SENSITIVITY OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) TO QUIZALOFOP-P-ETHYL IN CENTRAL OKLAHOMA AND KANSAS

By

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SENSITIVITY OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) TO QUIZALOFOP-P-ETHYL IN CENTRAL OKLAHOMA AND KANSAS

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Abstract: CoAXium® Wheat Production System, developed by Colorado Wheat Research Foundation, Albaugh Chemical, and Limagrain, is a new herbicide tolerant wheat that allows for the use of Aggressor™ herbicide [active ingredient: quizalofop-p-ethyl (quizalofop)] for control of grassy weeds. An increase in applications of quizalofop may increase the likelihood of physical drift and/or tank contamination to nearby sensitive plants, including wheat that is not tolerant to quizalofop. To further evaluate this challenge, a trial was conducted at four locations in the central Great Plains, during the 2018-2019 and 2019-2020 growing seasons. Five quizalofop rates were used: 1X (92 g ai ha^{-1}), 1/10X, 1/50X, 1/100X, and 1/200X, along with two different application timings: 2- 3-leaf (fall) and 3- 4-tiller (spring). Visual injury was evaluated every two weeks throughout the growing season, along with the collection of end-of-season biomass, harvest index, and grain yield. For yield, herbicide rate by application timing interaction was significant for half of the site years. At the other four site years, a herbicide rate main effect was observed. For the interaction, regardless of application timing, the field-use rate 1X resulted in complete crop loss or near crop loss. For the 1/10X rate with the fall application, yield loss ranged from 0 to 39% whereas with the spring application, loss ranged from 80 to 100%. No significant yield reduction was observed following the three lowest rates, except for Stillwater 2019 and 2020, then Perkins in 2019. At Stillwater there was an 11% reduction in yield at the 1/200X rate in 2019, and 20% yield reduction at the 1/50X rate in 2020. Perkins 2019 also had an 8% yield reduction followed the 1/50X rate When rate was a significant main effect, all 1/10X applications led to 86 to 100% yield loss. There was no significant visual injury or yield loss with the three lowest rates with the exclusions above. The environment had a substantial impact on wheat response with the 1/10X rate. Minimal response was most likely when it was cold and dry before and after application because wheat plants were not actively growing, thus not translocating the herbicide effectively.

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Literature Review

Weed Management in Winter Wheat in Oklahoma/Southern Great Plains

In Oklahoma, winter wheat (*Triticum aestivum L.*) is the number one agricultural commodity, when considering the cattle, forage, and grain production components. In 2019, 1,699,680 ha were planted with an average yield of 2,690 kg ha^{-1}. Of the almost 1,700,000 ha planted, 1,112,885 were harvested for grain. (USDA 2019). Winter wheat in Oklahoma is unique as many systems utilize the crop for forage and/or grain. Wheat can be planted from early September for stocker cattle/grain or even into November for grain only systems, with harvest in late May into June. Kansas, on the other hand, planted 2,873,268 ha of wheat in 2019 with most of the hectares (2,711,393) being harvested for grain (USDA 2019). The cattle component in Oklahoma is more prevalent than that of Kansas.

Due to the flexibility that winter wheat systems offer, many growers in Oklahoma and the southern Great Plains are continuous wheat growers, growing wheat in the same field year after year. This practice fails to break up pest cycles and often results in many weed species taking over fields. Additionally, similar herbicide products or herbicide sites of action often are used year after year, which contributes to the selection of herbicide resistant weed biotypes.

Winter annual grass weeds are a top challenge for many wheat producers as they germinate in the fall and have a similar life cycle as wheat. Fast et al. (2019) stated that out of the top 10 most difficult and common weeds in winter wheat in Oklahoma, five were grassy weeds and included true cheat *(Bromus secalinus* L.*),* Italian ryegrass *(Lolium perenne* L. *spp. Multiflorum* (Lam.) Husnot*),* feral rye *(Secale cerea* L.*),* jointed goatgrass *(Aegilops cylindrical* Host*),* and wild oat *(Avena fatua* L.*)*. Fast et al. (2019) named true cheat the most prevalent of all grassy weeds in Oklahoma wheat, causing a yield reduction up to 19% when 89 cheat plants m^{-2} were present. There was 16 to 20% yield loss when 30 plants m^{-2} of Italian ryegrass were present, a 55% reduction in yield from 80 feral rye plants m^{-2}, and 17 jointed goatgrass plants m^{-2} led to an 18% yield loss. Fields overwhelmed with true cheat also experienced dockage at the mill that was upwards of 40%. Today, these winter annual grass weeds are still difficult-to-manage. Other *Bromus* species, such as Japanese brome (*Bromus japonicus* Houtt.) and rescuegrass (*Bromus catharticus* Vahl) also are critically important.

Cultural weed management practices, which increase crop competition over weeds, should be considered by agricultural stakeholders battling winter annual grassy weeds. Closer row spacing for wheat to better compete with weeds, like cheat, is a viable option, along with higher seed populations (Justice et al. 1993). If one is not a dual-purpose wheat producer, requiring forage in late summer, a delayed planting can create opportunities to kill early weed flushes of bromes or feral rye using a burndown herbicide or mechanical operation. When infestations are severe and weeds do not respond well to in-season herbicides, crop rotation to a summer crop or winter annual broadleaf crop might be considered.

Winter canola (*Brassica napus* L.), for example, was incorporated into Oklahoma wheat rotations in order to create the opportunity to spray group 1 herbicides (clethodim, quizalofop, and sethoxydim) to control grassy weeds. Use of Roundup Ready® canola varieties also allowed for the use of glyphosate, a group 9 herbicide. Peak planted hectares of canola occurred in Oklahoma in 2013 at around 160,000 hectares (Oklahoma Farm Report 2013). Unfortunately, hectares have dramatically decreased since then due to low canola prices, poorly adapted varieties, and what some consider a crop that is too intensive to manage, especially when compared to wheat.

In-season chemical use is a short-term management option for many annual grass weeds in wheat. Most of the products labelled for grass control are Weed Science Society of America (WSSA) group 2 or acetolactate synthase (ALS) inhibiting herbicides. In the early 90s, a PRE application of chlorsulfuron and metsulfuron controlled 72% or more true cheat in Oklahoma (Driver et al. 1993). However, today, most of Oklahoma's critically important grass weeds have developed resistance to group 2 herbicides (Heap 2020). A true cheat population even exists in the state that is cross-resistant to group 2 herbicides imazamox, propxycarbazone-sodium, pyroxasulam, and sulfosulfuron (Heap 2020).

Other sites of action that might be utilized to control grasses in wheat include group 1 (pinoxaden), 3 (pendimethalin), 5 (metribuzin), 14 (carfentrazone), and 15 (flufenacet and pyroxasulfone) herbicides. Pinoxaden is a common group 1 herbicide used in Oklahoma for Italian ryegrass control. The herbicide successfully controls Italian ryegrass plants that have not exceeded the third tiller growth stage unless they are resistant to the herbicide. Unfortunately, Italian ryegrass biotypes resistant to pinoxaden were documented just last year in Oklahoma (Heap 2020). Other weeds that pinoxaden is effective on include wild oat, a winter annual grass that still infests many fields in southwestern Oklahoma. Pinoxaden and similar group 1 herbicides currently labelled for use in wheat do not have any activity on feral rye or *Bromus* species.

The WSSA group 3 herbicides, sometimes referred to as “yellows” because of their color, also can control/suppress several grassy weeds as well as small-seeded broadleaves in wheat. Target weeds include Italian ryegrass, wild oat, true cheat, downy brome, and Palmer amaranth (*Amaranthus palmeri* S. Wats.). Pendimethalin and trifluralin are two group 3 herbicides labelled for use in wheat. However, pendimethalin is not commonly used because of the high cost of the chemical, required POST application timing (which is usually after emergence of key grassy weeds), and ability to only suppress some troublesome grasses. Additionally, trifluralin must be physically incorporated, and wheat seed must be placed below this zone at a depth that is typically greater than six cm (Anonymous 2011a). This requirement isn’t always conducive, depending on current and future moisture conditions.

Metribuzin, a WSSA group 5 herbicide, also can suppress bromes. Durutan (1975) conducted a study to evaluate metribuzin application timing in winter wheat and concluded that metribuzin applied at the three to four tiller stage provided the highest wheat yield along with the greatest true cheat control out of five application timings (PRE, one leaf, three leaf-tillering, three to four tiller, and early joint). They also found that PRE and at spike applications caused the most damage to wheat, anywhere from 15 to 37% injury. Justice et al. (1993) documented that metribuzin controlled 80 to 100% of bromes in central Oklahoma; however, with rates upwards of 510 g ai ha^{-1} that can be detrimental to the wheat (Justice et al. 1993). Flufenacet plus metribuzin is a common herbicide premix used in Oklahoma today to control resistant Italian ryegrass biotypes. It can control Italian ryegrass from 80 to 99% but can cause 7 to 45% wheat injury (Koepke-Hill et al. 2011). There are several factors that contribute to wheat response following flufenacet plus metribuzin applications such as: temperature, rainfall, soil texture, soil organic matter, variety of wheat, and growth stage of the wheat at application.

