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Cover crops and fall residual herbicides for managing Italian ryegrass

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Abstract

North Carolina growers have long struggled to control Italian ryegrass, and recent research has confirmed Italian ryegrass biotypes resistant to nicosulfuron, glyphosate, clethodim, and paraquat. Integrating alternative management strategies is crucial to effectively control such biotypes. The objectives of this study were to evaluate Italian ryegrass control with cover crops and fall-applied residual herbicides and investigate cover crop injury from residual herbicides. This study was conducted during the fall/winter of 2021-22 in Salisbury and fall/winter of 2021-22 and 2022-23 at Clayton, NC. The study was designed as a 3x5 split-plot, where the main plot consisted of three cover crop treatments (no-cover, cereal rye at 80 kg ha^{-1}, and crimson clover at 18 kg ha^{-1}), and the subplots consisted of five residual herbicide treatments (S-metolachlor, flumioxazin, metribuzin, pyroxasulfone, and nontreated). In the 2021-22 season at Clayton, metribuzin injured cereal rye and crimson clover 65% and 55%, respectively. However, metribuzin injured both cover crops $\leq$6% in 2022-23. Flumioxazin resulted in unacceptable crimson clover injury with 50% and 38% in 2021-22 and 2022-23 in Clayton and 40% at Salisbury, respectively. Without preemergence herbicides, cereal rye controlled Italian ryegrass 85% and 61% at 24 WAP in 2021-22 and 2022-23 at Clayton and 82% in Salisbury, respectively. In 2021-22, Italian ryegrass seed production was lowest in cereal rye treatments at both locations, except when cover crop was treated with metribuzin. For example, in Salisbury, cereal rye plus metribuzin resulted in 39324 seeds m^{-2}, compared to $\leq$4386 seeds m^{-2} from all other cereal rye treatments. In 2022-23, Italian ryegrass seed production in cereal rye was lower when either metribuzin or pyroxasulfone were used PRE (2670 and 1299 seeds m^{-2}, respectively) when compared to cereal rye without herbicides (5600 seeds m^{-2}).

Nomenclature: Cereal rye, crimson clover, Italian ryegrass, *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot; residual herbicides, *S*-metolachlor, flumioxazin, metribuzin, pyroxasulfone, seed production

Keywords: Integrated weed management, cover crops, preemergence herbicides, PRE.

Introduction

The world population is expected to reach 9.7 billion by 2050 and peak at approximately 10.4 billion people in 2086 (Ritchie et al. 2024)This prospect creates unprecedented demands for more efficient and sustainable agriculture. Consequently, minimizing yield losses is a crucial step to achieving optimal crop productivity. Weed management is a major challenge for agricultural systems worldwide, and substantial yield losses are expected if weeds are left uncontrolled. Oerke (2006) identified weed competition as the biggest threat to the major crops cultivated worldwide, with an average of 34% potential yield loss. In the United States (US) and Canada, researchers estimated 50% and 52% potential yield loss in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] if weeds are left uncontrolled, respectively (Soltani et al. 2016, 2017).

Chemical weed management is the most adopted and cost-effective weed control method in the US (Owen 2016); however, the rapid evolution of herbicide resistance threatens the long-term sustainability of agricultural systems (Evans et al. 2016). Currently, there are 533 unique cases of herbicide resistance documented worldwide across 273 species (Heap 2024). Italian ryegrass is a winter annual weed species notorious for evolving resistance to herbicides with 75 unique cases of herbicide resistance across 8 distinct sites of action (SOAs) reported worldwide (Heap 2024). In the US, this weed has evolved resistance to 7 herbicides SOAs, including HRAC/WSSA groups 1, 2, 5, 9, 10, 15, and 22 (Heap 2024; Liu et al. 2014).

Italian ryegrass has ranked as the most troublesome weed in small grains and among the top 20 most troublesome weeds in corn (Webster and Nichols 2012). Previous studies have shown significant yield losses in wheat (*Triticum aestivum* L. 'Stephens’) and corn if Italian ryegrass is left uncontrolled, with up to 92% and 60% yield loss, respectively (Hashem et al. 2000; Nandula 2014). Moreover, Italian ryegrass has vigorous growth, with greater leaf production rates and root surface area than wheat (Ball et al. 1995; Cralle et al. 2003). Bararpour et al. (2017), while investigating morphological characteristics of *Lolium* ssp. accessions from Arkansas reported that Italian ryegrass produced more tillers, more spikes plant^{-1}, and more spikelets spike^{-1} than rigid (*Lolium rigidum* Gaudin), perennial (*Lolium perenne* L.), and poison (*Lolium temulentum* L.) ryegrass, which resulted in Italian ryegrass producing 3.2 to 10.4 times more seeds per plant than any of the other *Lolium* spp. and as much as 45,000 seeds plant^{-1}.

