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Russian thistle (*Salsola tragus*) ecology in wheat-cropping systems of the Pacific Northwest

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Abstract

Russian thistle (*Salsola tragus* L.) is a significant summer annual weed in the semiarid Pacific Northwest, causing yield losses of up to 50%. Understanding the biology and ecology of *S. tragus* is vital for developing effective integrated weed management strategies. This study focused on (1) *S. tragus* emergence and seedbank persistence in two cropping systems: fallow–winter wheat (*Triticum aestivum* L.) and spring wheat–fallow–winter wheat rotations, and (2) *S. tragus* plant biomass and viable seed production in fallow and spring wheat fields. A 4-yr experiment (2020 to 2023) was conducted at the Columbia Basin Agriculture Research Center in Adams, OR, using a randomized block design with four replications. *Salsola tragus* seeds were sprinkled only at the beginning of the experiment, and seedling numbers were recorded throughout. Most seedlings emerged in the first year, with the highest rates in spring wheat (72%) and fallow (32%), followed by significantly lower rates (0.25% to 5%) in subsequent years. Seedling emergence began in late March and early April in the first and second years but was delayed to May in the third year. Plant biomass and viable seed production were greater in fallow than in spring wheat, with early-season plants having more biomass than later-emerging plants. Plants emerged between early and mid-May produced the most viable seeds. Viable seed production was very low until it peaked in mid-September. Findings indicated that most *S. tragus* seedlings emerged in the first year after dispersal coinciding with spring precipitation and lasting approximately 2 mo. Additionally, most *S. tragus* plants produce viable seeds in September, and seeds persist in the soil for more than 2 yr. These results demonstrate the need for growers to control *S. tragus* emergence to prevent reinfestations and ultimately the need to control *S. tragus* plants before September to prevent the species from producing viable seed.

Introduction

Russian thistle (*Salsola tragus* L.) is a summer annual weed native to arid regions of southeastern Europe and central Asia. It was introduced in South Dakota in 1837 and has since become widely distributed throughout the arid and semiarid regions of the Pacific Northwest (PNW) (Beckie and Francis 2009). In spring wheat, *S. tragus* can drive yield losses of up to 50% in severe infestations (Young 1988). Furthermore, *S. tragus* can regrow after harvest in August and September, leading to future yield losses by using up to 100 L of soil water and producing an average of 46,000 seeds per plant (Schillinger and Young 2000).

Growers in the PNW have overwhelmingly adopted minimal or no-till systems to reduce soil erosion and increase soil water content during fall and winter precipitation periods (Williams et al. 2014). Growers rely on pre- and postemergence herbicides, such as 2,4-D, bromoxynil, carfentrazone, dicamba, flumioxazin, glufosinate, metribuzin, paraquat, saflufenacil, and sulfentrazone, as the primary method to manage *S. tragus* (Kumar et al. 2017; Lutcher 2015; Lyon et al. 2021), but particularly on glyphosate to control *S. tragus* in fallow and/or postharvest. This reliance on herbicides has selected for herbicide-resistant *S. tragus* biotypes that are resistant to acetolactate synthase inhibitors (Heap 2023) and glyphosate (Barroso et al. 2018; Kumar et al. 2017). The escalating prevalence of herbicide-resistant *S. tragus* is diminishing herbicide efficacy in the region and intensifying weed pressure. Consequently, growers are considering a return to traditional tillage as an option to manage this species.

The concept of integrated weed management (IWM) is a holistic strategy that combines various weed control techniques. When applied systematically, this integrated approach achieves more effective weed control than any single method alone (Swanton and Weise 1991). Understanding the biology and ecology of problematic weeds, such as *S. tragus*, in a region is crucial to implementing a successful IWM program (Harker and O'Donovan 2013).

For instance, understanding population dynamics, emergence patterns, competitive ability, fecundity, dispersal mechanisms, and seedbank persistence will ensure that management plans focus on the most sensitive life stages of target weeds to achieve the greatest long-term efficacy.

The ecology of a weed growing with or without crop (or depending on the crop type) can differ, not only because of the direct competitive interactions for light, nutrients, and water (Patterson 1995), but also the indirect noncompetitive interactions related to changes in temperature, humidity, or light (Roach and Wulf 1987). Therefore, the environment in which *S. tragus* seeds are found may impact germination, plant development, seed production, and seed viability. This study aimed to characterize *S. tragus* emergence, plant biomass, viable seed production, and seed longevity in the two most common crop rotations (winter wheat [*Triticum aestivum* L.]–fallow and winter wheat–spring wheat/spring barley (*Hordeum vulgare* L.)–fallow rotations) of the semiarid PNW, where *S. tragus* is most problematic.

