AN ABSTACT OF THE THESIS OF

Kyle C. Roerig for the degree of Master of Science in Horticulture presented on October 26, 2020

Title: Measuring Combine Facilitated Transport of Italian Ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] Seed During Wheat Harvest and Preventing the Distribution of Italian Ryegrass Seed During Harvest by Removal or Destruction of Chaff

Abstract approved:

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Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] resistant to multiple herbicide sites of action continues to limit winter wheat production in western Oregon. In addition to impacting wheat production, multiple resistant Italian ryegrass may threaten the market for annual ryegrass seed for cover crops if wheat fields with severe infestations are subsequently planted to annual ryegrass and the seed from these fields is sold as cover crop seed. Italian ryegrass resistant to diclofop was first documented in western Oregon in 1987 (Stanger and Appleby 1989), after less than 10 years of use. Since that time the list of herbicides Italian ryegrass populations have been observed to be resistant to has grown to include diclofop (WSSA group 1), diuron (WSSA group 7), mesosulfuron (WSSA group 2), flucarbazone (WSSA group 2), flufenacet (WSSA group 15), pinoxaden (WSSA group 1), propoxycarbazone (WSSA group 2) and pyroxsulam (WSSA group 2) . For example, in a 2013 wheat field trial, plots treated with pyroxsulam alone and flufenacet-metribuzin followed by pyroxsulam yielded 45 and 72 bu/a respectively. Untreated plots and plots where Italian ryegrass was

controlled yielded 28 and 110 bu/a, respectively (Roerig et al. unpublished data). In 2014, pyroxasulfone a new group 15 herbicide that provides preemergent control of grass weeds in wheat, including those resistant to flufenacet, was registered. Previous patterns of resistance development in Italian ryegrass indicate that Italian ryegrass will likely develop resistance to pyroxasulfone as well.

An Italian ryegrass plant does not have the means to distribute its seed more than a meter or two, however harvest equipment does. McManny and Cavers (1988) found that proso millet in corn at harvest was moved in excess of 50m by combines and observed in surveys that proso millet could be spread across most of a field from an isolated patch in two years. As such, combines appear to pose the greatest risk of moving seed from an initial site of resistance development across an entire field. A combine separates harvested material into three parts: grain, straw, and chaff. The combine threshes and sifts the desirable portion of the crop along with anything that is similar in size and weight, often some weed seeds, into the grain tank. The straw is any long piece of the crop which is discarded either by spreading or dropping into a windrow for later baling. The chaff is the material that is too light to be grain and is blown out the back. In most cases the majority of weed seeds exit the combine in the chaff portion.

Some progress has been made in controlling weeds seeds in the chaff, such as use of chaff collection carts, narrow windrow burning and placing the chaff on top of the straw for baling. Additionally, the Harrington Seed Destructor has been in limited use in Australia for several years. This device routes chaff exiting the combine through a cage mill where 90-99% of weeds seeds are destroyed (Walsh et al. 2012). There has also been discussion of major equipment manufactures integrating milling or microwave systems to destroy weed seeds into the machines they manufacture. This sort of equipment may become available for growers in the Pacific Northwest in future years. Research is needed to determine efficacy of this type of system in controlling locally important weeds such as Italian ryegrass in wheat.

Any time a weed seed is prevented from entering the soil seed bank it preempts the opportunity for that seed to become a plant that will compete with the crop, produce offspring or even develop or spread herbicide resistance. However, for a practice such as weed seed removal or destruction to have value it must have a net effect of reducing the total weed seed bank or preventing the spread of new infestations. This research intends to determine the efficacy of these practices when herbicides do not adequately control the weed population. The data collected will help growers determine whether the use of these systems would be able to prevent or reduce populations of herbicide resistant Italian ryegrass and be beneficial to their farming operation.

Combine harvesters are designed to separate desirable material, such as grain, seeds, and kernels, from undesirable material such as stems, leaves, weed seeds and other foreign material while traveling through the field. The desired material is collected into the grain tank and everything else is typically discharged from the back of the combine into the field. Since this process occurs while the combine is moving, weed seeds entering the combine are typically discharged some distance from where the weed grew, potentially increasing the distance the seeds could travel beyond natural dispersal mechanisms. Studies were conducted in 2016 and 2017 to assess how far Italian ryegrass seeds travel during wheat harvest. Seed was prepared for the study by microwaving to prevent germination following the study and dyed to aid in detection and counting.

Twenty $0.74m^2$ pans were placed 11m apart and wheat harvest was conducted straddling the pans so they remained centered under the combine. At the beginning of each pass, thin paper bags containing a total of 5.5kg of one color of Italian ryegrass seed were attached to the heads of the wheat. For each pass a different color of Italian ryegrass seed was used. The distribution of three colors was measured in 2016 and four colors in 2017. Since the colors were distinctly different it was not necessary to clean the combine between each color, allowing observations of the previous colors to be made during passes with a subsequent color at a distance of up to 873m. The first pan in the sequence had an average of 14,220 seeds and the number quickly decreased. By the end of the first pass, at 215m, the pans contained an average of 41 seeds of the color introduced at the beginning of the pass. In pans starting at 774 and up to 873m from the initial introduction, an average of 4.2 seeds per pan were collected, a rate of over 500,000 seeds/ha in the chaff row. These data provide evidence that weed seeds entering a combine during harvest can be transported great distances, readily facilitating the establishment of weed populations across a field from an isolated source from within the field.

Two additional studies assessed the effect of collecting chaff using a chaff cart during harvest on the population of Italian ryegrass in a field over time. In both trials there were four treatments: untreated, herbicide, herbicide plus chaff collection, and chaff collection alone. In one trail the entire area was planted with Italian ryegrass during the first year of the crop. In the other a strip of Italian ryegrass was planted at one end of each plot and harvest was conducted across the plot starting from the side with the strip. In both trials winter wheat was planted in years 1-3, red clover was planted in year 4 and harvested in years 4 and 5, and winter wheat was planted in year 6. In the solid planted field Italian ryegrass populations were the lowest in the herbicide plus chaff collection plots three out of the six years but the difference was never statistically significant (at p-value 0.05) from herbicide alone. It the trail where only a strip was planted Italian ryegrass populations were counted across the length of the plot. The plot was divided into ten groups. The herbicide plus chaff collection had the lowest population in each distance group, however this difference was only significant (at p-value 0.05) in the first group. These results suggest a trend towards lower Italian ryegrass populations when chaff collection is used in conjunction with herbicides than when herbicides are used alone, however further evaluation of the practice is needed to provide more conclusive results.

Measuring Combine Facilitated Transport of Italian Ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] Seed During Wheat Harvest and Preventing the Distribution of Italian Ryegrass Seed During Harvest by Removal/Destruction of Chaff

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Kyle C. Roerig, Author

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DEDICATION

To Dr. Corey Ransom who introduced me to weed science, Dr. Ralph Whitesides who made it look fun, and Bill Mace who taught me how to make it all work in the field.

Measuring Combine Facilitated Transport of Italian Ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] Seed During Wheat Harvest and Preventing the Distribution of Italian Ryegrass Seed During Harvest by Removal or Destruction of Chaff

Chapter 1

Introduction

Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] is a significant weed in western Oregon infesting many crops in the region. It competes fiercely for resources when grown in conjunction with desired crops and contaminates harvested grain or seed. Appleby et al. (1976) reported reductions in winter wheat yields ranging from 15-50% depending on Italian ryegrass density. In addition to being competitive, Italian ryegrass exhibits a high level of plasticity and has developed resistance to numerous herbicide modes of action.