Winter wheat variety tolerance to herbicides is seldomly studied; however, it is well documented that some varieties are more sensitive to the active ingredient, metribuzin, than others (Bhoite 2017). This information is listed on metribuzin labels; however, the varieties listed are not relevant to currently planted varieties (Anonymous 2004b). For herbicides that significantly injure crops, including metribuzin, it would be beneficial to further study the impact that these products may have on different varieties.

Preemergence herbicides that are safer for wheat include pyroxasulfone, a group 15 herbicide. In Oklahoma, pyroxasulfone containing products can be applied from 80% germination of wheat (½-inch long coleoptile) until the fourth tiller. If the product is not applied at the ideal timing and/or incorporated by rainfall, weed control will be greatly reduced. When applied on time and incorporated sufficiently by rain, pyroxasulfone provides nearly season long control of Italian ryegrass. However, its activity on other important grass weeds is minimal. Group 15 herbicides also are the last site of action that is widely controlling Italian ryegrass in Oklahoma. With the overuse of this site of action, the selection for herbicide resistance will follow if not integrated with other weed management practices.

For nearly the last two decades, the only herbicide tolerant wheat system available has been the Clearfield® or Clearfield Plus® systems. Clearfield® wheat varieties are tolerant to imazamox, a group 2 herbicide that has PRE and POST activity of many broadleaf and grass weed species. The Clearfield® Plus varieties were first released in 2012 and contained two genes that confer tolerance to imazamox. The two gene tolerance was developed to increase tolerance to imazamox and provide more flexibility in surfactant partners. Clearfield® wheat and other Clearfield® crops were developed using conventional breeding methods.

The labelled imazamox herbicide that is used in Clearfield® systems is Beyond®. Beyond® controls or suppresses over 50 broadleaf weeds and over 30 grassy weeds. Some of the more challenging weeds to control on the label include feral rye, wild oat, most bromes including rescuegrass, jointed goatgrass, three *Amaranthus* species, kochia (*Bassia scoparia* L.), several mustards, field bindweed (*Convolvulus arvensis* L.), and wild buckwheat (*Fallopia convolvulus* L.) (Anonymous 2019c). In the past, it has been the selected system to manage feral rye populations in Oklahoma as no conventional herbicides have activity on feral rye. However, in recent years, many agricultural stakeholders have complained about poor or inconsistent control of feral rye following imazamox applications. As a result of inconsistent results, the herbicide label now only supports feral rye suppression (Anonymous 2019c).

Italian ryegrass can be suppressed by imazamox if not resistant to group 2 herbicides. Grey (2012) observed 70 to 78% control of a susceptible Italian ryegrass population following imazamox at 80 g a.i. ha^{-1} when applied early POST. However, control levels in the 70s typically are not supported by producers especially when considering the cost of the technology. Control also may be much less than 70% if ryegrass plants are resistant to group 2 herbicides. Unfortunately, most in Oklahoma are. Additionally, the cost of the system may deter those who are averse to investing in seed and herbicide applications, and sometimes the costs are not justifiable for anyone in low wheat price years. For the seed and a single fall herbicide application, it costs approximately $57 per hectare. Finally, if the technology is not stewarded, it will contribute to the widespread selection of imazamox resistant weed biotypes. The system should not be used alone without the integration of other weed management practices such as crop rotation.

CoAXium® Wheat

The second herbicide tolerant wheat system is CoAXium® Wheat Production Systems, developed by the Colorado Wheat Research Foundation, Albaugh®, and Limagrain Cereal Seeds. The system allows for the use of quizalofop-p-ethyl (quizalofop) over-the-top of wheat. The AXigen® (AX®) trait in wheat was developed by EMS mutagenesis, by treating winter wheat with 60 mmol L^{-1} EMS and screening M_2 and $M_{2:3}$ populations with quizalofop to identify herbicide tolerant plants with an amino acid change from alanine to valine at position 2004 (Ostlie et al. 2015). There are currently nine varieties that are commercially available that have the AX® trait where Aggressor™ herbicide can be applied over-the-top of these wheat varieties with minimal crop response. Quizalofop is an acetyl-CoA carboxylase (ACCase) inhibitor [ACCase inhibitor (WSSA group 1 herbicide) that provides POST control of many spring and winter annual grasses in CoAXium® wheat. In Oklahoma, it may improve control of feral rye and many *Bromus* species. This is the first-time a group 1 herbicide (besides pinoxaden) can be used in wheat to manage difficult-to-control grassy weeds that are resistant to group 2 herbicides. The incorporation of a group 1 herbicide into existing herbicide systems may delay the selection for herbicide resistant weed species when used properly. However, overuse of the technology will do the opposite and will further select for group 1 herbicide resistant weeds.

It is critical that agricultural stakeholders assess the challenges that the technology might bring along with the benefits. The first and most obvious challenge is how stewardship will be preserved. In a typical Oklahoma wheat system where wheat will be planted in consecutive years, one cannot use Aggressor™ two years in a row, but it can be used every other year (Anonymous 2020d). However, pinoxaden, which is often used to control Italian ryegrass, can be used in the years Aggressor™ is not being applied, which would result in a group 1 herbicide being applied every year.

A second challenge for a grower who might want to invest in the technology is the price of the system vs. low wheat prices. The average price for wheat during harvest last season was $4.50 per bushel while prices were in the upper $5 range five years ago and south of $3 for some areas in 2016 (barchart.com). With declining wheat prices, it is difficult for producers to make an investment in herbicide applications let alone a herbicide tolerant wheat system such as Clearfield® or CoAXium®. One poor investment decision can be the difference between profit or loss in low-price years.

A third challenge that a CoAXium® user may encounter is the risk of off-target movement by either physical drift or tank contamination. If a grower has only some hectares planted to the AX® trait, it will be critical that proper tank cleanout procedures are followed when using the same sprayer in a field that does not contain the AX® trait. Physical movement of quizalofop at time of application also can be a concern, especially during poor spray conditions (high winds, high boom, improper nozzle selection, etc.).

Sensitivity of corn, grain sorghum, and conventional rice to low rates of quizalofop has been evaluated; however, response of conventional wheat to quizalofop has not been tested (Abit et al. 2012; Lancaster et al. 2017). Lancaster evaluated 1/10X, 1/25X, 1/50X, 1/100X, and 1/200X rates of quizalofop 1X=160 g a.i. ha^{-1}) applied these treatments in corn (*Zea mays* L.), grain sorghum (*Sorghum bicolor* L.), and rice (*Oryza sativa* L.). In corn, the 1/10X rate at the two to three leaf timing resulted in the greatest percent visual injury (58%) compared to the nontreated control. Quizalofop application at the 1/10X rate at tassel and silk reproductive stages resulted in only 4% and 5% visual injury, respectively. At the 1/10X rate at the two to three leaf application timing, yield was reduced by 57%, the greatest reduction of any rate or timing. Lower rates resulted in similar yields compared to the nontreated control.

Grain sorghum followed a similar patter with the 1/10X rate resulting in the greatest injury. At the two to three leaf application timing at the 1/10X rate, 31%, 2%, and 23% visual injury was observed following the two to three leaf, at boot, and panicle exertion application timings. Grain sorghum had a similar trend as corn for yield with the 1/10X rate applied at the two to three leaf and panicle exertion timings resulting in yield reductions of 45 and 71%, respectively. In the same study, rice responded differently than corn and grain sorghum. There was no statistical differences in visual injury, plant height, or yield relative to the nontreated control; because of rice having a natural tolerance to quizalofop at those rates (Lancaster et al. 2018).

Abit et al. (2012) also evaluated the response of grain sorghum to various quizalofop rates and application timings. The grain sorghum variety was a line developed at Kansas State University to be tolerant to aryloxyphenoxypropionate herbicides, including quizalofop; however, plants were still sensitive. Rates included a 1X, 2X, 3X, and 4X rate where the 1X rate equaled of 62 g a.i. ha^{-1} while application timings included an early POST, mid-POST, and a late POST. One week after treatment, the early POST application resulted in 9% visual injury at the 1X rate and 68% injury at the 4X rate. The mid-POST timing resulted in 2% injury at the 1X rate and 48% at the 4X rate. The late POST application resulted in 3% injury at the 1X application and 16% injury at the 4X rate. Application timing also influenced flowering date. Flowering date was delayed by four to ten days following the mid POST and late POST applications at the three highest rates compared to the nontreated control. Averaged over all four rates, no yield differences were detected at the Hays, KS location while a 17 to 19% reduction in yield was observed for the mid-POST application timing compared to the early POST and late POST timings, respectively.

