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Feral rye (*Secale cereale* L.) control in quizalofop-resistant winter wheat in Oregon

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Abstract

Managing winter annual grass weeds has long been a challenge in the dryland regions of the Pacific Northwest (PNW) where soft white winter wheat is grown. The recent development of quizalofop-resistant (CoAXium) wheat varieties allows growers to use quizalofop (QP), a herbicide that inhibits acetyl-CoA carboxylase (ACCase) for postemergence grass control. Field experiments were conducted over two winter wheat growing seasons in 2021–2022 and 2022–2023 near Adams, OR, to evaluate QP efficacy on feral rye and for crop safety. Downy brome and jointed goatgrass control with QP were assessed in 2021–2022 and 2022–2023, respectively. QP treatments provided effective control of feral rye (≥95%), downy brome (≥87%), and jointed goatgrass (99%) regardless of rate, adjuvant, and spray volume tested. Spring-applied QP caused no injury to winter wheat. Results indicate that the QP-resistant wheat technology can help PNW wheat growers selectively control winter annual grasses.

Introduction

Winter annual grass weeds such as downy brome, feral rye, and jointed goatgrass are difficult to control in the dryland regions of the Pacific Northwest (PNW) where winter wheat is grown (Ball et al. 1995). When uncontrolled, these weeds can cause substantial wheat yield loss and negatively affect growers' net returns (Rydrych 1974; White et al. 2006). Previous research showed that downy brome densities of 24, 40, and 65 plants m^{-2} reduced winter wheat yield by 10%, 15%, and 20%, respectively (Stahlman and Miller 1990). Feral rye densities >40 plants m^{-2} resulted in wheat yield loss as high as 90% (Pester et al. 2000). Jointed goatgrass at 18 plants m^{-2} decreased winter wheat grain yield by 27% and 17% when emerging simultaneously or 42 d after crop emergence, respectively (Anderson 1993).

Management of winter annual grass weeds in winter wheat crops is difficult because of their similarities in biology, emergence time, and maturation time, which thus limits selective herbicide options (Daugovish et al. 1999; Lyon and Baltensperger 1995). Herbicides that inhibit acetolactate synthase (ALS) have been used primarily for postemergence (POST) control of winter annual grass in winter wheat crops for more than two decades. Several ALS-inhibiting herbicides are registered for downy brome control in winter wheat crops, including mesosulfuron-methyl, sulfosulfuron, propoxycarbazone-sodium, and pyroxsulam (Ostlie and Howatt 2013). Herbicide options for POST feral rye and jointed goatgrass control in winter wheat fields are limited to the ALS-inhibiting herbicide imazamox when used with imidazolinone-resistant wheat varieties (i.e., the Clearfield Production System) (Tan et al. 2005). ALS-inhibiting herbicides are often used every other year in a winter wheat–summer fallow rotation (which is common in the region), or every year in annual cereal cropping systems (which is less common in the region). As a result, the overreliance on these herbicides has resulted in the development of ALS-resistant grass populations in winter wheat production systems in the PNW (Ribeiro et al. 2023; Zuger and Burke 2020).

In 2018, the Colorado Wheat Research Foundation and Colorado State University in collaboration with Albaugh LLC (Ankeny, IA) and Limagrain Cereal Seeds (Walla Walla, WA) developed a quizalofop (QP)-resistant wheat technology known as the CoAXium Wheat Production System (Bough et al. 2021; Ostlie et al. 2015). The resistant trait (AXigen®) was selected via ethyl methanesulfonate mutagenesis and phenotypic screening of winter wheat plants ('Hatcher'; Haley et al. 2005) for resistance to QP (Ostlie et al. 2015). Researchers identified a novel mutation in the plastidic acetyl co-enzyme A carboxylase (*ACC1*) resulting in an alanine to valine amino acid substitution at position 2004 (Ala-2004-Val) on the A, B, and D genomes of the winter wheat mutant lines (Ostlie et al. 2015). However, the mutation in the B genome conferred a lower level of resistance to QP compared with the mutation in the A or D genomes. Commercially available QP-resistant wheat varieties have mutations from the A, B, or D *ACC1* homoeologs (two-gene trait), which confer higher levels of resistance to QP compared to single-gene mutant lines (Bough and Dayan 2022).