Materials and Methods

Experiment Description

Two sites were chosen in 2020 to establish a no-till farming experiment at the Columbia Basin Agriculture Research Center (CBARC) (45.7196°N, 118.6225°W) in Adams, OR, with two main goals: (1) studying *S. tragus* seedling emergence and seed longevity and (2) investigating plant biomass and timing of viable seed production, both in two cropping systems. One site (45.7198°N, 118.6261°W) followed a fallow–winter wheat rotation (hereafter referred to as F/WW) and the other site (45.7261°N, 118.6261°W) followed a spring wheat–fallow–winter wheat rotation (SW/F/WW) (Table 1).

F/WW and SW/F/WW each had two subsites. Subsites F/WW1 and SW/F/WW1 were initiated in 2020, and subsites F/WW2 and SW/F/WW2 were initiated in 2021. Subsites F/WW1 and F/WW2 began in fallow, while subsites SW/F/WW1 and SW/F/WW2 began in spring wheat. Rotation phases are documented in Table 1 for each year of this study. The experimental design was a randomized complete block design with 4 replications and 10 plots (3 m by 4.5 m) per replication. Nine of the 10 plots were sprinkled with 400 *S. tragus* seeds in two 1-m^2 areas in the center of each plot in early March of 2020 (in F/WW1 and SW/F/WW1) and of 2021 (in F/WW2 and SW/F/WW2). The remaining plot per replication was used as a control for potential *S. tragus* seeds already in the soil seedbank. Emerged seedlings were counted and removed in all plots on all evaluation dates, with the exception of 10 seedlings per replication and evaluation date: March 16, March 31, April 14, April 28, May 12, May 26, June 9, June 23, and July 7 in F/WW1 and SW/F/WW1; and April 7, April 21, May 5, May 19, June 2, June 16, June 30, July 14, and July 28 in F/WW2 and SW/F/WW2. Those 10 seedlings were chosen by randomly assigning 1 of the 9 evaluation dates to each sprinkled plot (9 per replication). In this way, on each evaluation date, the evaluators knew in which plots they had to count but leave alive 10 seedlings. Those 10 seedlings were marked to avoid being recounted and removed in following evaluation dates.

Seeds were sprinkled in F/WW1 and SW/F/WW1 on March 5 and 23, 2020; and in F/WW2 and SW/F/WW2 on March 13 and 10, 2021. Seeds for F/WW1 and SW/F/WW1 in 2020 were collected in October 2019 from *S. tragus* plants in a grower's field south of Ione, OR (45.3862°N, 119.8436°W). Seeds for F/WW2 and SW/F/WW2 in 2021 were collected in October 2020 from a different grower's field south of Ione, OR (45.4415°N, 119.8788°W). The viability of seeds collected in fall 2019 and 2020 was 86% and 58%, respectively. After sprinkling of *S. tragus* seeds, spring wheat ('Ryan') was planted on SW/F/WW1 and SW/F/WW2 using a no-till drill (Great Plains 606NT, Salina, KS, USA) with 25-cm interrow spacing at a seeding rate of 120 kg ha^{-1} (Table 1). All subsites were fenced for the duration of the experiment to prevent *S. tragus* plants from dispersing additional seeds throughout the experimental area. All plots were hand weeded. No postemergence or residual herbicides were applied that could affect the emergence of *S. tragus*.

The soil at CBARC is a Walla Walla silt loam (8% clay, 27% sand, and 65% silt) with 2.3% organic matter and pH of 5.4. Long-term average precipitation at CBARC is 420 mm yr^{-1} (Williams et al. 2020). Spring and winter wheat crops were managed following common no-till practices in the area. Fertilization and pest management practices were applied in all sites following standard recommendations (Wysocki et al. 2007). Precipitation and average daily air temperatures were obtained from a local weather station at CBARC (Figure 1).

Seedling Emergence and Seedbank Persistence

Emerged *S. tragus* seedlings were counted and removed approximately every 14 d from March to July in all plots during the first year of each subsite. However, in subsequent years, seedlings were only recorded in four plots per replication, the control plots and the three plots with the latest assigned emergence dates. This was because *S. tragus* plants in these plots were killed by freezing temperatures in October before they could produce viable seeds.

To account for the presence of seeds in the seedbank before the experiment, the *S. tragus* emergence observed in the control plots (which had not received any seeds and therefore represented the natural seedbank) was averaged per site and used to correct the counted emergence in the other plots. The correction consisted in subtracting the average emergence observed in the control plots from the emergence observed in the other plots (sprinkled plots), when a negative value was obtained, a zero value was recorded instead. Seedling emergence in percentage per plot was estimated by dividing the number of emerged seedlings per plot by the percentage of seed viability estimated in 400 seeds yr^{-1} and multiplying the result by 100.

Plant Biomass and Viable Seed Production

Plant biomass and viable seed production were recorded during the first year of each subsite. On every *S. tragus* emergence sampling date, in the plot assigned to that sampling date, 10 seedlings were marked with a 30-cm wooden stick and allowed to grow during subsequent emergence samplings dates. Starting in mid-August, one plant per plot was harvested weekly. Harvested plants were bagged individually and weighed. Plants were dried in an unheated greenhouse until a constant dry weight was achieved.

