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Interference of annual sowthistle (*Sonchus oleraceus*) in wheat

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Research Article

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Abstract

Annual sowthistle (*Sonchus oleraceus* L.) is a broadleaf weed that is increasing in prevalence in the northern cropping regions of Australia. Being a member of Asteraceae family, this weed possesses many biological attributes needed to thrive in varying environments and under differing weed management pressures. Interference of this weed in a wheat (*Triticum aestivum* L.) crop was examined through field studies in 2016 and 2017. Different densities of *S. oleraceus* were evaluated for their potential to cause yield loss in wheat: 0.0 (weed-free), low (9 to 15 plants m^{-2}), medium (29 to 38 plants m^{-2}), and high (62 to 63 plants m^{-2}). Based on the exponential decay model, 43 and 52 plants m^{-2} caused a yield reduction of 50% in 2016 and 2017, respectively. Yield components such as panicles per square meter and grains per panicle were affected by weed density. At the high weed infestation level, *S. oleraceus* produced a maximum of 182,940 and 192,657 seeds m^{-2} in 2016 and 2017, respectively. *Sonchus oleraceus* exhibited poor seed retention at harvest, as more than 95% of seeds were blown away by wind. Adverse effects on crop, high seed production, and wind-blown dispersal may lead to an increased prevalence of this weed in the absence of an integrated weed management strategy utilizing both herbicides and nonchemical options.

Introduction

Annual sowthistle (*Sonchus oleraceus* L.) is an emerging weed of global importance that is increasingly prevalent in the Australian cropping regions (Chauhan et al. 2006; Gomaa et al. 2014; Hassan et al. 2014; Manalil et al. 2017; Osten et al. 2007). Abundant seed production, small seed size, and wind dispersal of seeds are some of the features that are contributing to the invasive success of this weed (Chauhan et al. 2006; Widderick et al. 2010). Studies on germination ecology indicated the potential of *S. oleraceus* to germinate under a broad range of temperature conditions and varying environmental conditions, including pH, salinity, and water stress (Chauhan et al. 2006; Manalil et al. 2017). This weed was once considered to be only a winter weed, as it was mostly confined to the winter season, but currently it is present in summer, winter, and fallow phases of cropping due to its potential to emerge under a broad range of temperature conditions (Manalil et al. 2017; Werth et al. 2013; Widderick et al. 2010). Among the three agroecological grain-cropping regions of Australia, the western region (Western Australia) and the southern region (Victoria, Tasmania, and South Australia) are characterized by a Mediterranean-type climate with winter-dominant rains and cropping mostly confined to the winter season. Conversely, the northern region (New South Wales and Queensland) is characterized by well-distributed rainfall and intensive cropping during both the summer and winter seasons, providing enough opportunities for this weed to proliferate in the region (GRDC 2018). When present in fallow phases without competition from a crop, this weed could deplete substantial soil moisture (GRDC 2009). Interference studies in different agroecosystems indicate substantial yield loss due to *S. oleraceus* in crops (Hassan et al. 2014; Song et al. 2017). Suppression of other plants could be due to the depletion of resources and the allelopathic properties of this weed (Gomaa et al. 2014; Peerzada et al. 2019). Although *S. oleraceus* is quite prevalent in South Australia, Queensland, and New South Wales, specific studies on weed interference in crops are lacking (Manalil et al. 2017; Osten et al. 2007; Werth et al. 2013). Various surveys indicate an increase in prevalence of this weed in the grain crops and cotton (*Gossypium hirsutum* L.) production regions of Australia (Manalil et al. 2017; Osten et al. 2007; Werth et al. 2013).

Sochus oleraceus can thrive well under moisture-limiting conditions and under a wide range of pH, saline, and nutrient-deficient environments (Chauhan et al. 2006; Manalil et al. 2018; Widderick et al. 2010). This weed can germinate under a wide range of temperature conditions and can grow up to an altitude of around 2,500 m, indicating the potential to emerge and survive under cooler environments (Peerzada et al. 2019). Although *S. oleraceus* is categorized as a meso-xerophytic plant, it will flourish in moist fertile soils under noncompetitive fallow by using residual soil nutrients and soil moisture (Peerzada et al. 2019). The increase in the occurrence of this weed has been particularly noted in cropping systems that use conservation tillage and glyphosate-tolerant crops (Manalil et al. 2017; Peerzada et al. 2019; Werth et al. 2013). Germination ecology studies indicate low germination of this weed in darkness compared with illuminated conditions, indicating the likelihood of limited establishment in shaded environments or under residue cover (Chauhan et al. 2006; Manalil et al. 2018; Widderick et al. 2010). Additionally, germination was quite high at the soil surface, and no germination was observed at 6-cm depth (Manalil et al. 2018; Widderick et al. 2010). Despite the documentation of increased occurrence of *S. oleraceus* in the northern grain region of Australia, no specific study has explored the interference pattern of this weed.