In North Carolina, Italian ryegrass has been a problem in wheat and other crops since the late 1970s (Liebl and Worsham 1987). A state-wide herbicide investigation of Italian ryegrass accessions revealed widespread resistance to group 1 and 2 herbicides (Jones et al. 2021). Recently, a biotype resistant to nicosulfuron, clethodim, glyphosate, and paraquat (HRAC/WSSA groups 1, 2, 9, and 22, respectively) was identified in the Southern Piedmont region of North Carolina (De Sanctis et al. 2023), an important wheat production region of the state (USDA-NASS 2023). However, due to limited postemergence herbicide options labeled for small grains, growers have continued to rely on ACCase- (Group 1) and ALS-inhibiting (Group 2) herbicides to manage Italian ryegrass (Carleo and Everman 2020), increasing the selection for herbicide-resistant biotypes.

To mitigate the evolution and/or spread of herbicide resistance biotypes, alternative control tactics must be implemented to manage multiple herbicide-resistant weed biotypes successfully (Norsworthy et al. 2012). Among alternative control tactics, tillage, fall-applied residual herbicides, and cover crops have been studied for managing herbicide-resistant winter annual weeds across different US agronomic systems (Bond et al. 2014, 2022; Davis et al. 2010; Maity et al. 2022; Pittman et al. 2019; Sherman et al. 2020; Trusler et al. 2007). Tillage can be an effective practice for managing troublesome weeds when used in conjunction with a sound herbicide program (Farmer et al. 2017). However, due to its topography and soil characteristics, the Southern Piedmont region of North Carolina has an elevated risk of soil erosion, which may limit tillage in this area (Daniels 1987; Trimble 1975). Furthermore, many NC farmers are enrolled in government soil conservation programs that may restrict tillage practices (USDA-NRCS- 2024; NCDACS 2024). Cover crops planted after cash crop harvest are a promising weed control tactic that may suppress Italian ryegrass germination and growth during the late fall to early spring (Reeves 2022) as well as reduce the risk of erosion and improve soil health (Dabney et al. 2001). However, Italian ryegrass may germinate before or simultaneously to cover crops (Mohler et al. 2021), which can reduce cover crops establishment and competitiveness. In addition, previous research reports winter weed suppression to be driven by early-season cover crop establishment and growth (Baraibar et al. 2018; Dorn et al. 2015). Fall-applied residual herbicides have proven to be an effective tool to control Italian ryegrass during the late fall and early winter months; however, Italian ryegrass control is expected to diminish over time, allowing it to repopulate the area as residual herbicides lose their activity (Bond et al. 2014). It is hypothesized that combining fall-applied residual herbicides and cover crops, residual herbicides will limit early-season Italian ryegrass interference with cover crops. Once established, the cover crops will be crucial for late-winter and early-spring Italian ryegrass suppression, by this time, residual herbicides would have lost their activity. However, few studies have investigated fall-planted cover crop tolerance to preemergence (PRE) herbicides applied at planting, while many studies have investigated potential residual herbicides carryover from their use in a cash crop to a fall-planted cover crop (Cornelius and Bradley 2017a; Palhano et al. 2018; Rector et al. 2020). Therefore, the objectives of this study were to evaluate Italian ryegrass control and seed production as affected by cover crops and fall-applied residual herbicides and investigate cereal rye (*Secale cereale* L.) and crimson clover (*Trifolium incarnatum* L.) tolerance to different residual herbicides applied at planting.

Materials and Methods

Site Description

Experiments were conducted at the Piedmont Research Station near Salisbury, NC, during the fall/winter of 2021-22 and at the Central Crops Research Station near Clayton, NC, during the 2021-22 and 2022-23 fall/winter seasons. Soils included a Lloyd clay loam (fine-loamy, mixed, active, thermic typic hapludalfs) with 5.4 pH and 0.4% humic matter at Salisbury and a Wagram loamy sand (coarse-loamy, siliceous, active, acid, thermic cumulic humaquepts) with 5.6 pH and 0.8% humic matter at Clayton. Following the NC Department of Agriculture and Consumer Services soil test report recommendations at Salisbury, 336 kg ha^{-1} of 10-20-20 fertilizer plus 2500 kg ha^{-1} of lime was applied to optimize cover crop growth. Experiments were conducted in a no-till system with cover crops planted on October 20, 2021, at Salisbury. At Clayton, cover crops were planted on October 19, 2021, and October 19, 2022, into soil prepared with conventional tillage. Paraquat at 840 g ai ha^{-1} was used just before cover crop planting to ensure fields were weed-free at planting. Cover crops were drilled into 19 cm rows with cereal rye and crimson clover seeded at 80 and 18 kg ha^{-1}, respectively. All research sites were naturally infested with Italian ryegrass.