Combines have the capacity to move weed seeds harvested with the crop, such as Italian ryegrass, great distances. This can lead to isolated patches, stemming from a new introduction or new cases of herbicide resistance, becoming widespread in a field. Integrated weed management (IWM) seeks to utilize multiple approaches to mitigate the effect of weeds on crops. Harvest weed seed control (HWSC) is a form of IWM that sits at the intersection of herbicide resistance and combine transport of weed seeds. HWSC seeks to reduce the population or spread of weeds that are discharged by the combine during harvest by some form of destruction or removal.

The main objectives of this research are: 1) Determine the distance Italian rye seeds can be transported by a combine harvester during harvest, 2) Determine whether an out-of-control population of Italian ryegrass in a field can be brought back into control by using HWSC, 3) Determine whether HWSC can prevent or slow the spread of new weed problems, such as patches of newly developed herbicide resistance.

Chapter 2

Literature Review

Italian ryegrass

Lolium perenne L. ssp. *multiflorum* (Lam.) Husnot is significant in western Oregon as both weed and a crop. It is a robust annual, introduced from Europe and growing to 1 meter in height (Hitchcock 1971). Weedy biotypes are usually referred to as Italian ryegrass and crop biotypes are usually referred to as annual ryegrass. Annual ryegrass grown for seed is a major crop in western Oregon. Crop biotypes are rarely problematic as volunteers in other crops due to the continuous nature of annual ryegrass production and the fact that it normally exhibits a high degree of herbicide susceptibility. However, in western Oregon it is somewhat common for a weedy population of Italian ryegrass to take over a field where wheat has been planted and then the weedy biotype is harvested and sold as annual ryegrass crop.

Competition

Italian ryegrass is an aggressive competitor. In western Oregon it is frequently found infesting cereal crops, mostly wheat, and in grasses grown for seed. In grasses grown for seed, Italian ryegrass presents a significant threat to seed lots as a contaminant with the harvested seed. In wheat, dockage can occur due to contamination of harvested grain, but Italian ryegrass seeds can be easily removed, and yield loss due to competition is the primary concern. Pavlychenlo and Harrington (1937) reported a survey of Canadian grain fields with infestations of numerous annual weeds early in the season wherein the fields ranged from nearly weed free to so infested as to have very little crop, depending on weed species. Italian ryegrass has the potential to leave very little crop in severe infestations. Appleby et al. (1976) reported reductions in winter wheat yields ranging from 15-50% when wheat was grown with 66-118 Italian ryegrass plants per square meter. Roerig et al. (2015) recorded a 75% reduction in untreated plots and a 53% reduction in wheat yield in plots treated with flufenacet-metribuzin followed by pyroxsulam in a commercial wheat field with an infestation of multiple resistant Italian ryegrass as compared to plots with 98% or greater control of Italian ryegrass. Numerous similar studies have documented reductions of up to nearly 100% in wheat yield when grown in competition with Italian ryegrass (e.g., Appleby and Brewster, 1992; Brewster et al, 1977; Bailey et al., 2003; Griffin, 1986; Hashem et al., 1998; Justice et al., 1994; Khodayari et al., 1983; Scursoni et al., 2012, Trusler et al, 2007).

When a model was developed to predict wheat yield loss due to Italian ryegrass competition in various climatic situations, precipitation and cumulative heat did not predict relative competitiveness of wheat and Italian ryegrass; Italian ryegrass population was the only factor evaluated to reduce wheat yield (Stone et al. 1999). Field studies resulted in a 40% reduction in leaf area and above ground biomass of wheat early in the growing season when a low density of Italian ryegrass was present at 40 plants/m^2 (Stone, 1994). Although wheat does have a slight competitive advantage over Italian ryegrass in terms or early above ground biomass (Ball et al. 1995), Italian ryegrass can still be the dominate species.

Italian ryegrass was less competitive during vegetative stages, but more competitive during reproductive stages (Hashem et al., 1998). The competition between Italian ryegrass and wheat appears to occur mostly below ground. Stone et al. (1998) documented minimal effect when plants of the two species are grown in close proximity, but with the roots partitioned and strong competition when the roots are allowed to interact at the same density.

Rigid ryegrass (*Lolium rigidum* Gaudin) is a similar species to Italian ryegrass, differing from Italian ryegrass primarily in that is has somewhat less propensity towards seed shatter at maturity. It infests wheat growing areas of Australia and has develop resistance to many herbicides. The issues with rigid ryegrass in Australia are very similar to the issue with Italian ryegrass in the US, however rigid ryegrass infestations are more widespread and the development and spread of herbicide resistance is greater. While rigid ryegrass is not common in western Oregon, studies of rigid ryegrass in Australian can give some indication of what to expect from Italian ryegrass locally. Wheat and rigid ryegrass compete equally for nitrogen up to the 3-leaf stage. If nitrogen was application was delayed to the 4-leaf stage, then rigid ryegrass had the competitive advantage (Forcella, 1984). In greenhouse experiments Italian ryegrass was more efficient at taking up nutrients than wheat (Liebl and Worsham, 1987). Nonetheless, adding excess rates of nitrogen only increase Italian ryegrass straw, but do not increase grain yield in winter wheat infested with Italian ryegrass (Albeke, 1963). Italian ryegrass was more competitive with wheat when ample water was provided and wheat competitiveness with Italian ryegrass was enhanced by drought (Carson et al. 1999). Wheat tillers correlated negatively with Italian ryegrass population while heads size and kernel size remained relatively unchanged, so yield losses were primarily attributed to a reduction in tillering (Liebl and Worsham, 1987).

In addition to competing fiercely with wheat during the growing season, Italian ryegrass also can produce vast quantities of seed. Pedreros (2002) reported 80 Italian ryegrass plants/m^2 added more than 28,000 seeds/m^2 to the seed bank. As wheat density increased the effect of rigid ryegrass on wheat yield diminished until at the highest wheat density, there was no effect as compared to a pure stand of wheat. However, this population density was so high that yield was reduced as compared to pure stands of wheat alone of lower density due to intraspecies competition (Rerkasem et al., 1980). Competition between wheat plants and between wheat plants and rigid ryegrass are both detrimental to wheat yield. Growth of rigid ryegrass was strongly suppressed by increased wheat densities (Medd et al., 1985). Wheat planting arrangement did not have a significant effect on rigid ryegrass growth (Medd et al., 1985) or Italian ryegrass (Appleby and Brewster, 1992). Nor did seeding rate and row spacing affect competitiveness of wheat vs. Italian ryegrass (Justice et al., 1994). The effect of competition of rigid ryegrass in wheat varied greatly by cultivar and year, making it difficult to identify cultivars suited to competing with the weed (Cousens and Mokhtari, 1998). The authors suggest that cultivar selection is not likely to play a consistent role in reducing the impact of weed competition. Italian ryegrass population dynamics were modeled considering an increase in average air temperature of 2.5C as may occur due to anticipated climate change (Pagnoncelli, 2020). The model indicates an 18-26% increase in the seed bank equilibrium density of Italian ryegrass. The results of the studies indicate that climate change could enhance the competitiveness of Italian ryegrass.