QP-resistant soft white winter wheat (SWWW) varieties were commercially released for the first time in autumn 2022 in the PNW. To our knowledge, no published information currently exists on the effectiveness of QP for winter annual grass control in QP-resistant SWWW crops in dryland regions of the PNW. Therefore, the primary objective of this study was to evaluate the efficacy of QP for control of feral rye and for crop injury in a QP-resistant SWWW variety in Oregon. Additional evaluations of QP efficacy were performed on naturally occurring populations of downy brome and jointed goatgrass.

Materials and Methods

Site Description

Field experiments were conducted at the Columbia Basin Agricultural Research Center near Adams (45.7185456°N, 118.6253943°W), Oregon, during the 2021–2022 and 2022–2023 wheat growing seasons. The soil at this site is a Walla Walla silt loam (8% clay, 27% sand, 65% silt) with 2.3% organic matter, pH 5.4. The fields were fallow the year prior to experiment establishment in both years. Before winter wheat establishment, fields were vertically tilled at a depth of 8 cm. A QP-resistant SWWW variety ('LCS Dagger AX'; Limagrain Cereal Seeds) was seeded on October 4, 2021, and September 22, 2022, using a double-disc conventional drill set at a depth of 2 cm, with 19-cm row spacing, and a 123 kg ha^{-1} seeding rate in 2021; and a depth of 7 cm, with 19-cm row spacing, and 134 kg ha^{-1} seeding rate in 2022. The seeding depth was deeper in 2022 than in 2021 to reach moisture. Feral rye seeds were mixed with the wheat seed at a rate of 20% by weight before planting in both years. The fields had a naturally occurring downy brome and jointed goatgrass infestation in the 2021–2022 and 2022–2023 growing seasons, respectively. The crop was fertilized at seeding with 240 kg ha^{-1} of urea in both years and was top-dressed with 60 kg ha^{-1} of urea on March 3, 2022. The premixed herbicide pyrasulfotole (33 g ai ha^{-1}) plus bromoxynil (184 g ai ha^{-1}, Huskie®; Bayer CropScience, St. Louis, MO), and the premixed fungicide azoxystrobin (83 g ai ha^{-1}) plus propiconazole (71 g ai ha^{-1}, MiCrop™; Albaugh, LLC) were mixed and applied for broadleaf weed and stripe rust (*Puccinia striiformis*) control, respectively, on April 7, 2022, and April 25, 2023. Monthly accumulated precipitation and average temperature during the wheat growing season were recorded for both years (Figure 1).

Experimental Design and Herbicide Application

Experiments were conducted in a randomized complete block design with four replications. Plot dimensions were 3 m wide by 9 m long. Herbicide treatments included pyroxasulfone (PYR; Zidua®; BASF, Research Triangle Park, NC) and pyroxasulfone + carfentrazone-ethyl (PYR + CARE; Anthem® Flex; FMC, Philadelphia, PA) applied preemergence (PRE), and QP (Aggressor® AX; Albaugh LLC) applied POST in the spring (Table 1). Adjuvants included a nonionic surfactant (NIS) and methylated seed oil (MSO). Detailed information about the treatment rates and adjuvants is provided in Table 1. An untreated check (UTC) was included for comparison.

PRE treatments were applied on October 8, 2021, and September 29, 2022, before wheat and weed emergence. QP spring treatments were applied on March 18, 2022, and April 14, 2023. In 2022, QP was applied when wheat was at Feekes growth stage 5 (i.e., plants were 11 to 20 cm tall), feral rye had eight leaves (plants were 13 to 23 cm tall), and downy brome had six to eight leaves (plants were 5 to 10 cm tall). In 2023, QP spring treatments were applied when wheat was at Feekes growth stage 6 (plants were 20 to 44 cm tall), feral rye was fully tillered with the first node visible (plants were 38 to 44 cm tall), and jointed goatgrass had three to eight leaves (i.e., plants were 11 to 20 cm tall).