The total number of seeds per plant was determined by threshing to obtain all seeds, then weighing a 1-g subsample of all threshed material and counting all filled seeds in the subsample. Seed viability was evaluated using germination tests in a germination chamber. The number of viable seeds was estimated based on the total number of seeds per plant and the seed germination percentage observed in the germination tests.

Table 1. Crop rotations, planting dates, and cultivars in all subsites and years.

Subsite[a]	Management	Year[b]			
		2020	2021	2022	2023
F/WW1	Phase	Fallow	Winter wheat	Fallow	Winter wheat
	Planting date	—	October 14, 2020	—	October 12, 2022
	Cultivar	—	'Bobtail'	—	'0755'
SW/F/WW1	Phase	Spring wheat	Fallow	Winter wheat	Spring wheat
	Planting date	March 24, 2020	—	October 7, 2021	April 6, 2023
	Cultivar	'Ryan'	—	'ORCF'	'Ryan'
F/WW2	Phase	—	Fallow	Winter wheat	Fallow
	Planting date	—	—	October 18, 2021	—
	Cultivar	—	—	'ORCF 2X2'	—
SW/F/WW2	Phase	—	Spring wheat	Fallow	Winter wheat
	Planting date	—	March 11, 2021	—	October 3, 2022
	Cultivar	—	'Ryan'	—	'Bobtail'

[a] F/WW, fallow–winter wheat rotation; SW/F/WW, spring wheat–fallow–winter wheat rotation.
[b] The crop in each column indicates the year of harvest.

Seed Germination Tests

Salsola tragus seeds were stored at room temperature until germination tests were performed. In 2020, 50 seeds per harvest date were placed in plastic boxes with blotter paper moistened with 10 ml of water. In 2021, 25 seeds per plant and harvest date were germinated in the same manner. Seeds were incubated at 25 C with a 12-h photoperiod for 28 d in a germination chamber. All germination tests were repeated twice. Germination was checked and recorded every other day. Water was added to the boxes if needed.

Statistical Analysis

Salsola tragus seedling emergence was analyzed with a mixed, nested ANOVA. The statistical model included year and cropping system as fixed effects and subsite nested within year as a random effect. The random effect accounted for variability among subsites within each year, recognizing that different locations might have unique characteristics impacting seedling emergence. Seedbank persistence in the two cropping systems was analyzed using a two-way ANOVA, with cropping system (site) and the chronological year as fixed factors. Plant biomass and number of viable seeds were analyzed with a multi-way ANOVA, with year, emergence date, harvest date, and cropping system as fixed effects.

In all ANOVA analyses, the normality of data distribution and homogeneity of variance assumptions were tested using Levene's test and the Shapiro-Wilk test. When these assumptions were not met, a square-root-arcsine transformation was applied to normalize the data. If the assumptions remained unmet, the generalized least-squares (GLS) method with adjustments for heterogeneity of variances was employed. The significance of the effects was evaluated using *F*-tests, with P-values adjusted for multiple comparisons. Post hoc comparisons were conducted using Tukey's honestly significant difference (HSD) test at 0.05 significance level to identify specific differences between factor levels, utilizing the NLME package (Pinheiro et al. 2018). Analyses were performed with R v. 4.3.1 (R Core Team 2023).

Gompert, Weibull, and logistic regression models commonly used to describe weed emergence (Gonzalez-Andujar et al. 2016) were fit to the cumulative seedling emergence data. The logistic model provided the best fit to our data. This model is described in Equation 1 and the estimated parameters in Supplementary Table S1:

$$E\ \%\ \frac{a}{1\ e^{\frac{x t_{E50}}{b}}} \qquad [1]$$

where E is the cumulative emergence over time, a is the maximum emergence, x is the time in days, t_{E50} is the time to reach 50% final emergence (days), and b indicates the slope around t_{E50}. The regression model, fit using GraphPad Prism v. 6 (GraphPad Software, La Jolla, CA, USA), was used to calculate the number of days required to reach 10% and 50% of seedlings emerged for each experiment.

Results and Discussion

Weather Data

Accumulated precipitation was 174 mm in 2020, 62 mm in 2021, 225 mm in 2022, and 72 mm in 2023 from mid-March to mid-July. Additionally, temperatures during June and July were approximately 5 C warmer in 2021 than in 2020, 2022, and 2023 (Figure 1). The accumulated precipitation during the *S. tragus* growing season, from March to September, was 44% greater in 2020 (195 mm) compared with 2021 (85 mm).

Seedbank Persistence and Seedling Emergence

Salsola tragus seeds sprinkled in 2020 produced seedlings in both cropping systems (F/WW and SW/F/WW) for 4 yr, indicating that seeds in the soil seedbank remained viable for at least 4 yr. However, emergence during the fourth year was very low (0.25% in F/WW1 and 0.46% in SW/F/WW1), and data from the final year were excluded from the analysis. Considering the first three yr after seeding, total seedling emergence was 23.6% greater ($P = 0.003$) in the SW/F/WW cropping system compared with the F/WW system (47.2% vs. 23.6% respectively). Annual seedling emergence was greater ($P < 0.001$) in the first year (71.8%, 32.3%, and 19.2% in F/WW1, SW/F/WW1, and SW/F/WW2, respectively) compared with the second and third years (Figure 2). An exception was observed in F/WW2, where emergence was 6.9% in the first year and 5.6% in the second year.