Resistance

Herbicide resistant Italian ryegrass is a problem throughout the Pacific Northwest (Rauch et al., 2010; Mallory-Smith et al., 2007) and other parts of the United States (e.g., Kuk and Burgos, 2007 Ellis et al., 2008; Ellis et al., 2010). Italian ryegrass has developed resistance to at least six different herbicide modes of action in the United States (Heap 2020). In western Oregon there is documented resistance to herbicides from seven modes of action representing nearly all herbicides that control Italian ryegrass (Avila-Garcia and Mallory-Smith, 2011; Bobadilla et al., 2018; Kunjo 1992; Liu et al., 2014; Perez-Jones et al., 2005), with the notable exception of pyroxasulfone (Hulting et al., 2012). Pronamide is often used to control Italian ryegrass in fields rotated to clover and resistance to pronamide has not been observed by growers or extension personnel (Anderson, personal communication) but has been reported in one population in a greenhouse screen (Bobadilla et al., 2018). Populations of Italian ryegrass with resistance to flufenacet are susceptible to pyroxasulfone (Mingyang et al., 2016; Roerig et al, 2015), though both are WSSA group 15 herbicides. Currently there are three pyroxasulfone containing products on the market with labels allowing application on most of the large acreage crops in western Oregon. Even in the 1970's, before the current global herbicide crisis, it was recognized that due to weed plasticity and selection pressure alternating herbicide mode of action would only delay herbicide resistance, not prevent it entirely (Gressel, 1978). Now with very limited effective herbicide options available for Italian ryegrass control in several key western Oregon crops, selection pressure for pyroxasulfone resistance will be intense. In a screening of over 100 million rigid ryegrass seeds, none were found to have a major resistance gene for pyroxasulfone, however a population with multiple resistance that had never been treated with pyroxasulfone developed a 33% survival rate after three generations when treated with 240 g ai/a (2x rate). A population resistant to multiple herbicide modes of action but that had not been exposed to pyroxasulfone had a 10% survival rate when pyroxasulfone applied at 120 g ai/ha, whereas a susceptible population had a 2% survival rate at 90 g ai/ha (Busi et al, 2012). These results with a closely related species further illustrate the potential for the development of pyroxasulfone resistance in Italian ryegrass. The progression of Italian ryegrass herbicide resistance in the pacific northwest has closely followed that of rigid ryegrass in Australia where in a 2003 survey 64% of populations were resistance to two or more herbicide modes of action (Owen et al., 2007) and by 2010 in a similar survey 95% were resistant to two or more herbicide modes of action (Owen et al., 2014).

Reprieve from herbicide resistance has historically come from the release of new herbicide modes of action, particularly in the case of Italian ryegrass in western Oregon. Yet there have been no new herbicides modes of action introduced for over 30 years (Duke, 2012) and investment by corporations in herbicide discovery has decreased both financially and in terms of personnel (Stubler et al., 2016). Thus, new herbicide modes of action are not likely to resolve the issue of herbicide resistant Italian ryegrass in western Oregon.

Other factors relating indirectly to herbicide resistance may also affect herbicide efficacy. Burrill and Appleby (1978) evaluated control of Italian ryegrass with diuron at different rates and weed densities. As Italian ryegrass density increased the percent reduction of Italian ryegrass was reduced. Diuron applied at 2.8 kg/ha resulted in an 82% reduction of Italian ryegrass biomass when the population was 700 plants/m^2 and only 37 when the population was 7,500 plants/m^2. Such a response indicates that when herbicide resistance develops, and the typical increase in the seed bank occurs, even a new mode of action may be less able to control populations with large seed banks. Owen et al. 2011 found rigid ryegrass populations resistant to ACCase and ALS inhibitors were found to be more likely to germinate later, thus resisting herbicide applications in the traditional sense and avoiding them in time. Preplant non-selective herbicide use is common in this region. These examples underscore some of the undesirable secondary effects of herbicide resistance.

Weed Seed Movement

Transport

The ability of combines to transport weed seeds during harvest has been observed at least as early as the 1920's as combines were initially tested for use in Germany (Petzhold, 1952). Combines have a greater capacity to move weed seeds than any other farm machinery (Cousens and Mortimer, 1995; Thill and Mallory-Smith, 1997). McCanny and Cavers (1988) found an average of 3%, a small but significant amount, of proso millet seed produced in an isolated patch uniformly spread over 50 meters from the patch during corn harvest and observed that a black-seeded biotype of wild-proso millet had been spread to nearly cover an entire field after two years, presumably due to combine transport. McCanny and Cavers (1988) also documented large quantities of viable seed stored in the header of the combines used in the experiment. Similarly, Ghersa et al. (1993) recovered a steady rate of about 1% of Johnsongrass seeds entering the combine from isolated patches each meter of combine travel in seed traps for 50 meters during corn harvest.

An analysis of rigid ryegrass seed distribution at harvest found the majority of ridged ryegrass seeds remained within a few meters of their original location during harvest, however seeds were transported beyond the 18 meters the study measured

(Blanco-Moreno et al., 2004). Barroso et al. (2006) found the majority of wild oat plants growing within the perimeter of the original stand, but that isolated patches were found up to 20 meters from the edge of the original stand following two years of cereal gain harvest. Though most seed was shed before harvest and germinated where it was produced, the small number of seed moved is important as that provides the seed bank for the establishment of new patches. Italian ryegrass behaves similarly, with a majority of seed shattering before wheat reaches harvest maturity. Some seeds may cling tightly to the raceme during threshing and be discharged in the straw, but this is less common, and those seeds are likely to be immature. The remaining seed is either collected in the grain tank or discharged with the chaff. The relative proportion ending up in the grain tank or in the chaff depends on the machine and settings used (Shellard and Macmillian, 1978). As such, a reduced, but significant proportion of seeds are returned to the field in the chaff.

The movement of small quantities of seed is very important when dealing with the spread of herbicide resistant weeds. From a modeling exercise Ballare et al. (1987) concluded that the spatial dispersal of weed seed during harvest promotes exponential population growth by making additional space available to the plants and 95-99% control of seedling may not be adequate to reduce weed populations without removal of 80-90% of seeds during harvest. When modeling numerous factors Woolcock and Cousens (2000) indicated that good estimates of dispersal are needed to predict the rate of spread. Good estimates of Italian ryegrass seed dispersal by combines were not found in the literature.

Weed seeds are often moved between fields (Donald and Ogg, 1991, Horne 1953). Seeds moved by combines between fields would be either inside the machine or on the outside. Since it is significantly easier to clean the outside of a combine than the inside, harvest weed seed management techniques could play an important role in reducing inter-field transport of weed seeds, in addition to intra-field transport.

Dispersal by tillage in space is generally limited and is not substantially greater in distance than dispersal by seed shatter (Barroso et al., 2006 and Rew and Cussans, 1997). However, tillage can be an important factor in effectively distributing weed seeds over time. For example: 9-13% of rigid ryegrass seed carried over from the previous year. Seed decay accounted for a greater proportion of seeds not persisting past one year in no-till than in a minimum tillage treatment (Chauhan et al., 2006a). Rigid ryegrass seed germination was 16% on the soil surface, 49% at 1cm, 44% at 2cm, 10% at 5cm, and 0% at 10cm. Crop residue or 5cm burial favors germination and emergence and decreases decay compared to seeds that remain on the soil surface (Chauhan et al., 2006b). Deep burial or leaving seed on the soil surface to decay results in the lowest emergence the following year. A study was conducted near Corvallis Oregon where Italian ryegrass seed was distributed at a population density representative of typical field with a severe infestation and tilled into the soil. Emerging seedlings were counted and removed so no additional seed was added to the seed bank. Italian ryegrass emerged in a very high density the first two years. By the third year emergence was less than 10% of the first year, 1% or less the fourth and fifth year, and less than 0.1% years six through nine. It was only after ten years that no Italian ryegrass was observed (Mallory-Smith, unpublished data).