To evaluate the sensitivity of wheat that is not tolerant to quizalofop, experiments were conducted in central Oklahoma and Kansas during the 2019-20 and 2020-21 winter wheat growing seasons to better understand what might happen if quizalofop herbicide is moved off-target by physical drift or tank contamination onto wheat that does not contain the AXigen® trait. Physical drift and tank contamination was focused on instead of volatility as quizalfoop does not have substantial volatilization characteristics (Shaner

2014). A secondary objective of the experiment was to study the impact of carrier volume on wheat injury across various quizalofop rates. This was studied because the most scrutinized component of simulated physical drift studies is that herbicide rates are applied in constant and often high carrier volumes, typically 94 to 187 L ha^{-1} (Lancaster et al. 2017). This method is critiqued because many argue that when herbicide droplets move off-target in true physical drift scenarios, drift would decrease with movement downwind from the point of application and as water in the spray solution evaporates, remaining droplets would become more concentrated with herbicide and surfactant. It's also true that it's difficult to predict what the product concentration might be as the degree of water evaporation would depend on many variables, such as relative humidity and temperature (Roider et al. 2008).

The cuticular membrane and the concentration of the herbicide droplet influence its movement into the plant (Devine et al 1993) so the scrutiny of carrier volume is warranted. It's important that simulated drift studies strive to mimic what actually might happen during true physical drift scenarios in order to try to understand the relationship between visual injury and yield and/or quality loss, although crop yields are not always affected when physical drift occurs. Depending on the stage of the crop, it may recover and just have transient injury. The plant also may show growth reduction early after the drift occurs, but it may recover. If the plant displays season long negative response, the possibility of yield reduction is more likely (Al-Khatib and Peterson 1999).

Some have studied the concept of herbicide concentration in simulated drift experiments. Banks and Schroder (2002) were the first to evaluate this idea and used glyphosate in sweet corn and 2,4-D in cotton. For both crop – herbicide cases, Banks and

Schroder concluded that carrier volume did impact sweet corn and cotton fresh biomass; however, the impact was dependent on herbicide rate. At the lowest glyphosate rate (0.046 kg ha^{-1}), carrier volume did not affect sweet corn biomass, but when rates increased to 0.092, 0.185, and 0.37, the variable carrier volume (12, 24, 47, and 94 L ha^{-1}) did result in increased sweet corn injury and decreased biomass compared to the constant carrier volume of 281 ha^{-1}. For cotton, the same rates were applied but with 2,4-D instead of glyphosate. At the two lowest 2,4-D rates (0.046 and 0.092 kg ha^{-1}), the variable carrier volume resulted in increased cotton injury while the two highest rates (0.185 and 0.37 kg ha^{-1}) were not impacted by carrier volume.

Smith et al. (2017) agreed with Banks and Schroeder that constant carrier volumes with diluted herbicides were not giving an accurate representation of physical drift, in fact it was underestimating the impact that a more concentrated droplet would have. They stated that to correctly estimate drift injury, one must accurately reduce the carrier volume along with herbicide proportion, then compare that to the constant carrier volume and herbicide rate. Smith studied two application timings (six leaf and first square), two different herbicides (dicamba and 2,4-D), two rates (18.7 and 37.4 g ae ha^{-1}), and two variable carrier volumes (4.7 and 9.4 L ha^{-1}), along with a constant carrier volume of 140 L ha^{-1}. Each of the herbicide rates were sprayed with the constant carrier volume. When the carrier of 4.7 L ha^{-1} was sprayed, the herbicide rate was 18.7 g ha^{-1}, whereas the 9.4 L ha^{-1} carrier was sprayed at the 37.4 g ha^{-1} rate, which maintained the same herbicide concentration.

Dicamba applied at the sixth leaf growth stage with the constant carrier volume yielded 87% of nontreated control, which was the highest yield out of any carrier volume or application timing. For the variable carrier volume (herbicide rate averaged), there was less yield at 70% of the nontreated control. At the first square application timing, the variable carrier volume again resulted in less yield (59% of the nontreated) compared to the constant carrier volume, which yielded 81% of the nontreated. When 2,4-D was applied at the sixth leaf timing for the variable carrier volume, only 19% of the nontreated yield was recorded while the constant had more yield (32%). Finally, at the first square application timing, the variable carrier volume had just 3% yield and the constant carrier volume had a similar yield of 11%.

Roider et al. (2008) conducted a similar study where glyphosate drift was simulated on winter wheat to observe the effects of carrier volume on crop response. The rationale behind the study was that producers using glyphosate for burndown weed control prior to planting cotton and/or corn ground would also have fields planted to wheat that was at various growth stages. Factors included wheat growth stage (first detectable node and heading), carrier volume, and glyphosate rate (1,120, 140, and 70 g ai ha^{-1}). Glyphosate was applied in a constant carrier volume of 234 L ha^{-1} and in proportional carrier volumes of 30 L ha^{-1} for the 12.5% (140 g ai ha^{-1}) rate and 15 L ha^{-1} for the 6.3% (70 g ai ha^{-1}) rate, which maintained a constant herbicide concentration in the carrier. When glyphosate was applied in proportions (the two rates and carrier volumes combined) a greater yield reduction of 48% was observed compared to 26% yield loss following the constant carrier volume of 234 L ha^{-1}.

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CHAPTER II

SENSITIVITY OF NON-TOLERANT WINTER WHEAT TO QUIZALOFOP-P-ETHYL IN CENTRAL OKLAHOMA AND KANSAS

Introduction

In Oklahoma, winter wheat is the number one agricultural commodity, when considering the cattle, forage, and grain production components. In 2019, 1,699,680 ha were planted with an average yield of 2,690 kg ha^{-1}. Of the almost 1,700,000 ha planted, 1,112,885 were harvested for grain. (USDA 2019). Winter wheat in Oklahoma is unique as many systems utilize the crop for forage and/or grain. Wheat can be planted from early September for stocker cattle/grain or even into November for grain only systems with harvest in late May into June. Kansas, on the other hand, planted 2,873,268 ha of wheat in 2019 with most of the hectares (2,711,393) being harvested for grain (USDA 2019). The cattle component in Oklahoma is more prevalent than that of Kansas.

Due to the diversity that winter wheat systems offer, many growers in Oklahoma and the southern Great Plains are continuous wheat growers, growing wheat in the same field year after year. This practice fails to break up pest cycles and often results in many weed species taking over fields. Additionally, similar herbicide products or herbicide sites of action often are used repeatedly, which contributes to the selection for herbicide resistant weed biotypes.

Winter annual grass weeds are a top challenge for many wheat producers as they germinate in the fall and have a similar life cycle as wheat. Fast et al. (2019) stated that out of the top 10 most difficult and common weeds in winter wheat in Oklahoma, five were grassy weeds and included true cheat *(Bromus secalinus* L.*),* Italian ryegrass *(Lolium perenne* L. *spp. Multiflorum* (Lam.) Husnot*),* Feral rye *(Secale cerea* L.*),* jointed goatgrass *(Aegilops cylindrical* Host*),* and wild oat *(Avena fatua* L.*)*. Fast et al. (2009) true cheat named the most prevalent of all weeds in Oklahoma wheat, causing a yield reduction up to 19% when 89 cheat plants were present m^{-2}. There was 16 to 20% yield loss when 30 plants m^{-2} of Italian ryegrass were present, a 55% reduction in yield from 80 feral rye plants m^{-2}, and 17 jointed goatgrass plants m^{-2} led to an 18% yield loss. Fields overwhelmed with true cheat experienced dockage at the mill that was upwards of 40%. Today, these winter annual grass weeds are still difficult-to-manage. Other *Bromus* species, such as Japanese brome (*Bromus japonicus* Houtt.) and rescuegrass (*Bromus catharticus* Vahl) also are economically important.

Cultural weed management practices, which increases crop competition with weeds, are the best long-term solutions to managing winter annual grass weeds. Closer row spacing for wheat to better compete with weeds, like cheat, is a viable option, along with higher seed populations (Justice et al. 1993). If one is not a dual-purpose wheat producer, requiring forage in late summer, a delay in planting can create opportunities to kill early weed flushes of bromes or feral rye using a burndown herbicide application or mechanical operation. When infestations are severe and weeds do not respond well to in-season herbicides, crop rotation to a summer crop or winter annual broadleaf crop should be considered to allow for the use of other management options, including other herbicide sites of action. In the short-term, in-season chemical management is an option for control of many annual grass weeds in wheat. Most of the products labelled for grass control are group 2 or acetolactate synthase (ALS) herbicides. In the early 90s, a PRE application of chlorsulfuron and metsulfuron controlled true cheat 72% or more in Oklahoma (Driver et al. 1993). However, today, most of Oklahoma's critically important grass weeds have developed resistance to group 2 herbicides (Heap 2020). True cheat populations in Oklahoma even exist that are cross-resistant to group 2 herbicides imazamox, propxycarbazone-sodium, pyroxasulam, and sulfosulfuron (Heap 2020).