Soil seedbanks are classified into three types based on the presence of viable seeds in the soil. Species forming transient seedbanks produce seeds that will not remain viable in soil after 1 yr. In contrast, short-term persistent and long-term persistent seedbanks are defined by species that produce seeds remaining viable in soil for 1 to 3 yr or more than 5 yr, respectively

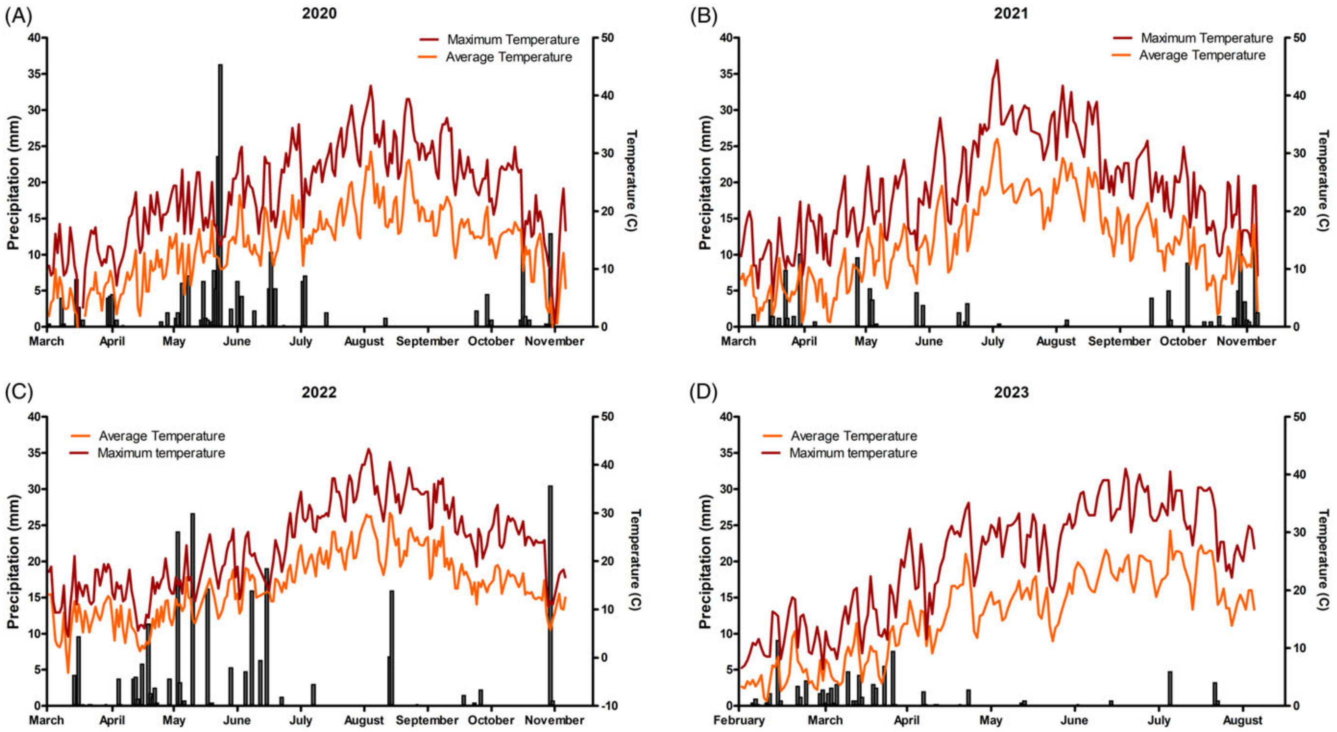

Figure 1. Average and maximum daily air temperature (lines) and precipitation (vertical bars) from March to November in (A) 2020, (B) 2021, (C) 2022, and (D) 2023 at the Columbia Basin Agricultural Research Center, Adams, OR.