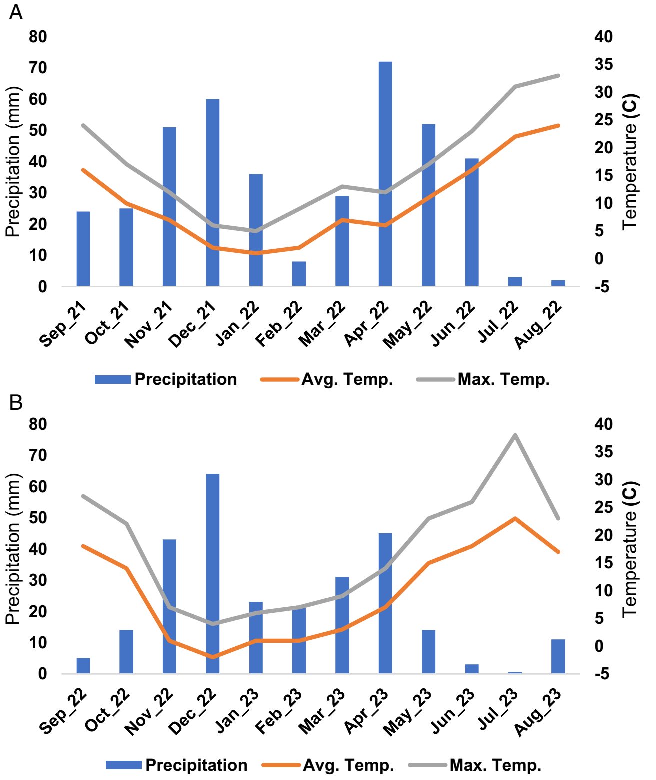

Figure 1. Monthly accumulated precipitation and average and maximum temperature during the 2021–2022 (A) and 2022–2023 (B) wheat-growing seasons.

Herbicides were applied using a CO$_2$-pressurized backpack sprayer equipped with six Teejet XR80015-VS nozzles (Spraying Systems Co., Wheaton, IL) spaced 46 cm apart, calibrated to deliver 140 L ha^{-1} of spray solution. Three QP spring treatments were applied with 32% urea ammonium sulfate (UAN-32; 5 L ha^{-1}), and MSO (1% v/v), using three different spray volumes of 94, 187, and 281 L ha^{-1} (Table 1).

Data Collection

Weed control and crop injury were visually assessed on a scale from 0% to 100%, where 0% indicated no weed control or no crop injury, and 100% indicated complete weed control or crop death. Crop injury was assessed at 14 and 21 d after the spring POST treatments (DASP). Visual weed control was assessed 9 wk after the spring POST treatments (WASP). Feral rye control ratings were taken in both 2021–2022 and 2022–2023. Downy brome control ratings were taken in 2021–2022, and jointed goatgrass ratings were taken in 2022–2023. Samples of aboveground biomass for each weed species were collected on June 30, 2022, and June 23, 2023, from two 0.5-m^2 quadrats placed within each plot, placed in paper bags, dried at 60 C for 1 wk, and weighed. Winter wheat yield was obtained by harvesting the center 1.2 m of

Table 1. Herbicides used in the field experiments.[a]

Herbicide	Rate	Spray volume	Mode of action	Application timing	Adjuvant[b]
	g ai ha^{-1}	L ha^{-1}			
PYR	119	140	VLCFA	PRE	–
PYR + CARE	123 + 9	140	VLCFA + PPO	PRE	–
PYR fb QP	119 fb 77	140	VLCFA fb ACCase	PRE fb spring	MSO
PYR + CARE fb QP	123 + 9 fb 77	140	VLCFA + PPO fb ACCase	PRE fb spring	MSO
QP	77	140	ACCase	Spring	MSO
QP	92	140	ACCase	Spring	MSO
QP	92	94	ACCase	Spring	MSO + UAN
QP	92	187	ACCase	Spring	MSO + UAN
QP	92	281	ACCase	Spring	MSO + UAN

[a] Abbreviations: ACCase, acetyl-coenzyme A carboxylase (categorized by the Weed Science Society of America [WSSA] as a Group 1 herbicide); CARE, carfentrazone-ethyl; fb, followed by; MOA, mode of action; MSO, methylated seed oil; PPO, protoporphyrinogen oxidase (WSSA Group 14); PRE, preemergence; PYR, pyroxasulfone; QP, quizalofop; UAN, urea ammonium nitrate; VLCFA, very long chain fatty acid (WSSA Group 15).