Other sites of action that might be utilized to control grasses in wheat include Weed Science Society of America (WSSA) group 1 (pinoxaden), 5 (metribuzin), and 15 (pyroxasulfone) herbicides. Pinoxaden is a common group 1 herbicide used POST in Oklahoma for Italian ryegrass control. Unfortunately, Italian ryegrass biotypes resistant to pinoxaden were documented just last year in Oklahoma (Heap 2020). Not many options exist for *Bromus* spp. control. Metribuzin is an option but is sparingly used due to crop response concerns (Durutan 1975; Justice 1993). Preemergence herbicides that are safer for wheat include pyroxasulfone, a group 15 herbicide, but this active ingredient only suppresses most *Bromus* spp. and has no activity on feral rye.

For nearly the last two decades, the only herbicide tolerant wheat system available has been the Clearfield® or Clearfield® Plus systems. Clearfield® wheat varieties are tolerant to imazamox, another group 2 herbicide that has PRE and POST control of many broadleaf and grass weed species unless herbicide resistant. In the past, it has been the selected system to manage feral rye populations in Oklahoma as no conventional herbicides have activity on feral rye. However, in recent years, many agricultural stakeholders have complained about the poor control of feral rye following imazamox applications. Still, the system is used to control *Bromus* spp. that are susceptible to imazamox (Japanese brome and rescuegrass).

The second herbicide tolerant wheat system to be released is CoAXium® Wheat Production Systems, developed by the Colorado Wheat Research Foundation, Albaugh®, and Limagrain Cereal Seeds. The system allows for the use of quizalofop-p-ethyl (quizalofop) over-the-top of wheat *(Triticum aestivum L.)*. The AXigen® (AX®) trait in wheat was developed by EMS mutagenesis, by treating winter wheat with 60mmolL^{-1} EMS and screening M_2 and $M_{2:3}$ populations with quizalofop to identify herbicide tolerant plants (Ostlie et al. 2015). There are currently nine varieties that are commercially available that have the AX trait where Aggressor™, the labelled quizalofop herbicide, can be applied over-the-top of these wheat varieties with minimal crop response when used within the application window. Quizalofop is an acetyl-CoA carboxylase inhibitor (ACCase) inhibiting, group 1 herbicide that provides POST control of many spring and winter annual grasses in wheat. In Oklahoma, feral rye and *Bromus* species will be critical weeds that the technology can aid in managing.

Although the new weed control option is exciting, it also is critical that agricultural stakeholders assess the challenges that the technology might bring alongside the benefits. The first and most obvious challenge is how stewardship with be preserved. In a typical Oklahoma wheat system where wheat will be planted in consecutive years, one cannot use Aggressor™ two years in a row, but it can be used every other year (Anonymous 2020). However, pinoxaden, which is often used to control Italian ryegrass, can be used in the years Aggressor™ is not being applied, which would result in a group 1 herbicide being applied every year.

A second challenge that a CoAXium® user may encounter is the risk for off-target movement by either physical drift or tank contamination. If a grower has only some hectares planted to the AX® trait, it will be critical that proper tank cleanout procedures are followed when using the same sprayer in a field that does not contain the AX® trait. Physical movement of quizalofop at time of application also can be a concern, especially during poor spray conditions (high winds, high boom, improper nozzle selection, etc.).

Sensitivity of corn, grain sorghum, and conventional rice to low rates of quizalofop has been evaluated; however, response of wheat has not (Abit et al. 2012; Lancaster et al. 2017). Lancaster evaluated 1/10X, 1/25X, 1/50X, 1/100X, and 1/200X rates of quizalofop where160 g a.i. ha^{-1} equaled the 1X rate and applied these treatments in rice (*Oryza sativa* L.), corn (*Zea mays* L.), and grain sorghum (*Sorghum bicolor* L.). In corn, the 1/10X rate resulted in the greatest height reduction at 58% compared to the nontreated control. Application at the 1/10X rate at tassel and silk reproductive stage had a 4% and 5% reduction in height, respectively. Grain sorghum followed a similar patter with the 1/10X rate resulting in the most injury. The 2 to 3 leaf stage had a height reduction of 92% while the application at boot only had 2% injury; however, at the panicle emergence timing the 1/10X rate resulted in 23% injury. In the same study, rice responded different than corn and grain sorghum. It showed no observable damage at any stage of plant life or following any rate (Lancaster et al. 2018).

Abit et al. (2012) also evaluated the response of grain sorghum to various quizalofop rates and application timings. Rates included a 1X, 2X, 3X, and 4X rate where the 1X rate equaled of 62 g a.i. ha^{-1} while application timings included an early POST, mid-postemergence, and a late POST. The early POST application resulted in 9% injury at the 1X rate and 68% injury at the 4X rate. The mid-postemergence timing resulted in 2% injury at the 1X rate and 48% at the 4X rate. The late POST resulted in 3% injury at the 1X application and 16% injury on the 4X rate (Abit et al. 2012).

To evaluate the sensitivity of wheat that is not tolerant to quizalofop, experiments were conducted in central Oklahoma and Kansas during the 2019-20 and 2020-21 winter wheat growing seasons in order to better understand what might happen if quizalofop herbicide is moved off-target onto wheat that does not contain the AX® trait.

Materials and Methods

Field experiments were conducted in Lahoma (36°23'08.6"N 98°06'46.4"W; elevation of 380m), Perkins (35°59'16.4"N 97°02'54.2"W; elevation of 273 m), and Stillwater (36°07'15.3"N 97°05'19.3"W; elevation of 300 m), in Oklahoma, and Hays (38°51'23.8"N 99°20'12.2"W; elevation of 616m), in Kansas, during the 2018-2019 and 2019-2020 winter wheat growing seasons (October to June). However, for the purpose of this chapter, field seasons are referred to as the year in which harvest took place. All Oklahoma fields were planted using a grain drill with 19 cm row spacing, while the Kansas location used a 25 cm row spacing, both with a seeding rate of 67 kg ha^{-1}. The Lahoma site was on a Grant silt loam (Fine-silty, mixed, superactive, thermic Udic Argiustolls) with an average pH of 6.3 and 1.8% organic material (OM). The Perkins site was on a Teller loam (Fine-loamy, mixed, active, thermic Udic Argiustoll) with an average pH of 6.4 and 0.8% OM. The Stillwater site was on a Kirkland silt loam (Fine, mixed, superactive, thermic Udertic Paleustolls) with an average pH of 6.4 and 2.1% OM. The Hays site was on a stilt clay loam with an average pH of 7.8 and 2.1% OM. In-season rainfall as well as wheat variety, planting date, herbicide application dates, and harvest date for all locations are listed in (Table 2.1). All studies were arranged as a factorial in a randomized complete block design with four replications. Individual plots were 2.1 or 3 m wide by 9.1 m in length. Herbicide applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1}, using Turbo TeeJet® 11002 nozzles. All treatments were applied POST. The fall application was made when wheat was 2- to 3-leaf, while the spring application was made at 3- 4-tillers.

All herbicide treatments were applied using water as the carrier. All treatments included a crop oil concentrate at 1% (vol/vol) and were applied once in the spring or fall. Six treatments consisting of various quizalofop-P-ethyl (Aggressor™, 105 g ai L^{-1}, Albaugh, LLC, 1525 NE 36th Street, Ankeny, Iowa 50021) rates (1X, 1/10X, 1/50X, 1/100X, and 1/200X) were applied in the fall or in the spring. The 1X rate represented 92 g ai ha^{-1}. The rate of 92 g ai ha^{-1} is the maximum single application rate according to the Aggressor™ label (Anonymous 2020). Wheat visual injury estimates were recorded approximately every two weeks beginning at 14 to 28 d after treatment (DAT) using a scale of 0 to 100 percent, where 0 equaled no crop injury and 100 equaled complete plant death. Herbicide application rates and plant growth stages at time of application followed guidelines of the Aggressor™ label (Anonymous 2020). Wheat was harvested with a

Wintersteiger (Wintersteiger Inc, Salt Lake City, UT) small plot combine. Prior to harvest, two 0.10 m^2 quadrats were harvested from each plot and dried in a drying oven at 50 C for two days. A weight was recorded for each dried samples and number of heads were counted. Samples were then threshed with an Almaco plant and thresher, model number SVSE-2 (Allan Machine Inc., Ames, IA) to collect grain per sample. Finally, harvest index was calculated by taking the grams of grain divided by the total grams of above ground biomass. The concept of harvest index (HI) was identified in the early 1960s and is the proportion of total aboveground biomass that goes into harvestable parts (David 1962). Harvest index is calculated by dividing seed weight by above-ground biomass; therefore, the value of HI will never be over 1.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.4, SAS Institute Inc., SAS Campus Drive, NC). No data sets were transformed as transformation did not increase stabilization. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an α level of 0.05. In the model, fixed effects included application timing and herbicide rate and random effects included replication.