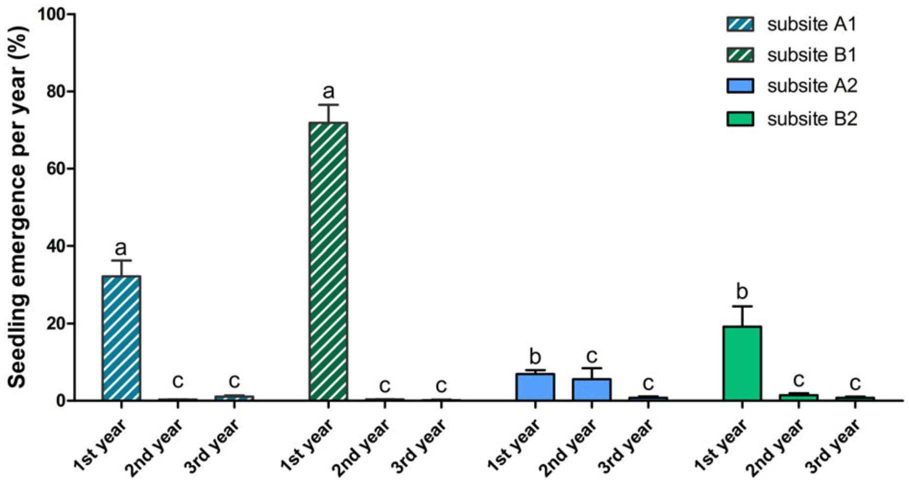

Figure 2. Mean percentage of seedling emergence registered for 4 yr in fallow–winter wheat (F/WW) and spring wheat–fallow–winter wheat (SW/F/WW) in the first, second, and third year after seeds were sprinkled. Bars indicate the means, and whiskers indicate the standard error of the mean (SEM). Different letters on bars mean treatments were significantly different, according to Tukey's multiple-comparison test (P < 0.05).

(Thompson et al. 1997; Walck et al. 2005). Previous research with *S. tragus* indicated that this species formed transient or short-term persistent seedbanks. Burnside et al. (1996) demonstrated that *S. tragus* seeds buried 20-cm deep in the soil profile remained viable for 1 yr, while Ogg and Dawson (1984) demonstrated that seeds tilled into the upper 5 cm of soil and irrigated continued to emerge after 2 yr.

Our work was performed with no-till farming practices where seeds on the soil surface are more exposed to harsh biotic and abiotic factors, including extreme temperatures, abrupt humidity changes (Anderson 2005; Moyer et al. 1994), and seed predation, compared with buried seeds (Hulme 1998). Our findings largely agree with those of Ogg and Dawson (1984), confirming that *S. tragus* most likely forms short-term persistent seedbanks in no-till systems in the PNW. Additionally, more seedling emergence in the SW/F/WW rotation compared with the F/WW rotation could be attributed to the spring wheat seeding, which provided better soil–seed contact at the time when temperatures are becoming favorable for *S. tragus* germination. Furthermore, seeds in fallow are more exposed to predation than those in spring wheat (Kalin 2022), which could have contributed to the reduced emergence observed.