Experimental Design and Treatments

The experiment was conducted as a split-plot design with four replications. The main plots consisted of three cover crop treatments organized in a randomized complete block design. Subplots consisted of five fall-applied residual herbicide treatments. The three cover crop treatments consisted of no cover crop (fallow), cereal rye, and crimson clover whereas the fall-applied residual herbicides included no residual herbicides (No-PRE), and flumioxazin, metribuzin, pyroxasulfone, and *S*-metolachlor applied PRE (Table 1). From hereinafter, the fallow treatment without residual herbicides will be referred to as nontreated. Residual herbicides were applied immediately after planting with a handheld CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} equipped with six AIXR11002 flat-fan nozzles (TeeJet® Technologies, Spraying Systems Co., Wheaton, IL 60187) spaced 45 cm apart. Subplot dimensions were 4 m x 12 m.

Data Collection

Data collection consisted of biweekly visual estimations of cover crop injury and Italian ryegrass control, with 0% representing no control or injury and 100% representing complete control or plant death. Italian ryegrass density was recorded 8 weeks after planting (WAP), while Italian ryegrass and cover crop biomass were collected at 24 WAP. Italian ryegrass seeds were collected once most plants reached maturity, occurring in early June during both years.

Density, aboveground biomass, and seed were collected using two 0.25 m^2 quadrants randomly placed within the corresponding subplot. Data from each quadrant were averaged and transformed to 1 m^2 basis. Cover crop and Italian ryegrass fresh biomass were placed in separate paper bags, dried in an oven at 55 C for 14 days until constant mass, and then weighed. Italian ryegrass seed samples were placed in paper bags and allowed to dry at 25 C for 21 days. Samples were manually threshed, cleaned using a series of standard laboratory sieves, and then weighted. Seed production was determined by weighing 50 seed subsamples to calculate 100 weights of cleaned seed.

Statistical Analysis

Data were subjected to ANOVA to test for significance of fixed and random effects and means separated using R base package (R Core Team 2019) and Agricolae package (Mendiburu

2019). Since only one year of data was collected from Salisbury, separate analyses were conducted for each location. For Salisbury, replications were treated as a random effect, while cover crop and residual herbicide as fixed effects. For data from Clayton, year was included as a fixed effect. Moreover, for cover crop injury, fallow treatments and cover crops without herbicides were excluded from the analyses; for cover crop biomass, only fallow treatments were removed. In Italian ryegrass visual estimates of control at 8 and 24 WAP, fallow with no-PRE treatment was considered the nontreated check and it was removed from the analysis. Fisher's least significant difference was used to separate means at α = 0.05.

Results and Discussion

Cover crop injury and biomass production

At Clayton, there was a significant year-by-cover crop-by-residual herbicide interaction for visual estimates of injury at 8 and 24 WAP and cover crop biomass. Therefore, to better interpret results, data was analyzed separately between 2021-22 and 2022-23. At Salisbury, the cover crop-by-residual herbicide interaction was significant for all variables at the α = 0.05 level.

During 2021-22 at Clayton, all residual herbicides injured cereal rye and crimson clover at 8 WAP (Table 2). However, at 24 WAP, metribuzin (65%) was the only injurious treatment to cereal rye. Crimson clover was injured by flumioxazin and metribuzin, resulting in 55% and 50% injury, respectively. Injury from all other residual herbicides was transient and resulted in ≤12% crimson clover and cereal rye injury. Similarly, Wallace et al. (2017) reported minimal to no injury from pyroxasulfone and *S*-metolachlor applied PRE in red clover (*Trifolium pratense* L.) with biomass similar to the nontreated check. Surprisingly, in 2022-23, metribuzin injury in cereal rye and crimson clover was 5% and 6%, respectively. Studies investigating metribuzin movement in the soil report the herbicide is readily leached in coarse soils with low organic matter (Shaner 2014; Kim and Feagley 1998). At Clayton 2022-23, 56 mm of rainfall was received 10 days after planting (Figure 1), which could have caused metribuzin to leach beyond the cover crop root zone. This may explain why cover crop injury by metribuzin was reduced in 2022-23. At the same time, flumioxazin (38%) was the most injurious herbicide to crimson clover. The response of the cover crop to residual herbicides at Salisbury was similar to that of Clayton 2021-22. All residuals were injurious at 8 WAP. At 24 WAP, metribuzin injured cereal rye 68%, whereas metribuzin and flumioxazin injured crimson clover 47% and 40%, respectively (Table 3).