Integrated Weed Management

Integrated weed management has historically focused on reducing pesticide use though coordinated use of multiple approaches (Swanton and Weise, 1991). Chemicals are only a component of a weed management system; IWM is a shift back to when chemical weed control was just a part of the approach (Walker and Buchanan, 1982). The impact of crop rotation to control weeds was well understood 100 years ago. Grass should follow grain which would outcompete weeds and any viable seeds remaining would germinate during a cultivated row crop and be destroyed before going back to grain. “Continuous grain cropping… give[s] noxious weeds every opportunity to accumulate on the farm and infest the land.” Conversely, crop rotation including grass and cultivated row crops, grass headlands, intensive grazing, provide conditions that prevent weed infestations (Parker, 1915 (Part II, Chapter IV, 71-97)). With the introduction of synthetic nitrogen sources, came the abandonment of crop rotation leading to intense weed problems and the solution suggested by Slife and Wax 1976 (as cited in Walker and Buchanan 1982) was more suitable herbicides. Dealing with intense weed problems primarily with herbicides has led to herbicide resistance. Widespread herbicide resistance has led farmers to consider alternatives to herbicide, whereas effective IWM is a proactive effort. Effective herbicides have led to the mentality that weeds can be dealt with once they become established. The need for alternatives to herbicides is often stressed to combat herbicide resistance, however IWM approaches are perhaps more likely forestall herbicide resistance when they supplement herbicides and are implemented before resistance is widespread. Even though IPM was a major focus in the management of insects and diseases by 1990’s, much less effort was put into integrated weed management. From an analysis of 4116 Weed Science papers from 1951 to 1990 over 70% dealt with herbicides and only 300 were categorized as pertaining to "other control methods" (Thill et al., 1991). IWM seeks to "create cropping systems unfavorable for weeds." Prevention is the most basic means of controlling weeds by delaying the introduction and spread of weeds. Prevention is one of many elements to an IWM program (Buhler 2002).

Even now as alternatives to herbicides are being pursued, it is often couched in the context of resistance management and IWM is rarely mentioned. IWM as a reaction to a problem (herbicide resistance) is less likely to be effective than a proactive IWM program. Small gains from a number of techniques will be required to combat herbicide resistance, including preseason herbicide application, delayed seeding with nonselective herbicide applications, pre-harvest nonselective herbicide application, increased seeding rates, and harvest weed seed management (Walsh and Powles, 2007). A combination of approaches is likely to be most effective (Matthews et al., 1996).

Harvest Weed Seed Control

Harvest weed seed control (HWSC) has been recognized as a potential tool to combat herbicide resistant rigid ryegrass in Australia since the mid-90's. The object of HWSC is to control weed seeds exiting the combine by some means. There are several systems, but the objective of each is to prevent seeds exiting the combine from contributing to the seed bank. The Ryetek system removed 66% of ridged ryegrass seeds during wheat harvest (Walsh, 1996, and Matthews et al. 1996). The seed bank ranged from 7284-577 where no seed sifting occurred, to 3613-346 in 1 x 1 x 0.1m of soil where the seed sifting device was used (Matthews et al. 1996), but this system never found widespread use. Some form of HWSC was utilized experimentally in grass seed crops in western Oregon to reduce volunteer problems. The systems tested were only able to recover 0.1-8.2% of seed (Schweitzer 1994). In the 1980's, HWSC was evaluated by researchers in Sweden. Based on 21 species the authors estimated that an average of 40% of seed shed before harvest but ranged 25-75%. Of the remaining seed, 5% was not harvested due to being lower than crop height, 3% spilled from the combine, 35% in the grain tank, 3% in the straw, and 14% in the chaff. The author anticipated a shift to earlier maturing species or biotypes and concluded that it is not a replacement for herbicides (Fogelfors 1982). However, modeling suggested that HWSC could forestall the evolution and spread of herbicide resistant weeds (Somerville et al, 2018).

Chaff cart, narrow windrow burning, and HSD yielded similar reductions in rigid ryegrass populations. The population reduction resulting from a single year of HWSC at 24 locations was 60%, ranging from 37-90% (Walsh et al., 2017). The benefits have been recognized by Australian growers with 43% adopting some sort of HWSC (Walsh et al., 2017). There are several HWSC methods currently employed, and for each of them seed retention at harvest is key.

Seed retention

The success of HWSC in Australia is due to the high level of seed retention of the most troublesome weeds, allowing a majority of seeds to be processed through the combine, rather than falling to the soil (Walsh and Powles, 2014). Italian ryegrass retention at wheat harvest above 15 cm in Washington has been reported to be 58% (Walsh et al., 2018). Seed retention of rigid ryegrass at harvest timing was positively correlated with increased wheat biomass in 71 fields surveyed in Australia (Walsh et al, 2018), thus a more competitive crop may aid in seed retention.

A growing degree days model was produced to characterize wild oat seed shatter relative to wheat harvest (Shirtliffe et al. 2000). A growing degree model for Italian ryegrass could aid producers in timing harvest to maximize collection of seed into the combine. Rigid ryegrass at 30 cm and above (wheat harvest height targeting crop only) retained 40% of seed produced, but at 10 cm and above 66% of seed was retained (Walsh et al., 2016). There is no conclusive evidence yet of selection for lower seed height or more shattering as a result of HWSC and lowering harvest height from 30 to 10 cm increase rigid ryegrass seed collection by 24% and only increase biomass processed by the combine by 15% (Walsh et al, 2018). Tidemann et al. (2016) reported that due to the high level of shatter (80%) prior to wheat harvest in wild oat, HWSC alone will not likely result in a population decline. The retention of seeds on the plant at a level that can be harvested by the combine are the key factors to successful HWSC. Italian ryegrass falls somewhere between the high level of retention reported for rigid ryegrass and the low level of retention for wild oat.

Chaff cart

When a chaff cart was used, approximately 75% of rigid ryegrass seed was removed from the field (Walsh and Parker, 2002). Walsh and Powles (2007) found 75-85% of rigid ryegrass seeds were collected by chaff collection during harvest, however the authors considered chaff cart use impractical due to large quantities of material. Shirtliffe and Entz (2005) reported a seven-fold reduction in the number of wild oat seeds discharged from the combine when a chaff cart was in use.

HSD, iHSD, and the Seed Terminator

Walsh et al. (2012) evaluated the initial version of the Harrington Seed Destructor (HSD) and recorded 98% destruction of rigid ryegrass seeds. Currently, there are two available impact mills commercially available for mounting on combines; the Harrington Seed Destructor® (iHSD; De Bruin Engineering, PO Box 52, Mount Gambier, South Australia 5290, Australia) and the Seed Terminator® (Seed Terminator, 1284 South Road, Tonsley, South Australia 5042, Australia). The iHSD is 98% effective at killing rigid ryegrass seed entering the system (Walsh et al., 2018; and Schwartz-Lazaro et al., 2017). Seed retention, weed height, and greater than 98% seed destruction efficacy on downy brome, feral rye, and jointed goat grass indicate that iHSD could be a valuable tool for controlling these species (Soni et al., 2020). For Italian ryegrass seed retention will be a key factor in determining the efficacy of HWSC.

Burning

Italian ryegrass seed density was reduced by 24% when standing stubble was burned and by 98% when residue was concentrated into a narrow windrow and burned compared to unburned residue (Lyon et al., 2016). Burning standing stubble resulted in 20% emergence of introduced *Lolium rigidum* and while burning standard windrows (1.2 m) resulted in 1% emergence. Narrow windrows (600-700 cm) produced higher temperatures and left approximately 10% of the field bare, vs 20% for windrow burning (Walsh, 2007).

Conclusion

Direct baling, narrow windrow burning, and HSD are similarly effective in controlling rigid ryegrass (greater than 95%) while carts were reported to provide 56-86%

control. Following a single year of HWSC in three locations infested with Italian ryegrass, seed head density was 29-69% lower than in untreated plots (Beam et al., 2019). Long term management of the seed bank is needed, not a focus on the effect on the current year's yield (Norris, 2007). Gill and Holms (1997) concluded from a review of relevant the literature that no single cultural method of controlling herbicide resistant rigid ryegrass would provide adequate control to produce maximum yield, but that a combination of methods such as delayed planting, burning, 'topping', grazing, increased seed density, and seed capture at harvest would be required to maintain maximum yield. A model by González-Andujar and Fernández-Quintanilla (2004) predicted a 96.7% reduction in the seed bank when a half-rate of herbicide (80% control), delayed seeding date, increased seeding rate, and HWSC were used, as opposed to 90.2% when a full-rate (90% control) of herbicide and no other management practices were applied for 10 years. This model output underscores the value of utilizing multiple approaches to weed management.