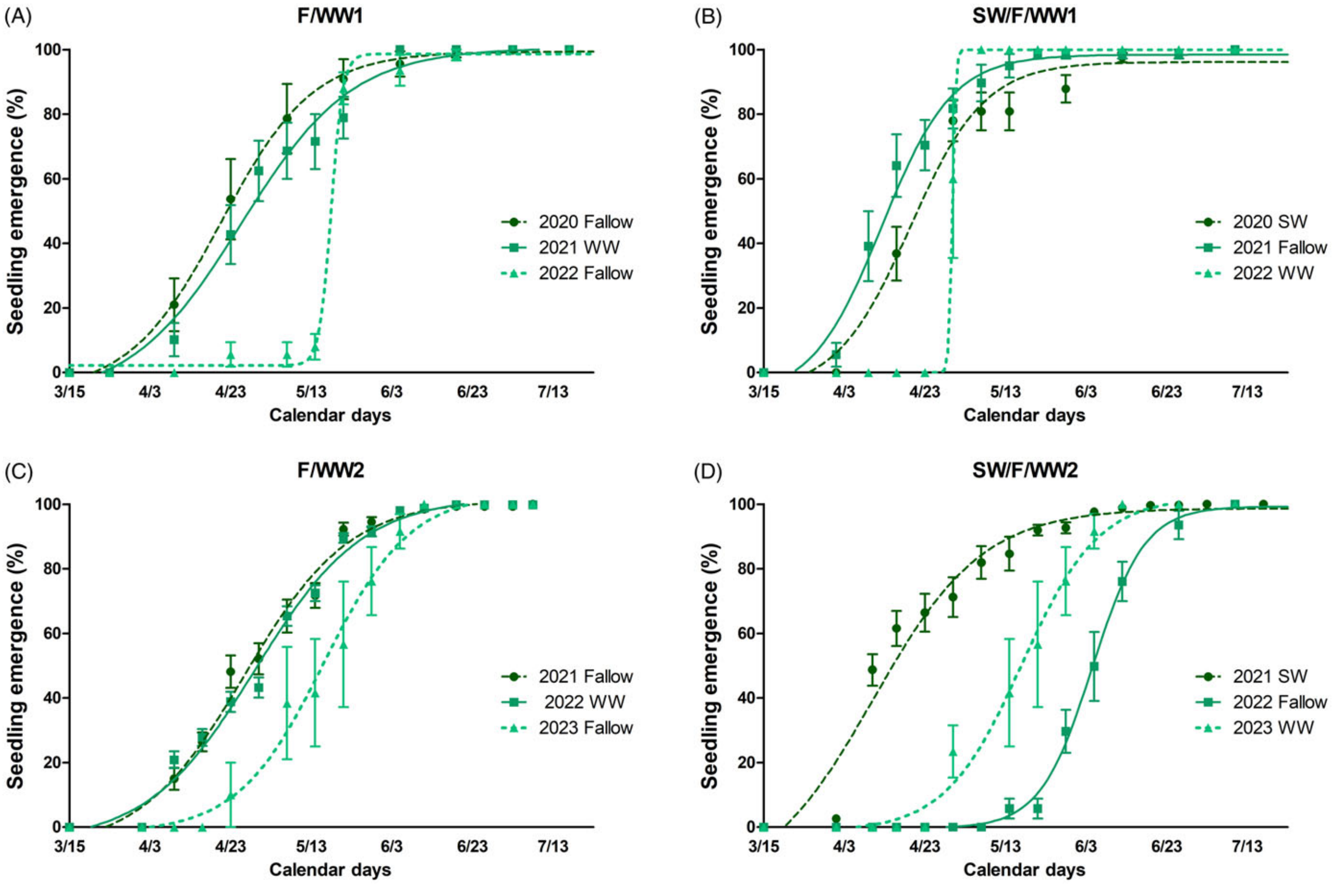

Figure 3. Cumulative seedling emergence registered for the first 3 yr in (A) F/WW1, (B) SW/F/WW1, (C) F/WW2, and (D) SW/F/WW2. Markers (circles, squares, and triangles) indicate the means at different emergence dates, and vertical whiskers are the standard error of the mean (SEM). F/WW, fallow–winter wheat rotation; SW/F/WW, spring wheat–fallow–winter wheat.

The onset date of seedling emergence, defined as when 10% of total emergence occurs, ranged between March 30 and April 6 in F/WW1, SW/F/WW1, and F/WW2 during the first 2 yr (Figure 3). However, seedling emergence was delayed for the third year until May 22, May 4, and April 19, respectively (Figure 3; Table 2). Onset was slightly different in SW/F/WW2, with emergence occurring on March 23 in the first year and May 23 and April 19 in the second and third years, respectively (Figure 3; Table 2). A similar pattern was observed for the time to reach 50% seedling emergence. Timing was similar in the first and second years for F/WW1 (April 23 and 20), SW/F/WW1 (April 21 and 15), and F/WW2 (April 29 and May 1), but there was a delay of 11 to 40 d in these sites during the third year (Table 2). However, SW/F/WW2 exhibited a slight variation, 50% emergence was observed on April 16 in the first year but was delayed in the second and third year to June 5 and May 12, respectively. These results from SW/F/WW2 align with those of Ogg and Dawson (1984), who noted that seedlings emerged earlier in the first year compared with the second year. However, most of our results indicated a germination delay in the third year for F/WW1, SW/F/WW1, and F/WW2.

Salsola tragus emerged until the end of June and early July, consistent with a study conducted in dryland crops in a low-precipitation region (Lind, WA) (Young 1986). However, Young (1986) related the end of *S. tragus* emergence to the field situation (fallow, spring wheat, or winter wheat), with emergence extending until late June in spring wheat and until mid-July in fallow. In our study, the presence of crops (winter or spring wheat) did not affect *S. tragus* emergence dynamics compared with fallow fields. Additionally, the emergence time reported in our work was later than in observations from a study conducted in an irrigated fallow field in Prosser, WA, where no *S. tragus* emergence was noted after May 1 (Ogg and Dawson 1984).

Plant Biomass and Viable Seed Production

No interactions among year, harvest date, or cropping system were observed, nor were there any differences in the main effect of harvest dates on biomass per plant. However, we found an interaction between cropping system and emergence date ($P < 0.001$) and differences between the main effects of cropping system, year, and emergence date. With regard to cropping system, *S. tragus* plant biomass was 4.4 times greater ($P < 0.001$) in fallow (466 g per plant) compared with spring wheat (105 g per plant), regardless of emergence date and year. This finding is consistent with Young's (1986) report of reduced *S. tragus* growth in competition with spring wheat. With regard to the year, *Salsola tragus* plant biomass (418 g per plant) was 1.4 times greater ($P < 0.001$) in 2021 than in 2020 (290 g per plant on average), regardless of the growth environment (fallow or spring wheat) or emergence date. And with regard to emergence date, in general, plants emerging early in the season exhibited greater biomass ($P < 0.05$) than those emerging later, irrespective of the growing environment or year (Figure 4). For *S. tragus* plants growing in competition with wheat, the reduction in biomass occurred earlier

Table 2. Predicted calendar days to 10% and 50% cumulative emergence from March 15 in the first, second, and third years in all subsites.

Subsite[a]	Cumulative emergence	First year	Second year	Third year
F/WW1	10%	18	16	69
	50%	39	37	77
SW/F/WW1	10%	17	16	51
	50%	37	31	52
F/WW2	10%	22	21	35
	50%	45	47	59
SW/F/WW2	10%	11	70	35
	50%	32	82	58

[a] F/WW, fallow–winter wheat rotation; SW/F/WW, spring wheat–fallow–winter wheat rotation.