Previous research reports that 5000 kg ha^{-1} of cover crop biomass is necessary to achieve satisfactory weed suppression (Nichols et al. 2020). In 2021-22 at Clayton, only cereal rye plus flumioxazin (5660 kg ha^{-1}) or pyroxasulfone (5642 kg ha^{-1}) reached that threshold and yielded significantly higher biomass than cereal rye plus metribuzin (1884 kg ha^{-1}). Within crimson clover treatments, all residual herbicides, except metribuzin (713 kg ha^{-1}), resulted in comparable biomass ranging from 3198 to 4642 kg ha^{-1}. However, at Clayton 2022-23, no biomass differences were observed between cover crop species or PRE herbicide treatments. Overall, less cover crop biomass was produced at this location and no treatments reached the 5000 kg ha^{-1} biomass threshold (2669 to 3995 kg ha^{-1}). At Salisbury, cereal rye plots had the highest biomass, ranging from 6036 to 7245 kg ha^{-1}, except for metribuzin, which resulted in 1216 kg ha^{-1}. Despite differences in residual herbicide injury, all crimson clover plots yielded comparable biomass (947 to 2395 kg ha^{-1}). Ribeiro et al. (2021), while investigating cereal rye sensitivity to different PRE herbicides under greenhouse conditions, reported 70% biomass reduction from metribuzin. The same researchers also reported that planting cereal rye 32 to 38 days after metribuzin was applied still decreased cereal rye biomass 35% compared to nontreated. In the same study, flumioxazin, pyroxasulfone, and *S*-metolachlor reduced cereal rye biomass at 30 days after planting 60%, 48%, and 61% respectively. Cornelius and Bradley (2017a), while investigating the risks of herbicide carryover to several cover crops, reported that metribuzin and *S*-metolachlor applied 3 months before cover crop plating reduced crimson clover biomass by 29%. Furthermore, these researchers concluded that crimson clover was the most sensitive cover crop to herbicide carryover among 8 cover crop species including Australian winter pea (*Pisum sativum* L); cereal rye, hairy vetch (*Vicia villosa* Roth), Italian ryegrass, oats (*Avena sativa* L.), soybean, and wheat. In this research, flumioxazin, due to significant injury across both sites and years, was considered injurious to crimson clover. Although environmental conditions likely reduced metribuzin injury at Clayton 2022-23, this herbicide still poses a risk to cereal rye and crimson clover; therefore, metribuzin was considered an injurious herbicide for both cover crops.

Italian ryegrass control, biomass, and seed production

At Clayton, the year-by-cover crop-by-residual herbicide interaction was significant for Italian ryegrass visible control estimates at 8 and 24 WAP, biomass, and seed production. Therefore, data for Clayton 2021-22 and 2022-23 were analyzed separately. At Salisbury, the cover crop-by-residual herbicide interaction was significant for all variables at the $\alpha = 0.05$ level.

At Clayton 2021-22, Italian ryegrass control 8 WAP in plots receiving both a cover crop and residual herbicides were similar. In cereal rye plots, residual herbicides controlled Italian ryegrass 83% to 92%, whereas herbicides used with crimson clover controlled the weed 74 to 81% 8 WAP (Table 4). By 24 WAP, Italian ryegrass control in cereal rye without herbicides (85%) was similar to cereal rye plus herbicides (80% to 85%), except for metribuzin, which resulted in 47% control due to cereal rye injury. Moreover, Italian ryegrass control in fallow reduced over time regardless of residual herbicide use; for instance, *S*-metolachlor without cover crops controlled Italian ryegrass 84% at 8 WAP and, by 24 WAP, control was reduced to 27%. At Clayton 2022-23, all cereal rye plus residual herbicide treatments resulted in similar Italian ryegrass control at 8 WAP (60% to 83%) and were more effective than cereal rye without a residual herbicide (28%). In the fallow system, all residual herbicides used resulted in comparable Italian ryegrass control (60% to 75%). At 24 WAP, Italian ryegrass control in cereal rye plots differed from the previous season. Cereal rye plus pyroxasulfone (88%) or metribuzin (85%) resulted in greater Italian ryegrass control than cereal rye plots without a residual herbicide (61%). Additionally, flumioxazin (73%) and *S*-metolachlor (66%) applied to cereal rye controlled Italian ryegrass similar to cereal rye without a residual herbicide.

In Salisbury, Italian ryegrass control at 8 WAP with pyroxasulfone was similar across all cover crop treatments, ranging from 86% to 96%. Furthermore, cereal rye plus metribuzin (93%) or pyroxasulfone (96%) resulted in greater Italian ryegrass control than cereal rye without herbicides (68%). A similar trend was observed in crimson clover, in which the presence of metribuzin (70%) or pyroxasulfone (86%) resulted in greater control than crimson clover without herbicides (55%). At 24 WAP Italian ryegrass control in cereal rye no-PRE was 82% and was comparable to cereal rye plus pyroxasulfone (83%), *S*-metolachlor (83%), and flumioxazin (75%; Table 5). However, when metribuzin was used, Italian ryegrass control was reduced to 37%. In 2021-22 at both locations, metribuzin injury to cereal rye reduced cover crop competitiveness; consequently, Italian ryegrass was able to repopulate the plot once residual activity of the herbicide diminished.