[b] MSO was used at 1% v/v, UAN-32 (32% nitrogen) was used at 5 L ha^{-1}.

each plot with a small-plot combine when the grain moisture content was approximately 13.5%.

Statistical Analysis

Statistical analyses were performed using R statistical software (version 4.2.2; R Core Team 2022). A generalized linear mixed model with Template Model Builder with a beta distribution and logit link (GLMMTMB package; Brooks et al. 2017) was fit to weed control and crop injury data while a linear mixed model (LME4 package; Bates et al. 2015) was fit to weed biomass and crop yield data. The linear mixed model assumptions for normal distribution and homogeneity of residual variance were assessed prior to analysis using the Shapiro-Wilk test (STATS package; Royston 1995) and Levene's test (CAR package; Fox and Weisberg 2019), respectively. Weed biomass data were square root transformed to meet the assumption of normality, and treatment means were transformed back to the original scale for presentation. Models were analyzed using the *Anova.glmmTMB* function (with the GLMMTMB package) for generalized linear mixed models and the *Anova* function (with the CAR package) for linear mixed models. In models for crop injury, weed biomass, feral rye control, and crop yield, "herbicide treatments" and "years" were included as fixed effects, and "replications" nested within "years" were included as random effects. Means were separated using the Fisher's protected LSD test (with the EMMEANS package; Lenth 2022) when interactions or fixed effects were significant ($\alpha = 0.05$). In models for downy brome and jointed goatgrass control, "herbicide treatments" were considered as fixed effects and "replications" as a random effect. If ANOVA indicated a significant herbicide treatment effect ($\alpha = 0.05$), means were separated accordingly using Fisher's protected LSD test.

Results and Discussion

The environmental conditions varied between crop years (Figure 1). Total precipitation, and average and maximum temperatures were 403 mm, and 10 C and 33 C, respectively, in the 2021–2022 growing season; and 275 mm, and 10 C and 38 C, respectively, in the 2022–2023 growing season. There was a significant herbicide treatment by year interaction for feral rye visual control, feral rye biomass, and crop yield ($\alpha < 0.01$); therefore, data were analyzed separately for each crop year.

Visible Weed Control and Biomass

Feral Rye

All QP treatments, regardless of rate, adjuvant, or spray volume, provided ≥95% control of feral rye in both growing seasons (Table 2). In contrast, the PRE-applied treatments of PYR and PYR + CARE did not have any effect on feral rye in either year (Table 2). Consistent with our results, ≥92% control of feral rye was observed with spring-applied QP at similar rates (77 and 92 g ai ha^{-1}) in QP-resistant wheat studies conducted in Colorado, Kansas, and Oklahoma over five site-years (Kumar et al. 2021). Similarly, QP applied at 77 and 93 g ai ha^{-1} provided ≥88% and 92% feral rye control, respectively, 60 DASP in a study conducted over a 3-yr period in eastern Colorado (Hildebrandt et al. 2022). Due to the lack of effective PRE herbicides and limited POST herbicide options to selectively control feral rye in winter wheat crops, stewardship strategies must be adopted to preserve the efficacy of QP in QP-resistant winter wheat production systems and prevent the selection and spread of ACCase-resistant populations.

Feral rye pressure was greater in the 2022–2023 growing season (356 g m^{-2}) than in 2021–2022 (175 g m^{-2}; Table 2). Feral rye biomass was reduced by 95% to 100% with QP treatments in both growing seasons. Conversely, feral rye biomass in plots treated with PYR and PYR + CARE alone was equivalent to that of the UTC. These results are similar to the visual control ratings and indicate that these herbicides do not have an effect on this weed species. Feral rye biomass reduction when treated with QP corresponded to the visual control evaluations recorded at 9 WASP. Previous dose-response studies also showed that QP applied at 77 to 92 g ai ha^{-1} reduced the growth of 10 feral rye populations by 90% (GR$_{90}$ ≤72 g ai ha^{-1}; Kumar et al. 2021). Therefore, the results of our study indicate that the adoption of QP-resistant wheat technology provides PNW wheat growers with an additional tool for selective feral rye control with QP.