Results & Discussion

Due to significant location by treatment interactions, all site years were analyzed independently.

End-of-season Visual Injury

There was a herbicide rate by application timing interaction for Lahoma and Stillwater in 2019 as well as Perkins and Stillwater in 2020 (Table 2.4). At Lahoma in 2019, little injury (1-5%) was observed following the three lowest herbicide rates (1/50X, 1/100X, and 1/200X). At the 1X rate, 100% visual injury was recorded regardless of application timings. However, at the 1/10X rate, only 7% visual wheat injury was observed following the fall application, whereas 100% wheat injury was observed at the same rate following the spring application. For Perkins 2020, 99 to 100% wheat injury was noted for fall and spring applications at the 1X rate and following the 1/10X in the spring. The 1/10X rate in the fall resulted in less wheat injury (82%). At the 1/50X rate, injury increased four times from the fall to spring application. At Stillwater in 2019, 99 to 100% wheat injury was noted for fall and spring applications at the 1X rate and following the 1/10X in the spring, but the 1/10X rate in the fall only resulted in 10% injury. Fall and spring applications of the three lowest rates never caused more than 2% injury except for the 1/50X rate in the spring. Finally, in Stillwater 2020, 100% injury was observed in the fall following the 1X rate, but only 75% injury was recorded at the 1X rate in the spring. At the 1/10X in the fall and spring, 25% and 89% wheat injury was observed, respectively.

For Hays in 2019 and 2020, Perkins 2019, and Perkins 2020, a herbicide rate main effect impacted winter wheat visual injury (Table 2.4). For Hays in 2019, 100% visual injury was observed following the 1X rate while 97% injury was observed following the 1/10X rate, regardless of application timing. When the three lowest rates of 1/50X, 1/100X, and 1/200X were applied, little injury, (no more than 1%), was recorded. Similar tends were observed for Perkins in 2019 and Hays and Lahoma in 2020. Lancaster et al. (2017) also observed significant visual injury following application of quizalofop on corn and grain sorghum. The highest rate evaluated (16 g ai ha^{-1}) resulted in visual injury of 31 to 58% at the two to three leaf application timing for sorghum and corn, respectively. Overall, corn and grain sorghum were more sensitive than rice and the two to three leaf application timing was the most sensitive when compared to applications made later in the season.

End-of-season Wheat Biomass

For end-of-season wheat biomass, there was an application timing by herbicide rate interaction at Lahoma and Stillwater in 2019 and at Perkins and Stillwater in 2020 (Table 2.5). Biomass at Lahoma in 2019 for the nontreated in the fall along with the three lowest rates were not significantly different following fall and spring applications. Wheat biomass following the 1X rate of quizalofop in the fall and spring and 1/10X rate in the spring was 1 g 0.10 m^{-2} and not significantly different. However, biomass following the 1/10X rate in the fall was greater at all four site years compared to biomass following the 1/10X rate in the spring and following the 1X rate in the fall and spring. The greater biomass after the fall application was likely a result of poor herbicide uptake and translocation compared to the spring timing (Table 2.2 and Table 2.3). Finally, variability observed between nontreated plots in the fall vs. spring at Lahoma in 2019 can be attributed to the trial location site, which was on a terrace where standing water and erosion took place in some areas.

There was a herbicide rate main effect for Hays and Perkins in 2019, and Lahoma in 2020 (Table 2.5). Wheat biomass at Hays in 2020 was not collected. End-of-season wheat biomass at all three locations for the nontreated control and three lowest herbicide rates were similar. However, a reduction in biomass (approximately 69, 73, and 100%) following the 1/10X rates was observed at Hays in 2019, Lahoma 2020, and Perkins 2019, respectively. Lack of complete crop loss at Hays in 2019 following the 1X and 1/10X rates and at Lahoma in 2020 following the 1/10X rate was likely due to less than ideal growing conditions after application (Table 2.2 and Table 2.3). For the month of December, the application month, the lowest maximum temperature for the growing season was recorded. Then at Lahoma in November, the fall application month, the lowest temperature and one of the lowest maximum temperatures for the growing season was observed, along with the second lowest rainfall month for the growing season Biomass for the nontreated control at Hays along with the three lowest rates were not significantly different, while the 1X and 1/10X rates produced less biomass than the other fourtreatements. At Perkins in 2019 and Lahoma in 2020, complete crop loss was observed following the 1X rate of quizalofop. At Perkins in 2019, there also was complete crop loss at the 1/10X rate. Conversely, 39 grams of biomass was collected at Lahoma in 2020 following the 1/10X; however this was over three times less than the biomass produced from the nontreated control and three lowest rates. At Perkins in 2019, biomass was similar for the nontreated control and lowest three rates (approximately 143 g 0.10 m^2).

Harvest Index

Harvest index was not determined for Hays in 2020 and is not discussed for Hays in 2019 as no interactions or main effects were significant (data not shown). For four of the six years assessed (Lahoma and Stillwater in 2019 and Perkins and Stillwater in 2020), there was an application timing by herbicide rate interaction (Table 2.6). For Lahoma in 2019, there was complete crop loss for the 1X rate regardless of application timing resulting in a HI value of zero or close to zero. Following the 1/10X rate in the fall, HI (0.21) was similar to the nontreated control (0.25) but greater than the HI for the same rate in the spring (0.06). The three lowest rates along with the nontreated control had a similar HI with an average of 0.26. A similar trend was observed at Perkins in 2020.

In Stillwater in 2019, HI for the 1X rate in the fall and spring and 1/10X rate in the spring were similar and not greater than 0.08. In the fall, all other HI values were similar (0.31 to 0.35). In the spring, a HI of 0.26 followed the 1/50X rate, which was greater than the HI for the 1/10X and 1X rates but less than the HI following the 1/200X rate. Finally at Stillwater in 2020, complete crop loss was observed following the 1X rate of quizalofop regardless of application timing. In the fall, all other values were similar to the nontreated control. In the spring, a HI of 0.26 followed the 1/10X rate and was less than the nontreated control and the three lowest herbicide rates.

A herbicide rate main effect for HI was observed for two site years: Perkins in 2019 and Lahoma in 2020 (Table 2.6). At Lahoma, the 1X and 1/10X rates resulted in complete crop loss while the nontreated control and the three lowest rates had a similar HI from 0.33 to 0.34. At Perkins in 2019, the 1X and 1/10X rates of quizalofop resulted in complete crop loss. The nontreated control and the lower rates had a similar HI of 0.34 being statistically more than the 1/50X.

Winter Wheat Yield

An application timing by herbicide rate interaction was observed for four site years: Lahoma and Stillwater in 2019 and Perkins and Stillwater in 2020 (Table 2.7). In 2019 at Lahoma there was complete crop loss following the 1X rate of quizalofop, regardless of application timing. In the spring at the 1/10X rate there also was complete crop loss, while yield following the fall application at the 1/10X resulted in 2,165 kg ha^{-1} of grain, which was similar to yield following the nontreated and the three lowest herbicide rates. Perkins in 2020 followed a similar trend where the nontreated and the three lowest rates produced similar yields. Complete crop loss also was observed following the 1X rate at both application timings while only 3% of grain of the nontreated control was produced in the spring following the 1/10X rate. Yield was reduced 40% following the 1/10X rate in the fall compared to the nontreated and three lowest herbicide rates (3,668 kg ha^{-1}).

Stillwater in 2019 also followed a similar pattern with little difference in yield in the spring at the 1X and 1/10X rate and at the 1/10X in the fall while complete crop loss was recorded following the 1X rate regardless of application timing and following the 1/10X in the spring. Yield in the fall following the 1/10X rate resulted in 47% yield reduction compared to yield for the nontreated and the three lowest rates (4,156 kg ha^{-1}). In the spring, yields for the nontreated, 1/50X and 1/100X rates were similar while yields following the 1/50X, 1/100X, and 1/200X rates were statistically the same. A yield reduction of 15% followed the 1/200X compared to the nontreated control. At Stillwater in 2020 in the fall, a similar story was observed. The nontreated control and lowest three rates had similar yields while the 1X rate resulted in complete crop loss regardless of timing. In the spring only the nontreated, 1/100X, and the 1/200X rate had similar yields with an average of 5,270 kg ha^{-1}. The 1/10X had a yield reduction of 79 while complete crop loss followed the 1X rate.