There is limited information on the combined activity of cover crops plus residual herbicides for Italian ryegrass control; however, fall-applied residual herbicides have been studied for Italian ryegrass management. Bond et al. (2014) reported that pyroxasulfone (165 g ai ha^{-1}) and *S*-metolachlor (1420 g ai ha^{-1}) controlled Italian ryegrass 61% and 52% 24 WAP which equated to 79% and 82% reductions in biomass, respectively. The researchers also observed that Italian ryegrass control reduced over time. For example, pyroxasulfone applied at 50 g ai ha^{-1} controlled Italian ryegrass 84% 14 WAP but control decreased to 55% 24 WAP. Similarly, Burrell (2024) reported that fall-applied pyroxasulfone controlled Italian ryegrass 63% at 18 WAP whereas *S*-metolachlor at the same time resulted in 74%. From a cover crop standpoint, cereal rye and crimson clover may suppress other troublesome winter annual weeds. Pittman et al. (2019) reported ≥88% horseweed density reduction in cereal rye or crimson clover cover crops when compared to fallow. In contrast, Cornelius and Bradley (2017b) reported that cereal rye and crimson clover reduced winter annual weed density by 68% and 25%, respectively. Therefore, under ideal conditions, cover crops alone may provide excellent winter annual weed suppression. However, cover crop productivity is affected by many factors, such as species selection, seeding rates, water availability, soil fertility, planting date, and tolerance to herbicides (Balkcom et al. 2018; Brennan and Boyd 2012; Cornelius and Bradley 2017b; Florence et al. 2019; Nielsen et al. 2015). These adverse conditions can reduce cover crop competitiveness, and, under these circumstances, the presence of a non-injurious fall-applied residual herbicide might be necessary to maintain satisfactory weed control levels.

In general, Italian ryegrass biomass reflected visual estimates of control. For example, at Clayton 2021-22, among cereal rye plots, metribuzin resulted in the highest Italian ryegrass biomass at 94 g m^{-2}, compared to ≤23 g m^{-2} for all other cereal rye treatments including the No-PRE treatment (Table 4). At the same location, within crimson clover treatments, pyroxasulfone and *S*-metolachlor resulted in the lowest Italian ryegrass biomass with 43 g m^{-2} and 30 g m^{-2}, respectively. Furthermore, throughout the entire study, Italian ryegrass biomass in cereal rye without a herbicide was comparable to cereal rye plus pyroxasulfone, *S*-metolachlor, and flumioxazin. In Salisbury, cereal rye without a herbicide resulted in 13 g m^{-2} Italian ryegrass, whereas biomass when pyroxasulfone, *S*-metolachlor, or flumioxazin were used PRE was 15, 11, and 33 g m^{-2}, respectively, and cereal rye plus metribuzin resulted in 203 g m^{-2}. Similarly to Clayton 2012-22, pyroxasulfone (70 g m^{-2}) or *S*-metolachlor (78 g m^{-2}) had the lowest Italian ryegrass biomass among crimson clover plots. Cechin et al. (2021) observed that, in the first year of cover crop implementation, cereal rye reduced Italian ryegrass biomass by 65% compared to nontreated fallow. By the third year of cereal rye, the cover crop reduced Italian ryegrass by 97%. The researchers also reported significantly greater Italian ryegrass suppression was obtained by cover crops that produced more than 8,000 kg ha ha^{-1} of biomass. In a different study, the presence of a cereal rye cover crop reduced Italian ryegrass density 95% compared to nontreated plots at soybean planting (Reeves 2022).

Italian ryegrass seed production at Clayton 2021-22 was the lowest when grown with cereal rye alone or without an injurious herbicide (741 to 1356 seeds m^{-2}); up to 98% reduction in Italian ryegrass seed production were achieved by these treatments compared to nontreated plots (31058 seeds m^{-2}). Similarly, Cechin et al. (2021) reported up to 90% reduction in the Italian ryegrass soil seedbank when cereal rye was used as a cover crop. Italian ryegrass seed production in crimson clover was higher than what was observed in aforementioned cereal rye treatments; however, weed seed produced in crimson clover without a herbicide (20428 seeds m^{-2}) was comparable to all crimson clover plus herbicide treatments (13404 to 27446 seeds m^{-2}). At Clayton 2022-23, Italian ryegrass seed production in cereal rye was lower when either metribuzin or pyroxasulfone were used PRE (2670 and 1299 seeds m^{-2}, respectively) when compared to cereal rye without a herbicide (5600 seeds m^{-2}). These differences were attributed to lower cover crop injury by metribuzin and reduced cereal rye biomass in 2022-23. This highlights the importance of integrated weed management and the need to hedge against unfavorable cover crop growing conditions with a residual herbicide applied at or after cover crop planting. Moreover, even though Italian ryegrass was more prolific at the Salisbury location, with 100743 seeds m^{-2} in the nontreated, lower seed production was observed in cereal rye plots. Cereal rye without a herbicide reduced Italian ryegrass seed production by 99% (1396 seeds m^{-2}) and was comparable to cereal rye plus pyroxasulfone (4389 seeds m^{-2}), *S*-metolachlor (2053 seeds m^{-2}), and flumioxazin (1830 seeds m^{-2}). Similarly, within crimson clover plots, Italian ryegrass seed production was lower in the absence of an injurious residual herbicide, which consisted of pyroxasulfone, *S*-metolachlor, or No-PRE, ranging from 24529 to 27123 seeds m^{-2}. These results highlight the importance of selecting a residual herbicide that effectively controls Italian ryegrass without reducing the cover crop biomass. Safe residual herbicides, if activated, will control Italian ryegrass and enhance early-season cover crop growth, which will maximize late-season cover crop competition with the weed.