Downy Brome

QP efficacy was similar across all rates, adjuvants, and spray volumes tested in that all treatments provided effective control (≥87%) of downy brome based on visual estimates at 9 WASP (Table 3). The PRE herbicides PYR and PYR + CARE controlled downy brome by 63% and 45%, respectively, at 9 WASP (Table 3). Sequential applications of PYR and PYR + CARE followed by a QP application both provided ≥94% downy brome control (Table 3). Similar results were observed in a QP-resistant wheat study in

Table 2. Effect of herbicide treatments on feral rye control and biomass in quizalofop-resistant winter wheat.[a]

					2021–2022[b]		2022–2023[b]	
Herbicide	Rate	Spray volume	Application timing	Adjuvant[c]	Control	Biomass	Control	Biomass
	g ai ha^{-1}	L ha^{-1}			%	g m^{-2}	%	g m^{-2}
UTC	–	–	–	–	–	175 c	–	356 c
PYR	119	140	PRE	–	0 c	192 c	0 e	278 c
PYR + CARE	123 + 9	140	PRE	–	0 c	111 b	0 e	298 c
PYR fb QP	119 fb 77	140	PRE fb spring	MSO	97 ab	4 a	95 d	6 ab
PYR + CARE fb QP	123 + 9 fb 77	140	PRE fb spring	MSO	97 ab	0 a	95 d	6 ab
QP	77	140	Spring	MSO	97 ab	0 a	96 cd	17 ab
QP	92	140	Spring	MSO	97 ab	6 a	97 abc	2 ab
QP	92	94	Spring	MSO + UAN	98 a	9 a	98 ab	0 a
QP	92	187	Spring	MSO + UAN	96 b	8 a	96 bcd	0 a
QP	92	281	Spring	MSO + UAN	97 ab	3 a	99 a	0 a

[a] Abbreviations: CARE, carfentrazone-ethyl; fb, followed by; MSO, methylated seed oil; PRE, preemergence; PYR, pyroxasulfone; QP, quizalofop; UAN, urea ammonium nitrate; UTC, untreated control.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha = 0.05$).

[c] MSO was applied at 1% v/v; UAN-32 (32% nitrogen) was applied at 5 L ha^{-1}.

Table 3. Effect of herbicide treatments on downy brome and jointed goatgrass control and biomass in quizalofop-resistant winter wheat.[a]

					2021–2022[b]		2022–2023[b]	
					DB		JGG	
Herbicide	Rate	Spray volume	Application timing	Adjuvant[c]	Control	Biomass	Control	Biomass
	g ai ha^{-1}	L ha^{-1}			%	g m^{-2}	%	g m^{-2}
UTC	–	–	–	–	–	206 d	–	22 b
PYR	119	140	PRE	–	63 b	22 bc	0 b	24 b
PYR + CAR	123 + 9	140	PRE	–	45 b	48 c	0 b	27 b
PYR fb QP	119 fb 77	140	PRE fb spring	MSO	94 a	0 a	99 a	0 a
PYR + CARE fb QP	123 + 9 fb 77	140	PRE fb spring	MSO	95 a	0 a	99 a	0 a
QP	77	140	Spring	MSO	89 a	5 ab	99 a	0 a
QP	92	140	Spring	MSO	90 a	8 ab	99 a	0 a
QP	92	94	Spring	MSO + UAN	88 a	7 ab	99 a	0 a
QP	92	187	Spring	MSO + UAN	88 a	7 ab	99 a	0 a
QP	92	281	Spring	MSO + UAN	87 a	4 ab	99 a	0 a

[a] Abbreviations: CARE, carfentrazone-ethyl; DB, downy brome; fb, followed by; JGG, jointed goatgrass; MSO, methylated seed oil; PRE, preemergence; PYR, pyroxasulfone; QP, quizalofop; UTC, untreated control.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha = 0.05$).