The main effect of herbicide rate was significant at Hays in 2019 and 2020, Perkins in 2019, and Lahoma in 2020 (Table 2.7). At Hays in 2019 there was complete crop loss following the 1X rate while the 1/10X was similar and yielded 5% of the nontreated control. Yield following the nontreated and the three lower rates produced similar yields with an average of 5,413 kg ha^{-1}. Perkins in 2019 had complete or near to complete crop loss at the 1X and 1/10X rates. Yield following the 1/50X rate was 8% of the nontreated control but produced more grain than the 1X and 1/10X. Yields for Hays and Lahoma in 2020 followed a similar trend with the 1X rate resulting in complete crop loss, and the 1/10X rate reducing yield by 86 and 87%, respectively. Lancaster et al. (2017) also observed similar yield reductions in corn and grain sorghum where the highest rate (16 g ai ha^{-1}) resulted in a yield reduction of 58% in corn at the two to three leaf application timing and 45 and 71% in sorghum at the two to three leaf and panicle exertion timings, respectively.

Lahoma in 2019 and Perkins in 2020 experienced similar weather patterns that can help explain yield response (Tables 2.1, 2.2, and 2.7). Both locations experienced low temperatures during the fall application month of December where the minimum average temperature was -8ºC and the maximum temperature was 20°C, which resulted in wheat plants that were not actively growing. Conversely, during the spring application months of February and March, maximum temperatures reached 26°C and even higher in the weeks following application. During the more ideal temperatures fallowing the spring application, no more than 114 kg ha^{-1} of grain was produced following the 1/10X rate, whereas yield following the fall application were not less than 2,165 kg ha^{-1}. For both sites, fall conditions were not conducive for the plant to uptake and translocate the herbicide, as it was not actively growing and quizalofop primarily moves in actively growing regions of the plant, the phloem.

When understanding yield effects due to the rate as a main effect at Hays in 2019 and Perkins in 2019, temperature and rainfall also can help explain the story. Both site years had average low temperatures of 5ºC throughout the growing season and an average high of 27ºC. Average monthly rainfall received was 43 mm for Hays and 116 mm for Perkins. As a result, regardless of application timing, both sites resulted in wheat yields that were significantly lower than the nontreated control and three lowest herbicides rates following the 1/10X rate. The other two sites, Hays and Lahoma in 2020 were similar in yield reductions and also in weather patterns. Both locations had an average low of -6°C and average high of 28°C throughout the growing season. Average rainfall over the season was between 37 and 44 mm (Table 2.3). These conditions caused wheat plants to be stressed, which resulted in a similar lack of response following the 1X and 1/10X rates, regardless of application timing (Table 2.7).

The relationships between the environment and yield observations support that suitable wheat growing conditions will result in increased injury of quizalofop to wheat. Just like a weed, the crop needs to be healthy and actively growing to uptake the herbicide and translocate it to the site of action, in this case the ACCase enzyme. Cold temperatures accompanied by little rainfall appear to be two major factors that contributed to the variable response following the 1/10X rate in this study. Although this was not a weed control study, data also supports that actively growing weeds also are needed at time of quizalofop applications in order to observe proper kill.

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Table 2.1. Agronomic practices at Lahoma, Perkins, and Stillwater, Oklahoma, and Hays, Kansas during the 2018-2019 and 2019-2020 winter wheat growing seasons.

Year	Location	Wheat variety	Planting Date	Herbicide application dates	Harvest date
2018-2019	Lahoma	Iba	Oct 23	December 5 March 26	June 21
2018-2019	Perkins	Gallagher	Oct 29	December 5 March 26	June 13
2018-2019	Stillwater	Gallagher	Oct 31	December 6 March 26	June 19
2018-2019	Hays	Joe	Nov 15	December 18 April 1	July 17
2019-2020	Lahoma	Iba	Oct 17	November 25 February 27	June 2
2019-2020	Perkins	Gallagher	Oct 22	December 11 February 27	June 17
2019-2020	Stillwater	Gallagher	Oct 23	December 11 February 27	June 19
2019-2020	Hays	Joe	Oct 8	November 4 April 2	June 23

Table 2.2. Weather data at Hays, KS and Lahoma, Perkins, and Stillwater, OK during the 2018-19 winter wheat growing season.

	Hays 2019			Lahoma 2019			Perkins 2019			Stillwater 2019		
Month	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm
	Min	Max		Min	Max		Min	Max		Min	Max	
October				0	33	198	2	32	107	2	30	119
November	-15	19	12	-11	22	10	-9	23	20	-10	21	23
December	-12	15	43	-8	17	49	-6	17	97	-7	17	93
January	-15	18	13	-9	18	36	-9	19	72	-9	19	67
February	-17	19	8	-13	22	20	-11	21	36	-11	22	50
March	-22	27	18	-13	26	64	-13	26	54	-12	27	58
April	-2	29	23	-1	29	97	0	30	134	1	32	134
May	0	34	197	5	31	321	5	31	404	6	32	439
June	7	39	40	12	38	167	12	35	119	11	35	112
July	12	40	24									
Average	-7	27	43	-4	26	107	-3	26	116	-3	26	122
Total			378			962			1043			1095

[a] All Oklahoma rainfall data collected from the Oklahoma Mesonet (mesonet.org) and Kansas Mesonet (mesonet.k-state.edu)

[b] Rainfall was determined from planting date to harvest date.

Table 2.3. Weather data at Hays, KS and Lahoma, Perkins, and Stillwater, OK during the 2019-20 winter wheat growing season.

	Hays 2020			Lahoma 2020			Perkins 2020			Stillwater 2020		
Month	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm	Temperature ºC		Rainfall mm
	Min	Max		Min	Max		Min	Max		Min	Max	
October	-10	31	38	-7	34	58	-5	33	121	-5	33	99
November	-17	27	10	-11	24	30	-11	23	51	-11	24	67
December	-8	17	59	-6	22	37	-8	22	13	-8	22	12
January	-13	14	25	-6	20	36	-7	21	97	-7	22	82
February	-14	26	40	-10	24	29	-9	26	23	-10	27	29
March	-8	27	11	-3	27	77	-2	33	147	-4	33	128
April	-9	30	12	-3	31	25	-1	31	34	-1	33	30
May	2	31	81	2	34	49	3	33	67	3	33	87
June	11	38	61	11	39	57	12	36	76	11	36	66
Average	-7.3	27	37	-4	28	44	-3	29	70	-4	29	67
Total			337			398			629			600

[a] All Oklahoma rainfall data collected from the Oklahoma Mesonet (mesonet.org) and Kansas Mesonet (mesonet.k-state.edu)

[b] Rainfall was determined from planting date to harvest date.

Table 2.4. End-of-season percent visual wheat injury at Hays, KS and Lahoma, Perkins, and Stillwater, OK during the 2018-19 and 2019-20 winter wheat growing seasons.

	Hays 2019	Hays 2020	Lahoma 2019		Lahoma 2020	Perkins 2019	Perkins 2020		Stillwater 2019		Stillwater 2020	
						%						
Time*rate interaction			F	S			F	S	F	S	F	S
1X[a]			100 a[b]	100 a			100 a	100 a	99 a	100 a	100 a	75 b
1/10X			7 b	100 a			82 b	99 a	10 bc	99 a	25 cd	89 ab
1/50X			5 bc	4 cd			5 d	20 c	2 c	28 b	8 d	38 c
1/100X			3 cd	2 cd			1 d	3 d	0 c	0 c	1 d	6 d
1/200X			1 d	1 d			2 d	2 d	2 c	0 c	1 d	3 d
Rate												
1X	100 a	98 a			100 a	100 a						
1/10X	97 b	85 b			99 a	71 b						
1/50X	1 c	12 c			7 b	2 c						
1/100X	1 c	10 c			3 c	0 c						
1/200X	0 c	4 c			1 c	0 c						

[a] The 1X rate equaled 92 g ai ha^{-1} of quizalofop-P-ethyl. All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b] Means within a column for each site year followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$

Table 2.5. End-of-season winter wheat biomass (g 0.10 m^{-2}) at Hays, KS in 2018-19 and Lahoma, Perkins, and Stillwater, OK during the 2018-19 and 2019-20 growing seasons.