Evolution of herbicide resistance necessitates the inclusion of all possible nonchemical strategies for weed management (Chauhan et al. 2015; Owen et al. 2015; Preston et al. 2009; Riar et al. 2013). Surveys of glyphosate-tolerant cotton systems in Australia indicate a rapid progression of *S. oleraceus* as a major broadleaf weed and point to either a natural tolerance or resistance to glyphosate (Manalil et al. 2017; Werth et al. 2013). Adkins et al. (1997) observed chlorsulfuron-resistant populations of *S. oleraceus* in the 1990s. In Australia, Cook et al. (2014) observed glyphosate-tolerant populations of *S. oleraceus*, and Boutsalis and Powles (1995) reported resistance to acetolactate synthase–inhibiting herbicides. Werth et al. (2011), in a risk assessment study, included *S. oleraceus* in the "high-risk category" of weeds for its potential to develop resistance to glyphosate based on the biology and current management practices followed in the cotton production region.

There are many instances when major weeds fail to compete with crops and crops may smother weeds in competition, and such information is quite valuable for framing nonchemical weed management strategies (Cholette et al. 2018; Lazzaro et al. 2018; Mwendwa et al. 2018; Reiss et al. 2018). Emergence, growth, flowering, seed production, and seed dispersal in weeds in relation to crop phenological phases offer valuable inputs to frame appropriate weed management strategies (Andersen, 1992; Beckie et al. 2017; Chauhan et al. 2006; Devlaeminck et al. 2005; Hassan et al. 2014). Weeds that mature and disperse seed after crop harvest and have high seed retention during crop harvest provide opportunities for management through seed capturing and destruction during harvest operations, thereby reducing seedbank enrichment (Walsh et al. 2018; Walsh and Powles 2014). Although substantial *S. oleraceus* seeds could be dispersed by wind (Peerzada et al. 2019), a delayed maturity of weed compared with the crop may allow the capture of weed seeds during crop harvest. At present, knowledge gaps exist in regard to the competitiveness and seed set of *S. oleraceus* in winter crops in Australia. Therefore, a study was conducted to explore the pattern of interference of *S. oleraceus* in wheat (*Triticum aestivum* L.).

Materials and Methods

To explore the interference of *S. oleraceus*, field studies were conducted from May to October in 2016 and 2017 at the Research Farm of the University of Queensland (27.543°S, 152.334°E), Gatton, Australia. The soil of the experimental site was a heavy clay with a pH of 7.5 and an organic matter content of 2.7%. The nitrogen, phosphorus, and potassium concentrations of the soil were 62, 87, and 412 kg ha^{-1}, respectively. The long-term average rainfall of the site was 772 mm. In 2016, there was 562 mm of rainfall, of which 202 mm was during the crop-growing months of the winter season (May to September 2016). Only 82 mm of rainfall was received during the winter growing season in 2017, although annual rainfall was 797 mm (Figure 1).

The field was cultivated two to three times using a rotory cultivator to ensure a stale seed bed at the time of planting. Wheat ('Spitfire', Pacific Seeds, Toowoomba, Australia) was seeded at 60 kg ha^{-1} with an 18-cm row spacing using a hoe drill (John Deere, Moline, IL, USA). *Sonchus oleraceus* seeds were collected from a wheat field in Queensland (27.559°S, 152.324°E) and were established at four densities. The targeted densities were weed-free (0 plants m^{-2}), low (10 to 20 plants m^{-2}), medium (30 to 40 plants m^{-2}), and high (50 to 70 plants m^{-2}). The trial was established in using a randomized block design with three replications and plots measuring 5.0 m by 2.3 m. After wheat sowing (on the same day), weed seeds were mixed with dry soil and uniformly hand broadcast. Differential weed seeding rates were used based on the laboratory germination data so as to have different initial emergence rates to provide the required weed densities.