Practical Implications

The widespread distribution of multiple-herbicide-resistant Italian ryegrass biotypes in North Carolina is alarming (Jones et al. 2021). Additionally, the presence of a biotype resistant to herbicides from groups 1, 2, 9, and 22 limits postemergence herbicide options. Integrated weed management is crucial to mitigate the evolution and spread of herbicide-resistant weed biotypes. Results from this study highlight the importance of utilizing a diversified approach for Italian ryegrass management by combining fall-applied residual herbicides and cover crops. At both locations in 2021-22, greater control of Italian ryegrass, as well as lower biomass and seed production were observed where cereal rye was used as a cover crop. Additionally, cereal rye without residual herbicides was as effective in suppressing Italian ryegrass as cereal rye plus a non-injurious herbicide, with up to 5660 and 7245 kg ha^{-1} of biomass produced at Clayton and Salisbury, respectively. However, at Clayton 2022-23, cereal rye biomass was not as prolific with an average of 2890 kg ha^{-1}, far below the 5000 kg ha^{-1} threshold for ideal weed suppression (Nichols et al. 2020). Facing less cover crop biomass, the presence of a non-injurious residual herbicide was crucial to maximize Italian ryegrass suppression. Similarly, crimson clover biomass was ≤4642 kg ha^{-1} across locations, and higher Italian ryegrass control at 24 WAP was observed when pyroxasulfone or *S*-metolachlor was applied PRE to crimson clover. In general, fall-applied residual herbicides alone resulted in adequate Italian ryegrass control at 8 WAP. However, as time progressed, residual herbicide efficacy diminished, and by 24 WAP, Italian ryegrass control was ≤60% by all herbicides. In conclusion, we observed that a diversified weed management approach, utilizing both a cover crop and residual herbicide, may reduce Italian ryegrass seed production by as much as 98%. Furthermore, previous research reports that Italian ryegrass seed viability is reduced by≥ 95% following 18 months of burial (Cechin et al. 2021; Narwal et al. 2008). The ability of cover crops plus residual herbicides to reduce Italian ryegrass seed production employed over multiple seasons, coupled with the weed’s lack of seed viability after extended burial, may better position growers for managing this troublesome weed in the long term.

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Competing interests

No conflicts of interest have been declared.

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Table 1. List of herbicide products, rates, manufacturers, and WSSA herbicide group numbers used in field experiments conducted in 2021-22 and 2022-23 seasons.

Common name	WSSA group number	Rate	Trade name	Manufacturer
		g ai ha^{-1}		
Flumioxazin	14	61	Valor®	Valent, San Ramon, CA
Metribuzin	5	470	Tricor® 75 DF	UPL, King of Prussia, PA
S-metolachlor	15	1420	Dual Magnum®	Syngenta Crop Protection, Greensboro, NC
Pyroxasulfone	15	119	Zidua®	BASF Ag Products, Research Triangle Park, NC

Table 2. Cereal rye and crimson clover visible estimates of injury at 8 and 24 weeks after planting (WAP) and biomass production as influenced by residual herbicide treatments in the 2021-22 and 2022-23 seasons at the Central Crops Research Station, located near Clayton NC.

Cover crop	Residual herbicide	2021-22 [a]						2022-23 [a]				
		Injury						Injury				
		8 WAP		24 WAP		Biomass		8 WAP		24 WAP		Biomass
		---------- % -----------				kg ha^{-1}		---------- % -----------				kg ha^{-1}
Cereal rye	Flumioxazin	47	DE	2	B	5660	A	44	AB	19	B	2669
	Metribuzin	91	A	65	A	1884	CD	31	BC	5	B	2975
	S-metolachlor	70	BC	12	B	3299	BC	15	CD	15	B	2759
	Pyroxasulfone	42	DE	3	B	5642	A	7	D	9	B	2693
	No-PRE	---	---	---	---	4388	AB	---	---	---	---	3358
Crimson clover	Flumioxazin	85	AB	50	A	3198	BC	51	A	38	A	3036
	Metribuzin	67	BC	55	A	713	D	42	AB	6	B	3523
	S-metolachlor	52	CD	2	B	4639	AB	16	CD	19	B	3638
	Pyroxasulfone	30	E	12	B	4352	AB	8	D	4	B	3995
	No-PRE	---	---	---	---	4642	AB	---	---	---	---	3159

[a] Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference test at α = 0.05 level.