[c] MSO was applied at 1% v/v; UAN-32 (32% nitrogen) was applied at 5 L ha^{-1}.

eastern Colorado, which showed consistent downy brome control with QP regardless of the rates and adjuvants used (Hildebrandt et al. 2022). Downy brome control was ≥95% at 60 DASP for all QP rates (31, 46, 62, 77, 93, and 109 g ai ha^{-1}) and adjuvants (COC, MSO, NIS, UAN). Previous research also has demonstrated high levels of PYR activity on downy brome (Johnson et al. 2018; Kumar et al. 2017) and several other grass species such as Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) (Hulting et al. 2012), rigid ryegrass (*Lolium rigidum* Gaudin) (Boutsalis et al. 2014; Walsh et al. 2011), and Japanese brome (*Bromus japonicus* Thunb.) (Johnson et al. 2018). In a study conducted in Montana, PYR alone applied PRE (89 g ai ha^{-1}) and followed by an application of imazamox (44 g ai ha^{-1}) provided 80% and 99% downy control, respectively, 8 WASP in imidazolinone-resistant winter wheat (Kumar et al. 2017). In western Canada, Johnson et al. (2018) reported similar results (i.e., PYR applied at 112 and 150 g ai ha^{-1} controlled downy brome by >80% 50 DASP in winter wheat crops). The lower level of downy brome control with PYR applied alone in our study compared to the studies cited earlier might have been because during our study not enough rain fell to activate the herbicides in the soil. In our study, no rain fell before or within 3 d of herbicide application, and precipitation was low (25 mm) during the month of herbicide application. In contrast, the precipitation in the month of PYR application in the study by Kumar et al. (2017) ranged from 30 mm to 64 mm for the wheat growing periods of 2012 to 2016. In addition, we recorded 206 g m^{-2} of downy brome biomass in the UTC compared with 60 g m^{-2} in the study by Johnson et al. (2018). The integration of PRE herbicides such as PYR into a downy brome management program in winter wheat provides more options for producers, which will assist in delaying resistance to currently used herbicides and controlling ALS-resistant downy brome populations. Furthermore, using PRE herbicides in downy brome management reduces the weed population that must be controlled by POST herbicides.

Downy brome was the most abundant weed species in the UTC plot (206 g m^{-2}) in the 2021–2022 growing season (Table 3). QP treatments reduced downy brome biomass by 96% to 100%, while the PRE herbicides PYR and PYR + CARE applied alone reduced downy brome biomass by 89% and 77%, respectively. Reduction in downy brome biomass by QP treatments correlated with the level of control at 9 WASP. The difference between visual control and biomass reduction results for downy brome with PRE herbicide treatments might be explained by the subjectivity in visual control assessments and weed biomass variability within the experimental area. Early season downy brome control with the PRE herbicides including PYR followed by a POST application of QP in the spring

Table 4. Effect of herbicide treatments on quizalofop-resistant winter wheat grain yield.[a]

Herbicide	Rate	Spray volume	Application timing	Adjuvant[c]	Wheat yield[b] 2021–2022	Wheat yield[b] 2022–2023
	g ai ha^{-1}	L ha^{-1}			kg ha^{-1}	kg ha^{-1}
UTC	–	–	–	–	3,330 c	3,300 c
PYR	119	140	PRE	–	5,580 ab	3,510 bc
PYR + CARE	123 + 9	140	PRE	–	5,320 b	3,530 bc
PYR fb QP	119 fb 77	140	PRE fb spring	MSO	6,570 a	4,170 abc
PYR + CARE fb QP	123 + 9 fb 77	140	PRE fb spring	MSO	6,750 a	4,510 abc
QP	77	140	Spring	MSO	6,380 ab	4,590 ab
QP	92	140	Spring	MSO	6,490 ab	5,040 a
QP	92	94	Spring	MSO + UAN	6,010 ab	4,620 ab
QP	92	187	Spring	MSO + UAN	6,570 a	4,030 abc
QP	92	281	Spring	MSO + UAN	6,540 ab	4,390 abc

[a] Abbreviations: CARE, carfentrazone-ethyl; fb, followed by; MSO, methylated seed oil; PRE, preemergence; PYR, pyroxasulfone; QP, quizalofop; UAN, urea ammonium nitrate; UTC, untreated control.

[b] Means within a column followed by the same letter are not significantly different according to Fisher's LSD test ($\alpha = 0.05$).