Plots were sprinkle irrigated four times on alternate days beginning at seeding to ensure weed and crop emergence and during crop flowering in August (twice). In Australia, wheat is grown both under rainfed and irrigated environments; in this study, irrigation was provided initially (mainly to ensure uniform crop and weed emergence) and during anthesis. Diammonium phosphate at 25 kg N ha^{-1} and 28 kg P ha^{-1} was broadcast before irrigation. The plots were continuously hand weeded to remove all other weeds except the target weeds. Weed density and dry biomass were recorded within a 60 cm by 54 cm quadrat at two locations within each plot at the time of wheat anthesis and again before crop harvest. Wheat panicles were counted within 1-m row length of the crop in two places. Numbers of grains were averaged from 20 randomly picked panicles per plot, and 1,000-grain weight was measured from the harvested sample. Harvesting was carried out with a plot harvester, and grain yield (kg ha^{-1}) was adjusted at 12% moisture content.

Sonchus oleraceus seed production was computed by randomly picking 20 flower heads from each plot that were ready to open. Flower heads were dissected, and seeds were counted using a magnifying glass. Total flower heads (both dispersed and ready to disperse) were counted from the quadrated weed sample coinciding with wheat maturity. Based on this, total seed production and percentage of seed dispersal coinciding with crop maturity were computed. Emergence, flowering, and maturity of wheat and *S. oleraceus* were related to growing degree days base 5 (GDD_5).

$$\text{GDD}_5 = \sum\{[(\text{Maximum daily temperature} + \text{Minimum daily temperature})/2] - 5\} \quad [1]$$

ANOVA was performed to identify differences between treatments (R Development Core Team 2018) on yield attributes. Bartlett's test and a Shapiro–Wilk test were used to evaluate the homoscedasticity and normality assumptions before performing ANOVA. All experiments were carried out twice. Data were analyzed differently for the two field trials, as results were significantly different. Nonlinear regression analysis was performed to explore the relationship between weed density and crop yield, and weed