Even HWSC and other IWM practices subject weeds to selection pressure. Evaluating the possible effects of HWSC, Ashworth et al. (2016) found initial flowering of wild radish was 11 days earlier, moving from 600C to 344C growing degree days, and occurred in one quarter of the time after 5 generations selecting for early maturing plants.

As Parker (1915) put it: "There are no weed problems associated with good farming, only with the shiftless type of farming. Weed eradication, in a nutshell, is good farming." (Part VI, Chapter VI, 436-447). Though this may be a loftier goal than is obtainable, the concept underscores the importance of a long-term vision of weed control, especially in an era of rampant herbicide resistance and generations since farmers have practiced weed management in the absence of effective herbicides.

Chapter 3

Materials and Methods

Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] is a significant weed in western Oregon infesting many crops in the region. It competes fiercely for resources when grown in conjunction with desired crops and contaminates harvested grain or seed. Appleby et al. (1976) reported reductions in winter wheat yields ranging from 15-50% depending on Italian ryegrass density. In addition to being competitive, Italian ryegrass exhibits a high level of plasticity and has developed resistance to numerous herbicide modes of action.

Combines have the capacity to move weed seeds harvested with the crop, such as Italian ryegrass, great distances. This can lead to isolated patches, stemming from a new introduction or new cases of herbicide resistance, becoming widespread in a field. Integrated weed management (IWM) seeks to utilize multiple approaches to mitigate the effect of weeds on crops. Harvest weed seed control (HWSC) is a form of IWM that sits at the intersection of herbicide resistance and combine transport of weed seeds. HWSC seeks to reduce the population or spread of weeds that are discharged by the combine during harvest by some form of destruction or removal.

The main objectives of this research are: 1) Make direct measurements of the distance Italian rye seeds is transported by a combine harvester during harvest, 2)

Determine whether an out-of-control population of Italian ryegrass in a field can be brought back into control by using HWSC, and 3) Determine whether HWSC can prevent or slow the spread of new weed problems, such as patches of newly developed herbicide resistance.

Seed Transport Experiment

Site

Winter wheat was no-till planted in the fall of 2015 and planted in a conventionally tilled field in the fall of 2016. The wheat was managed with locally accepted standard conventional practices, including fertilizer, herbicide, and fungicide applications as needed. Wheat yield in the trial area was approximately 6,725 and 9,400 kilograms per hectare in 2016 and 2017, respectively.

Seed Preparation

To prevent contamination of the fields where the experiment was conducted, non-germinable seeds were used for the experiment. 'Golf' Italian ryegrass seeds from a commercial field were microwaved in a conventional home microwave oven for 2.5 minutes set on high. The seeds were microwaved in batches of 250 grams. Subsets of several batches were tested and found to have 0% germination after two weeks. It was anticipated that heating the seeds would affect the moisture content which would lower density of the seed. Seed that is lighter due to moisture removal may travel though the combine differently than seed that has not. Following microwaving, seed weight was reduced by 1.5-7.7%, however several weeks later the seed had absorbed moisture from the ambient air and the dyeing process and any difference in seed weigh was not significant.

The seeds for this experiment were dyed for three main reasons. First, dyed seed was distinctly different from any Italian ryegrass endemic to the field. Second, seeds could be identified by the exact location they were introduced into the experiment by their color. Third, they could easily be counted due to their vibrant, unnatural color. In 2016, seeds were dyed yellow, red, blue, and green. In 2017, yellow was replaced with brown due to the difficulty of identifying seeds dyed yellow. Seed dyed yellow was very difficult to distinguish from native non-dyed seed, so the yellow seed were excluded from the results and yellow was not used in 2017.

Chromatech seed dispersion colorants were used to dye the seed. Approximately 30 ml of dye was added to 2 liters of water and applied to 9 kilograms of seed. The seed was mixed in a 0.07 cubic meter capacity cement mixer with a plastic drum. Seeds were summarily dried to avoid clumping and to bring them back to the previous weight. Once dry, each color was divided into twelve paper bags containing 454 grams of seed each.

Plot Preparation

The objective was to measure the linear travel of the weed seed in the combine while the combine is harvesting. Thus, the maximum linear distance available was used for the experiment, resulting in plots that were 218 meters long. Starting at 6 meters wheat was removed every 11 meters to accommodate a 0.74 square meter collection pan. Twelve paper bags containing 454 grams of a single color of dyed seed were attached to the heads of wheat extending in a row perpendicular to the combines direction of travel from approximately 0.5 to 3 meters on either side of the first pan.

Harvest and Data Collection

The plots were harvested using a John Deere 7700 combine equipped with a 6.7-meter-wide header and the speed of the machine was 3.0 kilometers per hour. The combine was driven to straddle the collection pans and collect a 0.74 square meter sample. A pan was laid at 6 meters and every 11 meters thereafter. A new color was introduced every 218 meters. Before the introduction of each color, the combine was stopped and shut down while the bags of seed were prepared, and the collection pans placed. Since the colors were distinctly different it was not necessary to clean the combine between each color, allowing observations of the previous colors to be made during passes with a subsequent color at a distance of up to 873m (Figure 1). Following each pass, straw was carefully lifted off the pan and the remaining sample was collected for later evaluation.

The samples collected from the pans were later sifted to remove as much chaff as possible without losing any seed. The remaining material was then sorted by hand and the number of seed of each color was recorded. If the number of seeds in a sample was over 1000, the seeds were weighed, and the weight used to calculate an estimated number of seeds.

Data Analysis

Exponential decay was modeled using the exponential decay equation $Y=30.0e^{-0.003726X}$, where 30.0 is the number of seeds per meter squared at the initial point and -0.003726 is the slope of the observed point the model is based on. Observations from 300 to 654 meters were used. Observations from 0-300 meters were excluded because of the rapid reduction following the initial introduction of the seed. While this initial decay is an important factor, including this data created a model that was not representative of the results beyond 300 meters. After 654 meters there were only one or two observations at each interval, so these data were also excluded from the model. These data do not seek to characterize the rate seeds are picked up by the combine, influenced by population density and seed shatter, seed fate, or unaided seed dispersal; these data only attempt to characterize the movement of the weed seed once it enters the combine during harvest.

Chaff Collection, Seed Bank

Year 1 (2012-2013).

Italian ryegrass seed was distributed across the entire trial area on October 18, 2012 and incorporated to a depth of approximately 4 inches to simulate an out of control population. Wheat was planted October 22, 2012, following Italian ryegrass incorporation. The treatments include an untreated plot, application of an herbicide, application of an herbicide plus chaff removal at harvest and chaff removal at harvest without herbicide application. The treatment, whether harvest method or herbicide was applied to the entire plot. The plots were 61x18 m. The application of the herbicide treatment was conducted December 5th when the wheat and Italian ryegrass were established. Propoxycarbazone was chosen for the herbicide treatment during years (1-3, 6) wheat was the crop because it is expected to provide marginal control of Italian ryegrass which would be similar to a typical herbicide used for Italian ryegrass control to which herbicide resistance was developing. Sethoxydim was used at a 0.5X rate during the years that red clover was grown. Thus, annual ryegrass with no herbicide resistance could be planted and we could achieve approximately 50-70% control thereby simulating the kind of control that might occur in a wheat field with resistant Italian ryegrass using the best herbicides available without contaminating the site with herbicide resistant seed. Collection of chaff was accomplished by Echo Bearcat debris loader capable of moving 2500 cubic feet per minute which was mounted on a tractor and attached by a hose to a funnel on the back of a John Deere 7700 or 7720 combine. The mounting system and funnel were fabricated by GK Machine. This vacuumed the chaff as it exited the combine off the sieve and blows it into a wagon towed by a tractor. The chaff collection occurred during harvest, which was the first week of August 2013. Measurements during this year were Italian ryegrass population counts and yield data. Italian ryegrass counts were based on counts from randomly placed quadrats. The yield data is from the entire plot. These measurements only reflect the effect of the herbicide because the cultural weed management technique was not applied until harvest.