Table 3. Cereal rye and crimson clover visible estimates of injury at 8 and 24 weeks after planting (WAP) and biomass production as influenced by cover crop and residual herbicide treatments in the 2021-22 season at the Piedmont Research Station, located near Salisbury NC.

		Injury [a]					
Cover crop	Residual herbicide	8 WAP		24 WAP		Biomass	
		---------- % ----------				kg ha^{-1}	
Cereal rye	Flumioxazin	25	C	10	B	6508	A
	Metribuzin	94	A	68	A	1216	B
	S-metolachlor	60	B	7	B	6567	A
	Pyroxasulfone	50	BC	5	B	6036	A
	No-PRE	---	---	---	---	7245	A
Crimson clover	Flumioxazin	53	BC	40	A	1632	B
	Metribuzin	65	AB	47	A	947	B
	S-metolachlor	45	BC	12	B	1842	B
	Pyroxasulfone	25	C	10	B	2395	B
	No-PRE	---	---	---	---	1194	B

[a] Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference test at α = 0.05 level.

Table 4. Italian ryegrass visible estimates of control, biomass, and seed production as influenced by cover crop and residual herbicide treatments in the 2021-22 and 2022-23 seasons at the Central Crops Research Station, located in Clayton NC.

		2021-22 [a]				2022-23 [a]			
		Control				Control			
Cover crop	Residual herbicide	8 WAP	24 WAP	Biomass	Seed Production	8 WAP	24 WAP	Biomass	Seed production
		----------%----------		g m^{-2}	seeds m^{-2}	----------%----------		g m^{-2}	seeds m^{-2}
Cereal rye	Flumioxazin	83 AB	84 A	23 D	1356 G	60 AB	73 AB	32 EF	7985 EF
	Metribuzin	84 A	47 CD	94 C	23799 CDE	75 A	85 A	13 F	2670 HI
	S-Metolachlor	91 A	80 A	8 D	873 G	69 AB	66 ABC	55 DEF	3887 GHI
	Pyroxasulfone	85 A	85 A	9 D	1271 G	83 A	87 A	14 F	1299 I
	No-PRE	69 AB	85 A	7 D	741 G	28 CD	61 BC	44 DEF	5600 FG
Crimson clover	Flumioxazin	81 AB	55 BC	95 C	17181 EF	50 BC	32 D	54 DEF	13185 C
	Metribuzin	74 AB	38 CD	10 C	27446 BC	35 CD	47 CD	12 AB	9876 DE

						9			D					4			
	S-Metolachlor	85	A	78	AB	30	D	13842	F	78	A	74	AB	16	F	4276	GH
	Pyroxasulfone	80	AB	80	A	43	D	13404	F	75	A	67	ABC	44	DEF	9049	E
	No-PRE	37	C	45	CD	113	C	20428	DEF	12	D	47	CD	144	A	7632	EF
	Flumioxazin	61	B	37	CD	248	A	34452	B	60	AB	30	D	102	ABC	19969	B
	Metribuzin	81	AB	35	CD	158	B	42205	A	63	AB	52	BCD	69	CDE	11994	CD
Fallow	*S*-Metolachlor	84	A	27	D	94	C	25481	CD	69	AB	36	D	117	AB	27166	A
	Pyroxasulfone	90	A	50	CD	87	C	42107	A	75	A	60	BC	84	BCD	14470	C
	No-PRE	--	--	--	--	198	B	31058	BC	--	--	--	--	134	A	22514	B

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[a] Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference test at α = 0.05 level.

Table 5. Italian ryegrass visible estimates of control, biomass, and seed production as influenced by cover crop and residual herbicide treatments in the 2021-22 season at the Piedmont Research Station, located in Salisbury NC.

		Control [a]							
Cover crop	Residual herbicide	8 WAP		24 WAP		Biomass		Seed production	
		----------%----------				g m^{-2}		seeds m^{-2}	
Cereal rye	Flumioxazin	80	A-E	75	A	33	GH	1830	G
	Metribuzin	93	AB	37	BCD	203	BCD	39324	EF
	S-metolachlor	85	BCD	83	A	11	H	2053	G
	Pyroxasulfone	96	A	83	A	15	H	4389	G
	No-PRE	68	D-G	82	A	13	H	1396	G
Crimson clover	Flumioxazin	75	B-F	37	BCD	133	E	83562	BC
	Metribuzin	70	C-G	28	DE	254	B	142704	A
	S-metolachlor	65	EFG	50	BC	78	FG	27046	F
	Pyroxasulfone	86	ABC	54	B	70	G	27123	F
	No-PRE	55	H	30	CDE	162	DE	24529	F
Fallow	Flumioxazin	60	GH	35	B-E	326	A	55455	DE
	Metribuzin	90	AB	25	DE	238	BC	128593	A
	S-metolachlor	89	AB	15	E	188	CD	85884	BC
	Pyroxasulfone	94	A	37	BCD	123	EF	67410	CD
	No-PRE	---	---	---	---	232	BC	100743	B

[a] Means presented within the same column and with no common letter(s) are significantly different according to Fisher's Protected Least Significant Difference test at α = 0.05 level.