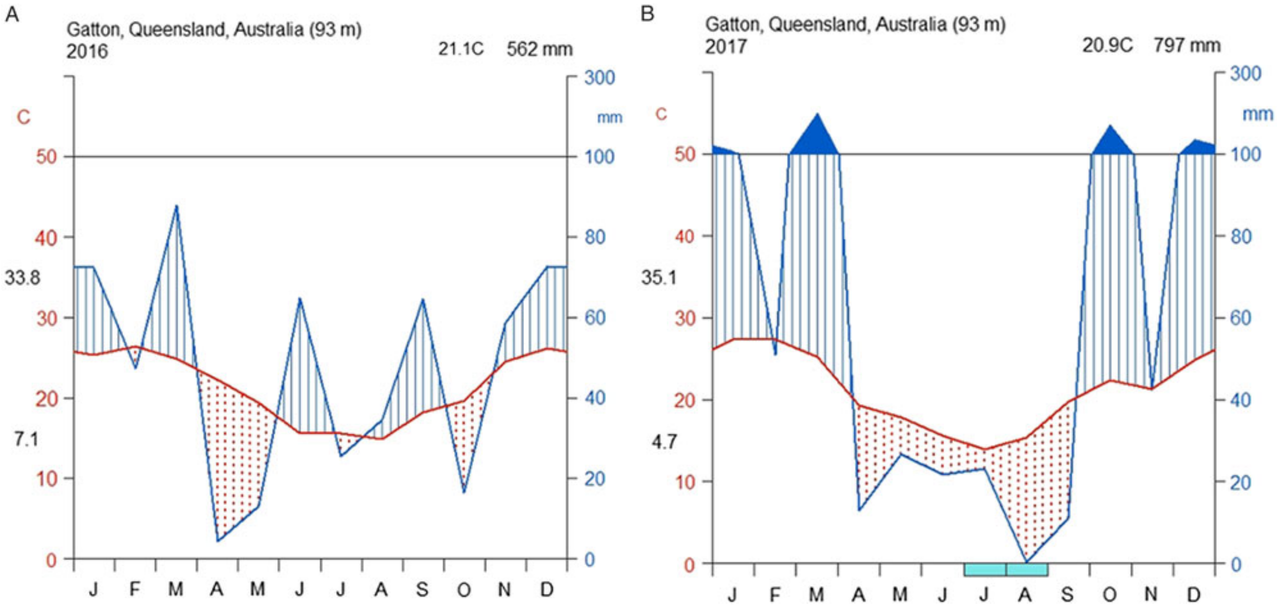

Figure 1. Walter-Lieth climate diagram for Gatton, Queensland, for 2016 (A) and 2017 (B). Mean monthly temperature (C) and precipitation (mm) are shown on the left axis (red) and right axis (blue), respectively. Letters "J" to "D" on *x* axis indicate January to December (experiment was carried out from May to October). Dry and wet months are represented by area speckled in red and blue vertical lines, respectively. Dark blue bars on the *x* axis indicate months with possibility of frost. Top and bottom black numbers on the left axis are the mean maximum temperature of the hottest month and mean minimum temperature of the coldest month, respectively.

density and weed seed production. ANOVA was performed on yield components, including panicles per square meter, grains per panicle, and 1,000-grain weight, and means separation was accomplished using Fisher's LSD ($\alpha = 0.05$).

A Walter-Lieth climate diagram was prepared using the CLIMATOL package (R Development Core Team 2018).

To assess the relationship between weed density and crop yield loss, several commonly used models were compared using the Akaike information criterion (AIC) (Table 1). The model with the lowest AIC was a two parameter modified exponential decay regression model:

$$g = a\left(1 - exp^{(-b*x)}\right) \qquad [2]$$

where g is the crop yield loss (%) to weed density (x), a is the maximum crop yield loss (%), and b is the rate constant (slope of regression) (Archontoulis and Miguez 2015).

Similarly, a four-parameter logistic model was fit to assess the relationship between weed biomass and crop yield loss:

$$\mathrm{g} = \mathrm{a} + \frac{d - a}{1 + \exp\{b[\log(x) - \log(e)]\}} \qquad [3]$$

where g is the crop yield loss (%) to weed biomass (x), e is the magnitude of independent variable producing a response halfway between upper limit d and lower limit a, and b denotes relative slope around e.

A two-parameter hyperbola model was used to explore the relationship between weed density at harvest and weed seed production (Archontoulis and Miguez 2015):

$$g = a * x/(b + x) \qquad [4]$$

where g is weed seed production corresponding to weed density (x), a is the maximum weed seed production as estimated by the model, and b is the rate constant (slope of regression).

Results and Discussion

Wheat emerged at 9 ($GDD_5 = 125$) and 12 ($GDD_5 = 120$) d after seeding in 2016 and 2017, respectively. Emergence of *S. oleraceus* was observed at 8 to 10 d after seeding in both years. *Sonchus oleraceus* flowered at 85 ($GDD_5 = 914$) and 89 ($GDD_5 = 889$) d after seeding in 2016 and 2017, respectively. The crop was mature and ready to harvest at 136 ($GDD_5 = 1{,}523$) and 139 ($GDD_5 = 1{,}647$) d after seeding in 2016 and 2017, respectively.

Wheat yielded 6,720 and 5,711 kg ha^{-1} in the weed-free control plots in 2016 and 2017, respectively (data not shown). Yield decreased exponentially with increasing densities of *S. oleraceus* (Figure 2). There were 55% and 57% reductions in crop yield in the high-density plots in 2016 and 2017, respectively (Figure 2). Based on the regression model, weed densities at anthesis corresponding to a 50% yield reduction were 43 and 52 plants m^{-2} in 2016 and 2017, respectively. The values for weed biomass (dry) corresponding to the 50% yield reduction were 98 and 140 g m^{-2} in 2016 and 2017, respectively (Figure 3). Among yield components, a significant reduction was observed for the number of panicles as a response to increasing weed density ($P < 0.001$); at the high density, there were 47% and 55% reductions for the number of panicles per square meter in 2016 and 2017, respectively. Reductions were also observed for grains per panicle ($P < 0.001$); there were 23% and 27% reductions in 2016 and 2017, respectively, due to maximum weed interference. However, significant differences were not observed for 1,000-grain weight (Table 2).