Year 2 (2013-2014)

In the second year, no additional Italian ryegrass was planted. Wheat was planted October 8, 2013. Italian ryegrass plants were counted before the year two herbicide application to quantify the effects of the treatments in year one. The herbicide treatment was applied February 26, 2014. Visual control ratings were conducted in the spring following the herbicide application. During harvest, chaff was collected in the appropriate treatments and yield was quantified for all treatments. Harvest was conducted during the last week of July. Differences in yield between treatments provide a good representation of the level of competition between wheat and Italian ryegrass.

Year 3 (2014-2015)

The third year proceeded in the same manner as the second. Propoxycarbazone was applied on March 3, 2015.

Years 4 and 5 (2015-2017)

Following the third harvest the trial was planted to red clover grown for seed and harvested in the fourth and fifth year. Red clover grown for seed is a commonly used as a rotational crop in wheat production in the Willamette Valley. Red clover grown for seed is a perennial crop and growers typically get two harvests before the field is replanted to another crop. Red clover seed fields are mowed in May or early-June to improve seed set. Harvest is conducted by first swathing, typically mid-August, and the crop is allowed to dry in windrows for 5-10 days. During these two years of the experiment sethoxydim was applied at 0.5X the label rate each year to continue the simulation of some level of resistance. At maturity, the plots were swathed and harvested. Chaff collection continued in the corresponding plots. Italian ryegrass populations were counted, and seed yield quantified each year red clover was grown.

Year 6 (2017-2018)

A final year of wheat was planted and managed as in previous years. Italian ryegrass populations and wheat yield were quantified. Following harvest, the ground was tilled, and emerging Italian ryegrass seedlings were counted.

Data Analysis

This study was a randomized complete block design. The treatments were compared for each year separately. Analysis of variance (ANOVA) was conducted on crop yield and emerging seedling density. Means were separated using a 5% significance level (Student-Newman-Keuls).

Chaff Collection, Seed Distribution

The previous trial focused on the removal of chaff for the reduction of reduction of an Italian ryegrass population, while this trial focused on the prevention of the movement of Italian ryegrass seed from a new point of infestation. This trial was established in 2014. An adjacent 7.2-acre field was planted with ‘Bobtail’ winter wheat. This trial was also maintained according to grower standards including fertilizer, fungicide applications and broadleaf herbicides and the plots were the same size as the former study. To accomplish this, a strip on one end of each plot was planted with Italian ryegrass. The strip of Italian ryegrass was planted in one pass across the width of the plot, two meters wide and three meters from the end of the plot. Harvest was conducted in one direction starting on the end where the annual ryegrass was planted. The treatments and crops rotations were the same for this trial as the previous.

Yield data was recorded each year, and prior to harvest in the final year the distribution of Italian ryegrass was recorded. The distribution of Italian ryegrass was recorded by counting along a transect every 0.6 meters and counting plants on either side of the transect in 0.3 meters in either direction. One person counted from each outside edge to the center. The number of plants on either side of the center were counted from 0-10, or if over ten due to the impracticality of counting numerous and merging plants were recorded as 11. With plants being planted in a strip at one end of the plot and harvest occurring in the same direction each year, these counts give an indication of movement of Italian ryegrass seed during the experiment. Tillage was conducted with the objective of moving as little soil as possible to reduce seed movement in the soil.

Data Analysis

This study was a randomized complete block design. Analysis of variance (ANOVA) was conducted on crop yield and emerging seedling density. Means were separated using a 5% significance level (Student-Newman-Kuels).

Italian Ryegrass Seed Retention

In 2020, Italian ryegrass shatter was estimated by counting seeds in ten seed heads each week for nine weeks from June 23 to August 18. This timing was selected to represent the time from when Italian ryegrass has nearly reached maturity, but not started to shatter up until the time wheat harvest generally concludes. The average number of seeds per head over time provided an estimate of the proportion of seed that has shattered over time. These estimates provide context to the results of the other experiments.

Chapter 4

Results

Seed Transport Experiment

Given a chaff row of 1.2 meters in width, pans every 11 meters, and a pan size of 0.74 square meters; the maximum recovery rate for this experiment was approximately 5.6% (Table 1). Of all the seeds entering the combine 0.89% were recovered, which is 16% of the maximum recovery rate and represents the proportion discharged from the combine. This means that approximately 84% of the seeds were retained in the combine; primarily in the grain tank, though a considerable amount likely remained inside the machine or was clinging to the outside or in the header. Though the number of pans varied by color due to the sequential nature of passes, there was no correlation between the number of pans and the percent recovery (Table 2). This is not surprising due to the high rate of initial discharge and the resulting disproportionate contribution to the total by the first few pans.

The first two pans, at 6 and 17m, following introduction into the combine, accounted for over 70% of the seeds that were recovered during the experiment (Figure 2). Pans from 302m to the end of the experiment at 873m collected a total of 0.52% of the seeds recovered during the experiment (Figure 3). Seeds were still collected at a steady rate averaging 4.2 seeds/m during the last 100m of the experiment (Figure 3). The exponential decay model of seed deposition based on 300-650 meters shows a rate of deposition of over four seeds per ha in the chaff row following 3000m of harvest distance (Table 3).

Chaff Collection, Seed Bank

Italian ryegrass density

Italian ryegrass population densities varied by year and treatment (Table 2). In 2013, 2018, and 2019 there was no difference in the Italian ryegrass populations (at p-value 0.05). In 2014, the population densities in all three treated plots were lower than in the untreated plots, though there was no difference among the treatments. In 2015, chaff collection alone did not significantly reduce Italian ryegrass populations. The herbicide alone and herbicide plus chaff collection did significantly reduce Italian ryegrass populations as compared to the untreated check. The herbicide plus chaff collection also was significantly lower than chaff collection alone. In 2016, the herbicide treatment and herbicide plus chaff collection were lower than the untreated check, but not different from each other. Chaff collection alone did not significantly differ from any of the other treatments. The 2017, populations were highly variable within the treatments, thus large numerical differences did not result in significant differences. Herbicide alone was lower than the untreated, but herbicide plus chaff collection did not result in a statistically significant reduction compared to the untreated.

From 2013 to 2017, there was a 32-fold increase in Italian ryegrass density. In 2018 following two years of clover seed production, no Italian ryegrass plants were recorded in the in the trial area. This is presumably because of the different management employed during clover seed production, such as spring mowing, which may have interfered with Italian ryegrass seed production. In 2019 following a year of wheat, Italian ryegrass was observed again in the plots, but at levels approximately seven-fold lower than the initial population in 2013.

Winter wheat and red clover seed yield

Because no treatments were applied that would affect the yield of wheat or red clover directly, differences in yield are primarily the effect of differences in competition between the crop and Italian ryegrass. In 2013 and 2014, both treatments including an herbicide yielded more wheat than either the untreated or chaff collection alone treatment (at p-value 0.05) (Table 3). In 2015, wheat yield was greater in the herbicide plus chaff collection plot than in any other plots. Chaff collection alone did not produce significantly more yield than the untreated. From 2016 to 2018 red clover and wheat yield did not differ among the plots.

