective control of *A. fatua* and *A. sterilis* due to their evolution of herbicide resistance against a large number of herbicides in Australia (Storrie 2007, 2019). Therefore, IWM

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approaches involving cultural weed control methods, such as improved crop competition, harvest weed seed control tactics, and judicious herbicide use could provide better control of *A. fatua* and *A. sterilis*.

The present study revealed that there is a great opportunity for harvest weed seed control for *A. sterilis*, as its seed retention at crop maturity is very high. Our results also demonstrated that high infestation levels of *A. fatua* and *A. sterilis* in a wheat field could change the impact of seed destruction, as the shattering tendency of weeds increased at high weed pressure. In another study, seed longevity of *A. fatua* and *A. sterilis* was found to be less than 12 mo for the surface seeds (Mahajan and Chauhan 2021b). These results suggest that in no-till production systems in Australia, effective control of *A. sterilis* can be achieved by adopting harvest weed seed control tactics in an IWM program. As these tactics (harvest weed seed control in IWM) could restrict seed replenishment in the soil, the remaining seedbank on the surface could decay within a year as the seed persistence of *A. sterilis* on the surface is short. However, in paddocks where *A. fatua* is dominant, or where mixed populations of *A. fatua* and *A. sterilis* occur, an attempt at early control of these species should be made with suitable PRE and POST herbicides to restrict yield loss in wheat. Delayed crop sowing, pre- and post-sowing tillage, summer fallowing, closer row spacing, and exploring weed-competitive cultivars that help in early canopy closure are valuable cultural strategies that can be combined with PRE and POST herbicides for early control of *A. fatua* and *A. sterilis* in the field (Brown 1953; Harker et al. 2016).

Various studies reported that the use of integrated approaches reduced biomass of *A. fatua* and *A. sterilis* by up to 90%, even when the populations were herbicide resistant (Anderson 2003; Beckie 2006; Blackshaw et al. 2008; Harker et al. 2009). Similarly, our results suggest that the adoption of a suitable integrated management program, including harvest weed seed control, could be the key to the successful management of *A. fatua* and *A. sterilis*. Our results demonstrated that the lowest weed density (i.e., 3 plants m^{-2}) did not cause a significant yield loss in wheat, but this infestation level produced sufficient seeds for reinfestation if not controlled. Therefore, an attempt should be made to completely control *A. fatua* and *A. sterilis* in the field.

In conclusion, this study revealed that *A. fatua* and *A. sterilis* infestation levels corresponding to 50% wheat yield loss were 15 and 16 plants m^{-2}, respectively. Further, our study suggests that more data are needed to relate yield loss parameters to genetic or environmental variables. Carlson and Hill (1985) suggested that the competitive ability of *Avena* spp. may vary with different wheat cultivars, fertilizer management, moisture regimes, and variation in *Avena* species and biotypes. Tillering capacity of wheat cultivars and relative time of emergence of *Avena* spp. and wheat may also influence the competitive ability of *Avena* spp. and wheat. In the eastern grain region of Australia, the major factors limiting weed-free wheat yields, like available soil water, nitrates, and delayed sowing, may affect the extent of competition between the crop and weed. Therefore, further research is needed to explore the potential of these practices under a wide range of environmental conditions and variables.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2021.25

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