[c] MSO was applied at 1% v/v; UAN-32 (32% nitrogen) was applied at 5 L ha^{-1}.

to control any late escapes can help to reduce downy brome seed production and distribution in future years (note that downy brome is a prolific species that can produce up to 1,350 seeds per plant; San Martín et al. 2021).

Jointed Goatgrass

The jointed goatgrass infestation was low in the UTC (22 g m^{-2}) in the 2022–2023 growing season (Table 3). Jointed goatgrass visual control and biomass reduction ranged from 99% to 100% for all QP treatments regardless of rate, adjuvant, and spray volume (Table 3). Conversely, the PRE herbicides PYR and PYR + CARE demonstrated no activity on jointed goatgrass (Table 3). In a study conducted over a 3-yr period in eastern Colorado, jointed goatgrass control ranged from 73% at 93 g ai ha^{-1} to 98% at 109 g ai ha^{-1} QP (Hildebrandt et al. 2022). Based on our results, the adoption of QP-resistant wheat associated with QP herbicide offers PNW wheat growers an effective option for jointed goatgrass control.

The potential for gene transfer between imidazolinone-resistant wheat and jointed goatgrass resulting in imazamox resistance through interspecific hybridization has been widely reported (Gaines et al. 2008; Hanson et al. 2005; Perez-Jones et al. 2010; Zemetra et al. 1998). Because jointed goatgrass shares the genome D with wheat and interspecific hybridization between these two species can naturally occur in the field, stewardship practices to prevent the introgression of the ACCase-resistance trait from wheat to jointed goatgrass are critically necessary.

Winter Wheat Yield

No crop injury was observed among herbicide treatments in either year, indicating that QP provides acceptable crop safety for the QP-resistant SWWW variety. In general, greater winter wheat yields were achieved in the 2021–2022 growing season (3,330 to 6,750 kg ha^{-1}) compared with the 2022–2023 growing season (3,300 to 5,040 kg ha^{-1}; Table 4). The 2021–2022 season was wet, particularly during April, May, and June, which may have favored grain filling in all tillers compared with the drier 2022–2023 growing season.

In the 2021–2022 growing season, all herbicide treatments ($\geq$5,320 kg ha^{-1}) resulted in higher winter wheat yield compared with the UTC (3,330 kg ha^{-1}; Table 4). There was no statistical difference in wheat yield among QP treatments. Winter wheat yields in plots that received PRE herbicides followed by QP and single spring QP treatments ranged from 6,010 to 6,750 kg ha^{-1}, while the winter wheat yields in plots that received PYR and PYR + CARE alone were 5,580 and 5,320 kg ha^{-1}, respectively.

In the 2022–2023 growing season, the single spring QP treatment applied at 92 g ai ha^{-1} with MSO at 140 L ha^{-1} resulted in higher crop yields (5,040 kg ha^{-1}) compared with yield from the UTC (3,300 kg ha^{-1}; Table 4). Winter wheat yields in plots that received only PRE (PYR or PYR + CARE) were not different than that from the UTC.

In conclusion, spring-applied QP caused no winter wheat injury. QP treatments regardless of rate, adjuvant, and spray volume, provided excellent feral rye control. The level of control ranged from 95% to 99%. The adoption of QP-resistant wheat technology integrated with a QP herbicide offers wheat growers an alternative herbicide mode of action (MOA) for selective control of feral rye. Stewardship strategies including rotational use of QP-resistant and imidazolinone-resistant wheat varieties, crop rotation, not allowing grass weed escapes to go to seed, and use of herbicides with alternate MOAs are recommended to prevent the evolution and spread of QP-resistant grass populations in wheat fields. Further research is needed to validate the findings of downy brome and jointed goatgrass control over time and/or space.

Practical Implications

The results of this study provide PNW wheat growers with useful information about QP use in QP-resistant wheat production systems. QP can be applied to wheat crops from the 4-leaf stage up to the jointing stage for control of actively growing grasses (i.e., fewer than four to five leaves). Regardless of QP rate, adjuvant, and spray volume, effective feral rye control was achieved. Prudent use and implementation of sound best management and stewardship practices of QP-resistant wheat are critically important for preserving the efficacy and longevity of this new technology.

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