Chaff Collection, Seed Distribution

Italian ryegrass density

There was a significant treatment by distance grouping interaction (p = 0.0014). In all treatments there was a reduction in the population of Italian ryegrass moving away from the initial point of infestation except for the herbicide plus chaff collection treatment (Figure 4). In the herbicide plus chaff collection plots, three of the four replications had 0-4 plants in the entire plot, however in one of the replicates of the herbicide plus chaff collection plots there were 183 plants counted. Additionally, in this plot the population increased as the distance from the initial source increased, which is the opposite of every other plot containing Italian ryegrass. This population pattern suggests a source different than the one planted experimentally.

From the beginning of the plot up to 34 meters from the initial infestation point, ryegrass density in the herbicide plus chaff collection plots was significantly lower than the untreated plots (at p-value 0.05) (Table 5). Chaff collection alone had no influence on ryegrass density at any distance from the initial source, and the herbicide only treatment was statistically lower than the untreated in only the first two distance groups. In each distance groups beyond 34 meters there was no statistical difference between the plots.

Winter wheat and red clover seed yield

Winter wheat yield did not vary significantly (at p-value 0.05) between treatments during 2015 or 2016 (Table 4). In 2017, winter wheat yield was greatest in the chaff collection treatment and significantly greater than ‘herbicide alone’ or ‘herbicide plus chaff collection’ treatments. These results are unexpected since the plots were managed the same except for these treatments, and more weed control would be expected to improve yield. In 2017, the plots had patchy take all disease. Though the distribution of take-all was not recorded, it is plausible that the disease affected some areas greater than others and led to the differences in yield. In 2018 and 2019, red clover seed yield was equivalent in all treatments. In 2020, wheat yield was significantly higher in the chaff collection plus herbicide plot. The herbicide alone or chaff collection alone was equivalent to the untreated and chaff collection plus herbicide plots.

Italian Ryegrass Seed Retention

On June 23, 2020, each Italian ryegrass head had an average of 229 seeds (Figure 6). Over the next four weeks there was progressively less seed retained in the seed heads each week when counts were made. From July 14, 2020, until the last counts were made on August 18, 2020, counts were fairly steady at 42% (+/- 5%) of the initial count. Winter wheat in western Oregon reached harvest moisture around mid-July in 2020, coinciding with the date that seed shatter leveled off. Though this is not a robust data set, this data suggests that approximately 40% of Italian ryegrass seed remain throughout wheat harvest.

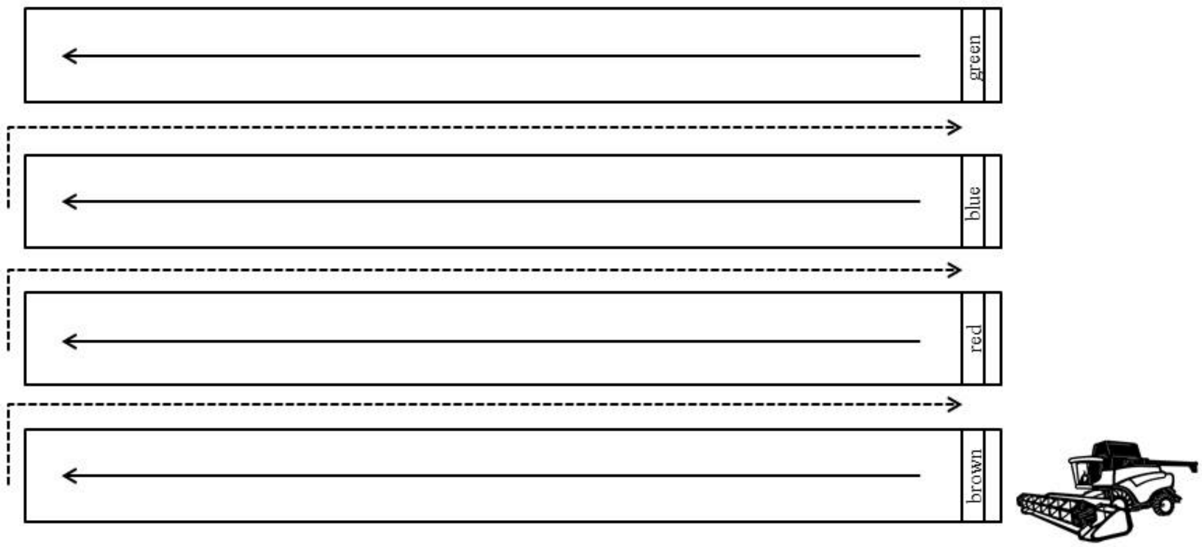

Figure 1. The order and manner of plot harvest in the seed transport experiement. A continous 218 meter strip was harvested after the introduction of each new color. After each strip the combine was stopped and a new color was introduced. The total distance harvested was 873 meters. The order havest was conducted in 2017 is shown here as an example.

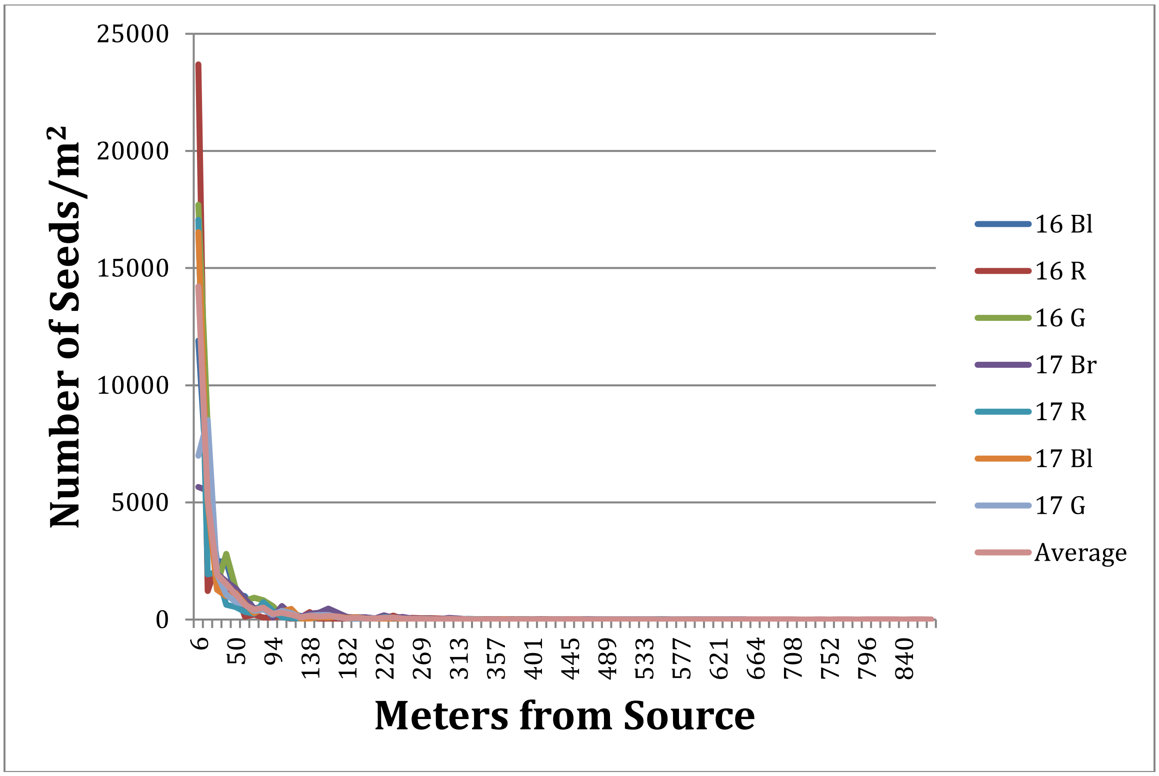

Figure 2. Deposition of Italian ryegrass seeds discharged from the combine in the seed transport experiment. The number of seeds per square meter deposited in the collection pans are shown here. These data represent points from 0-870 meters from the point of introduction in 2016 and 2017. 16 Bl = 2016 Blue, 16 R =2016 Red, 16 G = 2016 Green, 17 Br = 2017 Brown, 17 R = 2017 Red, 17 Bl = 2017 Blue, 17 G = 2017 Green.