(mid-May) compared with those growing in fallow (beginning of June). This earlier reduction in biomass is likely due to increased competition for light, water, and nutrients. By mid-May, wheat was likely near its peak biomass. The nearly complete canopy closure at that time intercepted most of the available light, and the absorption of soil resources by the wheat likely restricted *S. tragus* development more effectively than in the fallow treatment, where resource competition was absent.

No interactions were observed among year, emergence date, harvest date, and cropping system with respect to viable seeds per plant ($P > 0.05$), nor were there differences between years 2020 and 2021 ($P = 0.66$). However, differences were observed based on emergence date ($P = 0.029$), harvest date ($P < 0.001$), and cropping system ($P = 0.028$). A greater number of viable seeds were observed in plants growing in fallow compared with those in spring wheat, 1,084 versus 723 viable seeds per plant, respectively. There was a positive linear relationship between seed production and plant biomass, as previously described by Barroso and Genna (2021). The greater biomass observed in plants growing in fallow conditions, without competition, was also reflected in a greater number of seeds per plant.

In general, the number of viable seeds was greatest in plants emerging in mid-May (1,625 seeds). Plants emerging later (June) produced fewer seeds ($P < 0.05$), likely due to a shorter growing period resulting in smaller plants with reduced seed production, as noted by Schillinger and Young (2000). Plants that emerged very early (late March) also produced fewer viable seeds (Figure 5A). The number of viable seeds was influenced by both the emergence date and the harvest date. Seed numbers were very low (around 26 viable seeds per plant) during the early harvest dates (August 11 to September 1; Figure 5B), as plants harvested before the end of summer had insufficient time to produce seeds. The number of viable seeds increased in September, reaching a maximum on September 29 (3,083 viable seeds per plant).

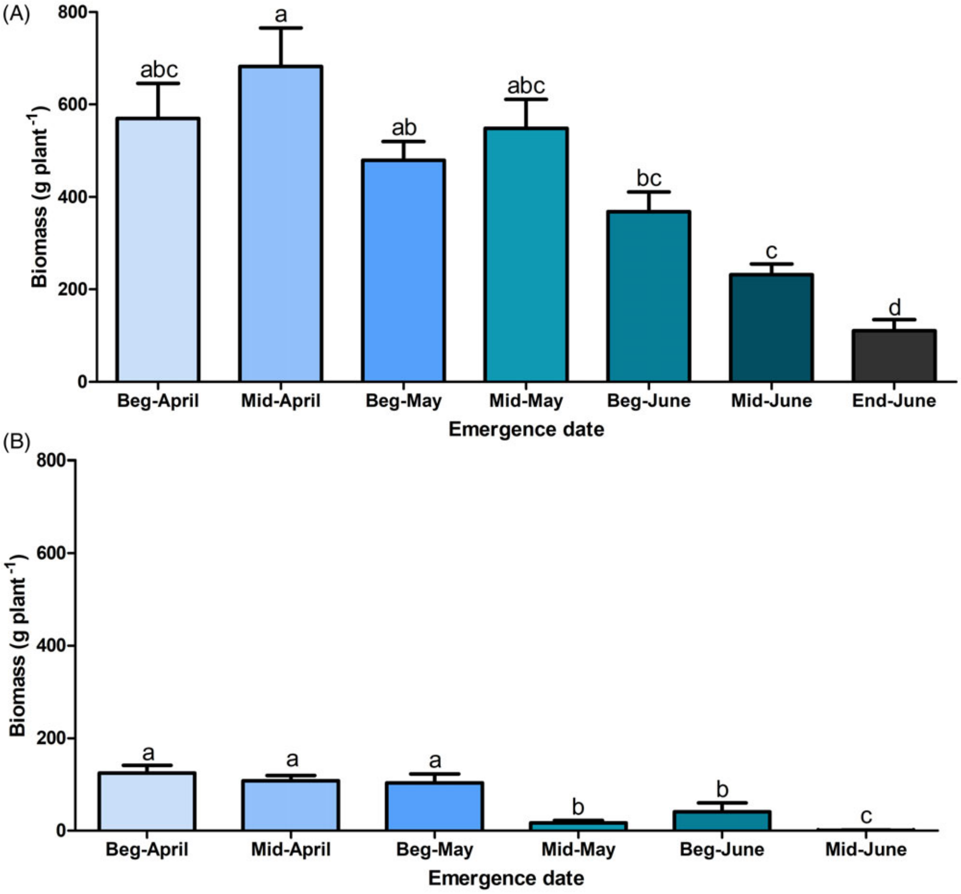

Figure 4. Plant biomass per emergence date (g) in the first year of each cropping system for: (A) F/WW (fallow; average between F/WW1 and F/WW2, and harvest dates) and (B) SW/F/WW (spring wheat; average between SW/F/WW1 and SW/F/WW2, and harvest dates). Bars indicate the means, and whiskers indicate the standard error of the mean (SEM). Bars with different letters indicate differences among emergence dates in each cropping system according to Tukey's multiple-comparison test ($P < 0.05$). F/WW, fallow–winter wheat rotation; SW/F/WW, spring wheat–fallow–winter wheat.