	Hays 2019	Lahoma 2019		Lahoma 2020	Perkins 2019	Perkins 2020		Stillwater 2019		Stillwater 2020	
	------- g -------										
Time*rate interaction		F	S			F	S	F	S	F	S
Nontreated		94 a[b]	63 c			121 a	111 a	149 a	147 a	153 a	156 a
1X[a]		1 d	0 d			0 c	0 c	3 c	0 c	0 d	0 d
1/10X		63 c	1 d			61 b	9 c	105 b	2 c	141 ab	44 c
1/50X		79 abc	66 c			122 a	126 a	152 a	139 a	140 ab	112 b
1/100X		87 ab	70 bc			127 a	133 a	147 a	144 a	127 ab	141 ab
1/200X		74 abc	60 c			130 a	116 a	148 a	145 a	148 a	128 ab
Rate											
Nontreated	156 a			143 a	136 a						
1X	29 b			0 d	0 d						
1/10X	49 b			39 c	0 d						
1/50X	176 a			144 a	144 a						
1/100X	188 a			132 ab	144 a						
1/200X	182 a			118 b	148 a						

[a] The 1X rate equaled 92 g ai ha^{-1} of quizalofop-P-ethyl. All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b] Means within a column for each site year followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$

Two samples pulled acquired from the back of each plot, using a 1/10th m^2 quadrats.

Table 2.6. Winter wheat harvest index (aboveground biomass in grams/seed weight in grams) at Lahoma, Perkins, and Stillwater, OK during the 2018-19 and 2019-20 growing seasons.

	Lahoma 2019		Lahoma 2020	Perkins 2019	Perkins 2020		Stillwater 2019		Stillwater 2020	
Time*rate interaction	F	S			F	S	F	S	F	S
Nontreated	0.25 abc	0.23 bc			0.36 a	0.33 ab	0.33 bc	0.44 a	0.32 ab	0.36 a
1X[a]	0.01 e	0 e			0 c	0 c	0.08 d	0 e	0 d	0 d
1/10X	0.21 c	0.06 d			0.25 b	0.08 c	0.32 bc	0.06 de	0.33 ab	0.26 c
1/50X	0.26 abc	0.23 bc			0.35 a	0.34 a	0.32 bc	0.26 c	0.36 ab	0.35 ab
1/100X	0.29 a	0.27 ab			0.33 a	0.33 ab	0.31 bc	0.33 bc	0.34 ab	0.35 ab
1/200X	0.26 abc	0.25 abc			0.34 a	0.32 ab	0.35 b	0.36 b	0.36 ab	0.31 ab
Rate										
Nontreated			0.34 a	0.30 a						
1X			0 c	0 b						
1/10X			0.19 b	0.01 b						
1/50X			0.33 a	0.29 a						
1/100X			0.34 a	0.30 a						
1/200X			0.33 a	0.31 a						

[a] The 1X rate equaled 92 g ai ha^{-1} of quizalofop-P-ethyl. All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b] Means within a column for each site year followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$

Table 2.7. Winter wheat yield (kg ha^{-1}) at Hays, KS and Lahoma, Perkins, and Stillwater, OK during the 2018-19 and 2019-20 growing seasons.

	Hays 2019	Hays 2020	Lahoma 2019		Lahoma 2020	Perkins 2019	Perkins 2020		Stillwater 2019		Stillwater 2020	
	---------- kg ha^{-1} ----------											
Time*rate interaction			F	S			F	S	F	S	F	S
Nontreated			2791 a[b]	2335 a			3694 a	3540 a	3971 abc	4394 ab	5745 a	5371 a
1X[a]			0 b	0 b			0 c	0 c	0e	0 e	48 e	0 e
1/10X			2165 a	8 b			2197 b	114 c	3385 d	0 e	4183 c	1090 d
1/50X			2376 a	2669 a			3824 a	3605 a	4427 a	3890 a-d	5761 a	4435 bc
1/100X			2693 a	2482 a			3548 a	3784 a	4256 abc	3857 bcd	5965 a	5192 ab
1/200X			2588 a	2579 a			3605 a	3629 a	3971 abc	3735 cd	5729 a	5249 a
Rate												
Nontreated	5382 a	2321 a			4915 a	4545 a						
1X	0 b	29 c			0 c	0 c						
1/10X	257 b	320 b			659 b	8 c						
1/50X	5509 a	2255 a			4447 a	4174 b						
1/100X	5390 a	2387 a			4618 a	4569 a						
1/200X	5369 a	2377 a			4634 a	4528 a						

[a] The 1X rate equaled 92 g ai ha^{-1} of quizalofop-P-ethyl. All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b] Means within a column for each site year followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$

CHAPTER III

EFFECT OF CARRIER VOLUME ON NON-TERLANT WHEAT TO QUIZALOFOP-P-ETHYL

Introduction

The most scrutinized component of simulated physical drift studies is that herbicide rates are applied in constant and often high carrier volumes, typically 94 to 187 L ha^{-1} (Lancaster et al. 2017). This method is critiqued because many argue that when herbicide droplets move off-target in true physical drift scenarios, drift would decrease with movement downwind from the point of application, and as water in the spray solution evaporates, remaining droplets would become more concentrated with herbicide and surfactant. It's also true that it's difficult to predict what the product concentration might be, as the degree of water evaporation would depend on many variables, such as relative humidity and temperature (Roider et al. 2008).

The cutic membrane does have an interaction between the concentration of the herbicide droplet and its movement into the plant (Devine et al 1993) so the scrutiny of carrier volume is warranted. It's important that simulated drift studies strive to mimic what actually might happen during true physical drift scenarios in order to try to understand the relationship between visual injury and yield and/or quality loss, although crop yields are not always affected when physical drift occurs. Depending on the stage of the crop, it may recover and just have transient injury. The plant also may show growth reduction early after the drift occurs, but it may recover. If the plant displays season long negative response, the possibility of yield reduction is more likely (Al-Khatib and Peterson 1999).

Some have studied the concept of herbicide concentration in simulated drift experiments. Banks and Schroeder (2002) were the first to evaluate the idea and used glyphosate in sweet corn and 2,4-D in cotton. For both crop – herbicide cases, Banks and Schroeder concluded that carrier volume did impact sweet corn and cotton fresh biomass; however, the impact was dependent on herbicide rate. At the lowest glyphosate rate (0.046 kg ha^{-1}), carrier volume did not affect sweet corn biomass, but when rates increased to 0.092, 0.185, and 0.37, the variable carrier volume did result in increased sweet corn injury and decreased biomass. For cotton, the same rates were applied but with 2,4-D instead of glyphosate. At the two lowest 2,4-D rates (0.046 and 0.092 kg ha^{-1}) the variable carrier volume resulted in increased cotton injury while the two highest rates (0.185 and 0.37 kg ha^{-1}) were not impacted by carrier volume.

Smith et al. (2017) agreed with Banks and Schroeder that constant carrier volumes with diluted herbicides were not giving an accurate representation of physical drift, in fact it was underestimating the impact that a more concentrated droplet would have. They stated that to correctly estimate drift injury, one must accurately reduce the carrier volume along with herbicide proportion, then compare that to the constant carrier volume and herbicide rate. Smith studied two application timings (six leaf and first square), two different herbicides (dicamba and 2,4-D), two rates (18.7 and 37.4 g ae ha^{-1}), and two variable carrier volumes (4.7 and 9.4 L ha^{-1}), along with a constant carrier volume of 140 L ha^{-1}. Each of the herbicide rates were sprayed with the constant carrier volume. When the carrier of 4.7 L ha^{-1} was sprayed, the herbicide rate was 18.7 g ha^{-1}, whereas the 9.4 L ha^{-1} carrier was sprayed at the 37.4 g ha^{-1} rate, which maintained the same herbicide concentration.

Dicamba applied at the sixth leaf growth stage with the constant carrier volume yielded 87% of nontreated control, which was the highest yield out of any carrier volume or application timing. For the variable carrier volume (herbicide rate averaged), there was less yield at 70% of the nontreated control. At the first square application timing, the variable carrier volume again resulted in less yield (59% of the nontreated) compared to the constant carrier volume, which yielded 81% of the nontreated. When 2,4-D was applied at the sixth leaf timing for the variable carrier volume, only 19% of the nontreated yield was recorded while the constant had more yield with 32%. Finally, at the first square application timing, the variable carrier volume yielded only 3% of the nontreated control while the constant carrier volume had a similar yield of 11%. Although application timing affected yield response, the variable volume consistently resulted in less yield compared to the constant volume.

(Roider et al. 2008) conducted a similar study where glyphosate drift was simulated on winter wheat to observe the effects of carrier volume on crop response. The rationale behind the study was that producers using glyphosate for burndown weed control prior to planting cotton and/or corn ground would also have fields planted to wheat that was at various growth stages. Factors included wheat growth stage (first detectable node and heading), carrier volume, and glyphosate rate (1,120, 140, and 70 g ai ha^{-1}). Glyphosate was applied in a constant carrier volume of 234 L ha^{-1} and in proportional carrier volumes of 30 L ha^{-1} for the 12.5% (140 g ai ha^{-1}) rate and 15 L ha^{-1} for the 6.3% (70 g ai ha^{-1}) rate, which maintained a constant herbicide concentration in the carrier. When glyphosate was applied in proportions (the two rates and carrier volumes combined) it had a greater reduction in yield at 48% compared to the 234 L ha^{-1} carrier volume which resulted in 26% yield loss. To assess the impact of carrier volume on wheat injury following low rates of quizalofop, greenhouse studies were conducted in Stillwater in 2020.