The trials were conducted using a high seeding rate (60 kg ha^{-1}) and a narrow row spacing (18 cm) to ensure maximum possible

Table 1. Regression models tested and their Akaike information criterion (AIC).[a]

	AIC values of models				
	Crop yield loss due to weed density		Crop yield loss due to weed biomass		
Name of model	2016	2017	2016	2017	References showing model details
	%				
Cousens model	82.81	62.73	80.61	71.01	Cousens 1985
Exponential decay	102.54	99.90	93.14	95.52	Archontoulis and Miguez 2015
Modified exponential decay	81.40*	61.76*	79.58	70.17	Archontoulis and Miguez 2015
Logistic (four parameter)	83.92	77.73	56.91*	55.52*	Ritz and Streibig 2005
Weibull (four parameter)	84.89	78.91	57.26	56.84	Ritz and Streibig 2005
	Weed density and seed production				
	2016		2017		
Hyperbola, single Rectangular (two parameter)	256.7*		246.2*		Archontoulis and Miguez 2015
Logistic (three parameter)	257.0		248.2		Ritz and Streibig 2005
Weibull (four parameter)	257.3		250.5		Ritz and Streibig 2005

[a]Asterisks (*) indicate model with lowest AIC values included in this study.

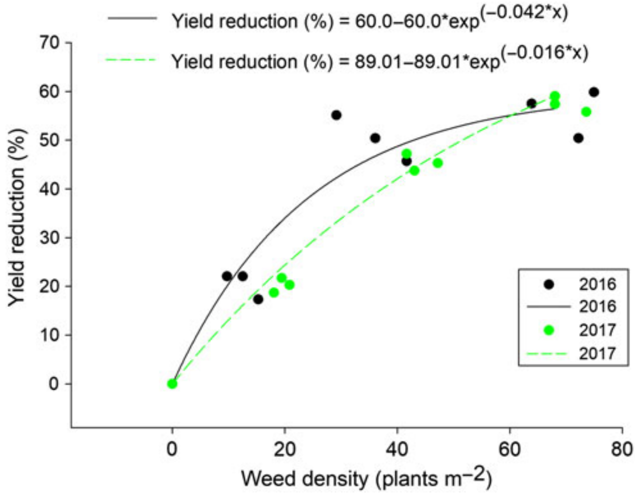

Figure 2. Effect of *Sonchus oleraceus* density on wheat yield in 2016 and 2017. The lines represent a modified exponential decay regression model fit to the data by year, and symbols represent weed density. The selected model had the lowest Akaike information criterion among several commonly used models tested.

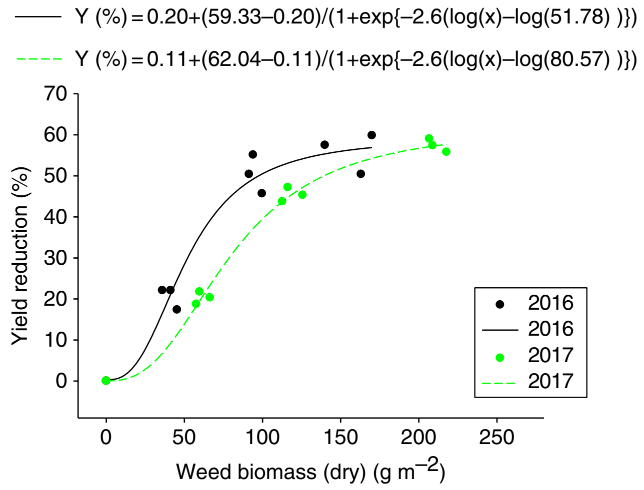

Figure 3. Effect of *Sonchus oleraceus* biomass on wheat yield in 2016 and 2017. The lines represent a four-parameter logistic model fit to the data by year, and symbols represent weed biomass. The selected model had the lowest Akaike information criterion among several commonly used models tested.

interference from wheat, and the trial practices represent those common in the northern region of Australia. Average wheat seedling density was 105 and 108 plants m^{-2} in 2016 and 2017, respectively. In the absence of weed interference, wheat yield exceeded 5,500 kg ha^{-1} in both years, representing a high output for wheat in this region. The lower wheat yield ($P = 0.015$) in 2017 can be attributed to less rainfall received during the crop-growing season in 2017 compared with 2016 (Figure 1). Interference from *S. oleraceus* caused a maximum yield reduction of 55% to 57%. Weeds from the Asteraceae family are highly competitive due to vigorous growth and their potential to exploit available resources (Brant et al. 2012; Hassan et al. 2014; Song et al. 2017). The results clearly indicate a high level of interference by *S. oleraceus* in wheat as a winter weed resulting in a significant wheat yield penalty.