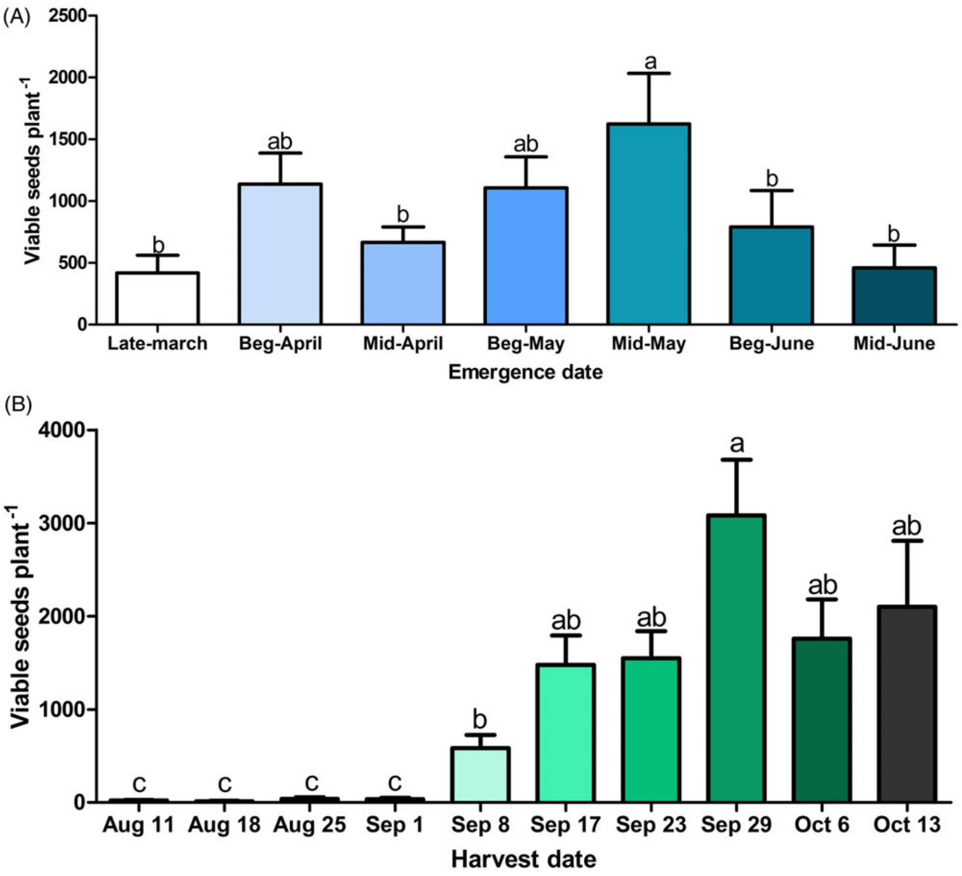

Figure 5. Viable seeds per plant and per emergence date (A) and per harvest date (B) in the first year of both cropping systems and years combined. Bars indicate the means, and whiskers indicate the standard error of the mean (SEM). Different letters on the colored bars indicate differences among dates according to Tukey's multiple-comparison test ($P < 0.05$).

Agronomic Implications

Salsola tragus can pose a long-term challenge for weed management in dryland cropping systems of the PNW due to seedbank persistence of at least 4 yr. Growers must pay careful attention to fields for growing infestations, likely the result of emergence following the first year of dispersal, and must continue to monitor fields following herbicide applications for seeds emerging after the first year.

Delayed emergence and reduced seedling emergence in subsequent years underline the importance of timely weed control measures, especially in the first year after seed dispersal. This can be addressed through the application of preemergence herbicides before or shortly after crop planting or by optimizing postemergence herbicide applications to target seedlings using emergence models (Oreja et al. 2024). This study also emphasizes the impact of environmental conditions, such as precipitation and temperature, on *S. tragus* emergence and growth.

Furthermore, competition with spring wheat reduced biomass and viable seed production compared with those in fallow, suggesting that crop competition is an effective strategy for suppressing *S. tragus* growth. However, winter wheat seemed to be a more effective competitor than spring wheat, as spring wheat seeding may favor *S. tragus* germination. Plants emerging from April to mid-May exhibited more biomass and fecundity, indicating that management practices should target these cohorts to reduce overall weed pressure and seedbank replenishment. Additionally, controlling plants before September in postharvest or fallow fields is crucial to minimize the reintroduction of seeds into the soil seedbank.

Supplementary material. To view supplementary material for this article, please visit https://doi.org/10.1017/wsc.2024.77

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Competing interests. The authors declare no conflicts of interest.

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