Materials & Methods

To assess the impact of carrier volume on non-tolerant wheat response to quizalofop-P-ethyl (quizalofop), a greenhouse trial was conducted two times in Stillwater, OK in 2020. The study was a factorial arranged in a randomized complete block design with six replications where one pot was a replicate. Factors included three winter wheat varieties (Gallagher, Iba, and Joe), five carrier volumes (19, 47, 94, 140, and 187 L ha^{-1}), and three quizalofop rates (1/10X, 1/50X, and 1/100X) plus a nontreated control. The 1X rate represented 62 g ai ha^{-1} which is the minimum rate labelled for application according to the Aggressor™ label (Anonymous 2020). Aggressor™ is the labelled formulation of quizalofop that can be used in CoAXium® wheat and this study was designed to study simulated physical movement of quizalofop on non-tolerant wheat.

Two greenhouse runs were performed with six replications per treatment. For each run, four to five seeds from each wheat variety were planted in pots 10 cm wide by 9 cm tall and later thinned to one plant per pot. Sungro® Professional Growing Mix, Metro-Mix® 902 RSi with 45-55% softwood bark (Sungro® Horticulture, Agawam, MA) was used. Wheat plants were sprayed when they reached three to four tillers in a

DeVries Generation III Research Sprayer (DeVries Manufacturing, Hollandale, MN). Pressure\ and nozzle selection were manipulated in order to achieve the desired carrier volume and speed was increased for the lowest carrier volume of 94 L ha^{-1}. For carrier volumes of 140 and 187 L ha^{-1}, Turbo Teejet® 80015 EVS nozzles were used. For 94, 57, and 19 L ha^{-1}, 8001 EVS, 800067 EVS, and 800005 EVS nozzles were used, respectively. Percent visual injury was observed at 28 and 42 days after application (DAA). Wheat plants also were cut at the soil surface at 42 DAA and placed in a dryer for 24 hours at 49ºC. Finally, plant dry weights were recorded.

A univariate analysis was performed on all responses in order to test for stable variance (Version 9.4, SAS Institute Inc., SAS Campus Drive, NC). No data sets were transformed as transformation did not increase stabilization. Data sets were analyzed using PROC MIXED with the pdmix 800 macro described by Saxton (1998) and treatments were separated by Fisher's Protected LSD at an α level of 0.05. In the model, fixed effects included wheat variety, carrier volume, quizalofop rate, and the various interactions among those effects while random effects included greenhouse run and replication.

Results and Discussion

Due to no significant greenhouse run by treatment effects, data was averaged over both greenhouse runs to assess significant interactions and/or main effects.

Visual injury

For percent wheat visual injury six weeks after application, the main effect of quizalofop rate was significant (Table 3.1). The 1/10X rate resulted in the highest visual injury (65%) relative to the nontreated control when compared to the 1/50X and 1/100X rates, which resulted in 45% and 36% visual injury, respectively. The main effects of wheat variety and carrier volume were not significant, and there was no significance among wheat variety, carrier volume, and quizalofop rate.

Biomass

All three main effects (wheat variety, carrier volume, and quizalofop rate) affected percent wheat biomass relative to the nontreated control six weeks after application (Table 3.1). Biomass for varieties Joe and Iba when averaged over carrier volume and quizalofop rate had similar biomass with 73 and 69% biomass of the nontreated control. Gallagher biomass was less than that of Iba and Joe at 59% of the nontreated control. However, this variety main effect was likely due to the variety characteristics alone since there was no interaction with carrier volume or herbicide rate. For the main effect of carrier volume, wheat biomass as a percent of the nontreated control was similar when 19, 94, 140, and 187 L ha^{-1} was used across wheat varieties and herbicide rates. However, percent wheat biomass was less following 47 L ha^{-1} compared to 94, 140, and 187 L ha^{-1}, which is consistent with what Roider (2008) observed in wheat with glyphosate, that as carrier volume is reduced and herbicide droplets are more concentrated, injury increases. Percent wheat biomass following the 1/10X rate was 58% of the nontreated control and less than biomass following the 1/150X rate (68%) and 1/100X rate (75%). Percent wheat biomass following the 1/50X rate also was less than biomass following the 1/100X rate.

In Table 3.2, four treatments from the greenhouse study were selected to assess the impact of constant vs. variable carrier volumes of wheat visual injury and biomass. The herbicide rates of 1/50X (1.24 g ai ha^{-1}) and 1/10X (6.2 g ai ha^{-1}) sprayed in carrier volumes of 19 and 94 L ha^{-1}, respectively, were selected because the herbicide concentration is the same for each of these treatments. These two treatments with variable carrier volumes were then compared back to treatments that were sprayed at the same rates but in a constant carrier volume of 187 L ha^{-1}. These comparisons were made in order to simulate methods of Banks (2002), Roider (2008), and Smith (2017).

When using this method and evaluating wheat visual injury, there was a carrier volume by herbicide rate interaction (Table 3.2) where wheat injury was less at the constant carrier volume for the high rate of 1.24 g ha^{-1} compared to the same rate applied in the variable carrier volume, as well as the higher rate of 6.2 g ai ha^{-1} applied at both the constant and variable carrier volumes. These results indicate that when the lower rate of 1.24 g ha^{-1} was used (our 1/50X rate), wheat visual injury was more severe when applied in the lower, variable carrier volume, likely due to the increase in herbicide concentration of the droplets. Banks and Schroeder 2002 observed this same effect when evaluating 2,4-D injury on cotton but witnessed the opposite trend when studying glyphosate injury to sweet corn.

When studying wheat biomass percent of the nontreated control, there was a wheat variety by carrier volume interaction and herbicide rate effect (Table 3.2). For the interaction, averaged across the two herbicide rates, biomass for wheat variety Joe was not impacted by carrier volume but was for Iba and Gallagher where the variable (lower) carrier volume resulted in a higher biomass for Gallagher but a lower biomass for Iba compared to the constant carrier volume. Biomass of Gallagher being greater following the variable carrier volume compared to the constant carrier volume does not agree with previously mentioned literature (Banks and Schroeder 2002; Smith 2017; Roider 2008).

On the other hand, impact of variety was not assessed in these studies. Recent literature on quizalofop in wheat does indicate that wheat variety may impact the plant's ability to metabolize the herbicide (Bough et al. 2020; Richter et al. 2020).

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Table 3.1. Winter wheat percent visual injury and biomass (percent of nontreated control) six weeks after application in a greenhouse study in Stillwater, OK in 2020.

	Visual injury	**Biomass**
	%	% of nontreated control
Variety		
Gallagher	51	59 b[a]
Iba	47	69 a
Joe	48	73 a[b]
Carrier volume ($L\ ha^{-1}$)		
19	55	65 ab
47	52	58 b
94	46	72 a
140	46	72 a
187	44	68 a
Rate		
1/10X[a]	65 a	58 c
1/50X	45 b	68 b
1/100X	36 c	75 a

[a] The 1X rate equaled 62 g ai ha^{-1} of quizalofop-P-ethyl. All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b] Means within a column for each interaction or main effect followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$.

Table 3.2. Winter wheat percent visual injury and biomass (percent of nontreated control) six weeks after application following low carrier volumes (variable) and high carrier volumes (constant) in a greenhouse study in Stillwater, OK in 2020

		Visual injury	**Biomass**
		%	% of nontreated control
Carrier volume (L ha ^{1}) *quizalofop rate (g ai ha^{-1}) interaction			
Constant[a]	1.24	28.9 b[b]	-
Variable	1.24	53.3 a	-
Constant	6.2	67.1 a	-
Variable	6.2	61.3 a	-
			-
Variety*carrier volume (L ha^{-1}) interaction			
Gallagher	Constant	-	50.3 c
Gallagher	Variable	-	69.5 ab
Iba	Constant	-	71.4 a
Iba	Variable	-	52.4 bc
Joe	Constant	-	73.6 a
Joe	Variable	-	74.7 a
Rate			
1/10X[a]		-	60 b
1/50X		-	72.6 a

[a]All herbicide treatments were applied using water as the carrier and included a crop oil concentrate at 1% (vol/vol).

[b]Means within a column for each interaction or main effect followed by a common letter were similar according to Fisher's protected LSD at $P < 0.05$.

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