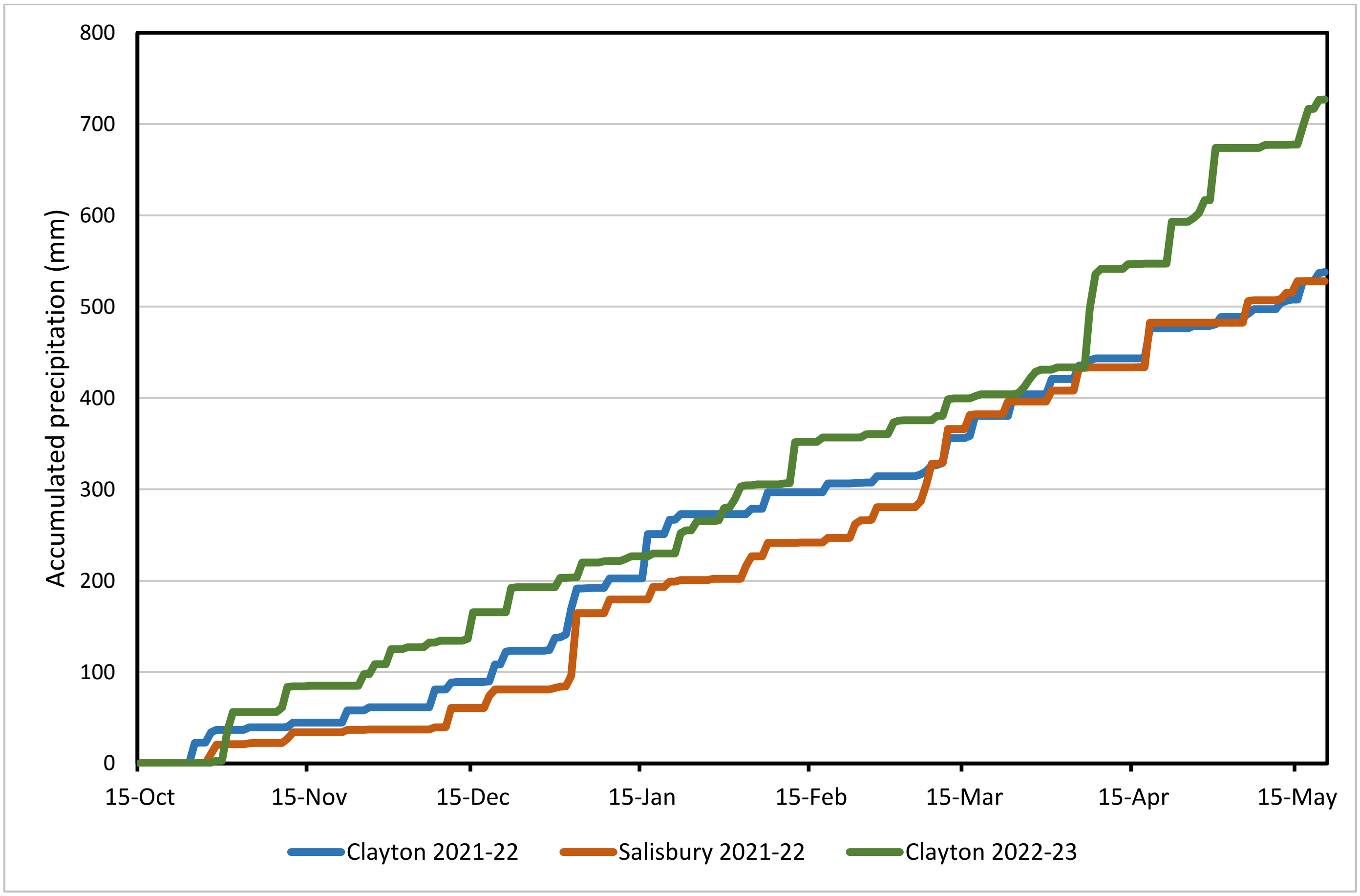

Figure 1. Cumulative rainfall at the Piedmont Research Station near Salisbury, NC, during the fall/winter of 2021-22 (orange) and at the Central Crops Research Station near Clayton, NC, during 2021-22 (blue) and 2022-23 (green) fall/winter seasons.