There was a hyperbolic relationship between weed density and seed production (Figure 4). Weed seed production increased as weed density increased, and there was a maximum of 1,82,940 and 1,92,657 seeds m^{-2} in 2016 and 2017, respectively. The amount of seed dispersal that occurred by crop harvest was 97% and 95% in 2016 and 2017, respectively (data not shown). *Sonchus oleraceus* flowered at 85 to 89 d after seeding, and a large proportion of seeds dispersed before harvest. Reproductive success of Asteraceae weeds are attributed to high seed production, seed dispersal by diversified means, and a prolonged reproductive phase (initial flowering to final seed dispersal) (Beckie et al. 2017; Devlaeminck et al. 2005). For many weeds, high seed retention at harvest offers an opportunity to minimize future infestations by destroying the weed seeds through seed capturing. Although rigid ryegrass (*Lolium rigidum* Gaudin) and wild radish (*Raphanus raphanistrum* L.) can produce a substantial amount of seeds, high seed retention at crop harvest gives an opportunity to reduce seedbank enrichment through employing harvest weed seed control (Walsh et al. 2018; Walsh and Powles 2014). This study indicates that seed-capturing techniques may not have similar desired results in reducing the infestation of this rapidly emerging weed in the northern region.

Studies exploring germination ecology of this weed indicated that it has a low level of seed persistence (Widderick et al. 2010). In a study in the northern grain region, only 2% of seeds

Table 2. Changes in wheat yield components due to competition from *Sonchus oleraceus*.[a]

	Panicles produced		Number of grains		1,000-grain weight	
Weed density[b]	2016	2017	2016	2017	2016	2017
	——panicles m^{-2}——		——grains $panicle^{-1}$——		————g————	
Control (0, 0)	315a	295a	44a	45a	47a	45a
Low (9, 15)	255b	244b	42a	43b	47a	45a
Medium (29, 38)	180c	153c	36a	39c	47a	44a
High (62, 63)	168c	133d	34b	32d	47a	44a

[a] Means separation was carried out by Fisher's LSD ($\alpha = 0.05$; $n = 3$); within columns, means followed by different letters indicate significant difference.
[b] Values in parentheses are mean weed densities (plants m^{-2}) in 2016 and 2017.

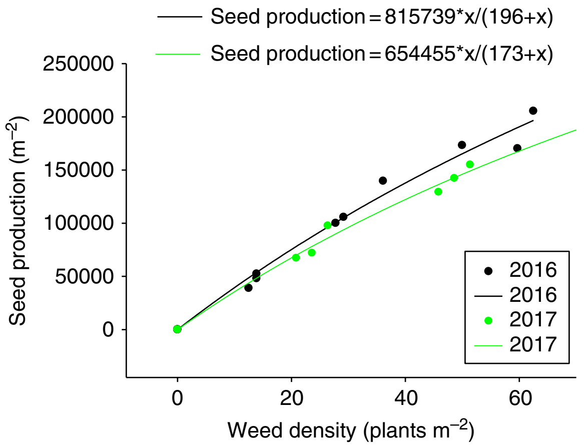

Figure 4. Seed production of *Sonchus oleraceus* in 2016 and 2017. The lines represent a hyperbolic model fit to the data by year, and symbols represent weed density. The selected model had the lowest Akaike information criterion among several commonly used models tested.

were viable at the soil surface after 6 mo, and 12% seeds remained intact at 10-cm depth after 30 mo (Widderick et al. 2010). In addition, poor emergence was observed when seeds were buried more than 2 cm below the soil surface (Chauhan et al. 2006) and when a thick crop residue cover was present (Manalil et al. 2018). Our results indicate that *S. oleraceus* can cause interference in winter wheat that leads to considerable reduction in yield. The majority of weed seeds disperse by harvest, so weed seed capture is not a feasible management option. Integrating tillage or employing residual cover along with POST and residual herbicides may help in containing this weed from further increasing in prevalence.

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