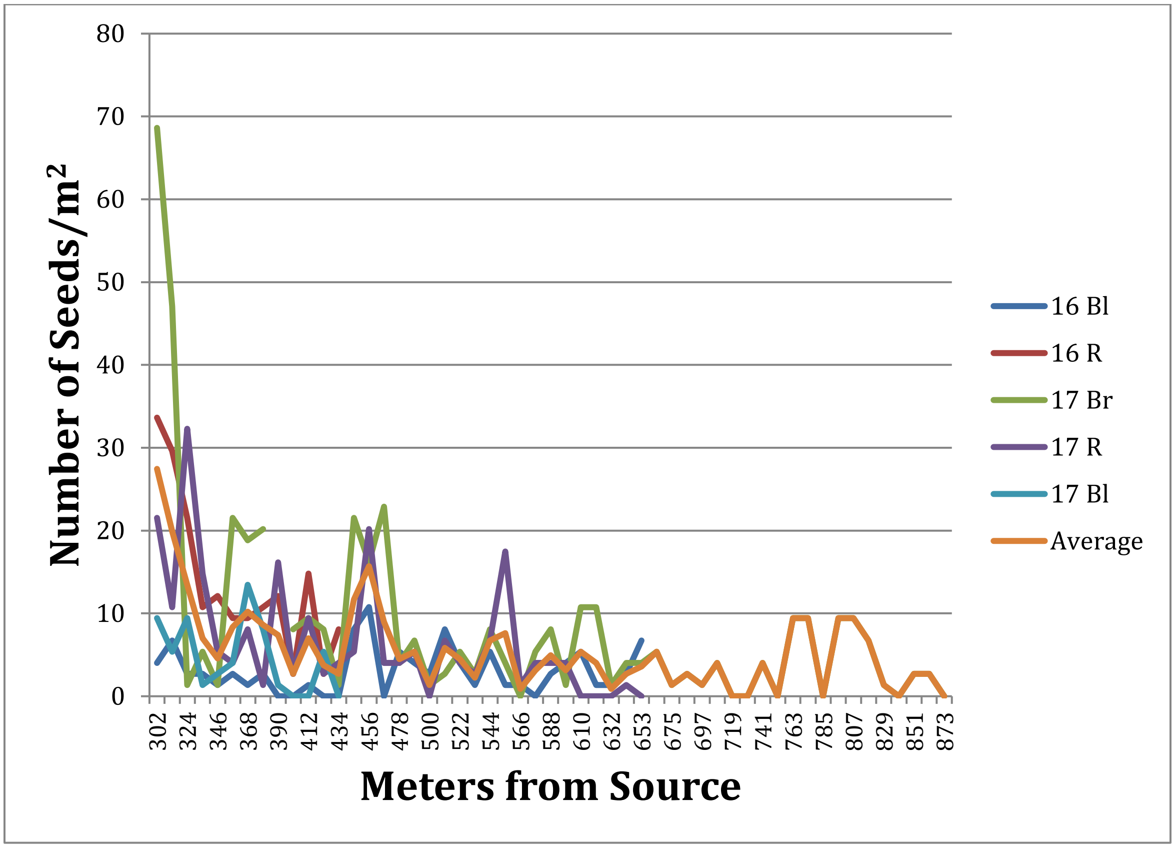

Figure 3. Deposition of Italian ryegrass seeds discharged from the combine in the seed transport experiment. The number of seeds per square meter deposited in the collection pans are shown here. These data represent points from 300-870 meters from the point of introduction in 2016 and 2017. Data from introduction to 300 meters are excluded to show the detail of the later portion of the experiment as the numbers decrease. 16 Bl = 2016 Blue, 16 R =2016 Red, 17 Br = 2017 Brown, 17 R = 2017 Red, 17 Bl = 2017 Blue.

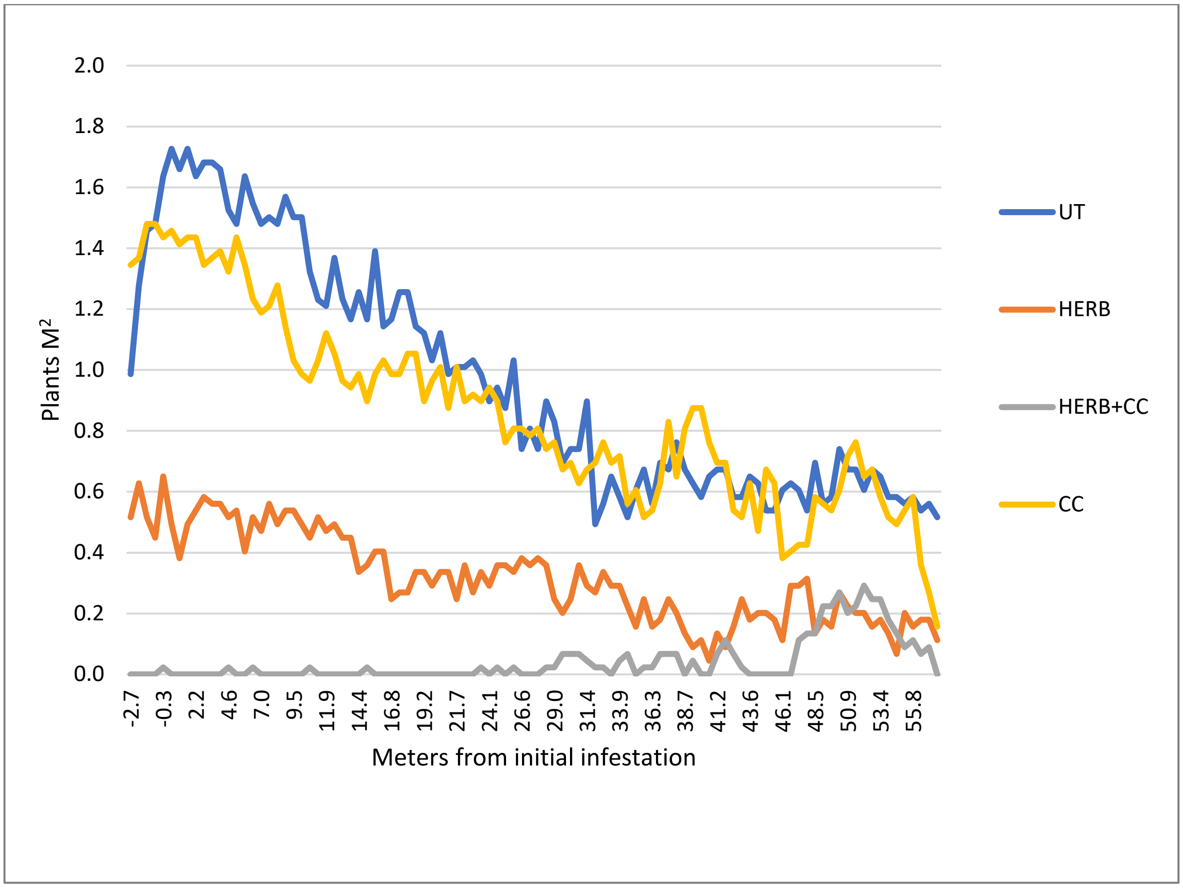

Figure 4. The number of Italian ryegrass plants per square meter by distance from initial source in the chaff collection, seed distribution study. UT = untreated, HERB = herbicide treatment, HERB+CC = herbicide plus chaff collection, and CC = chaff collection.

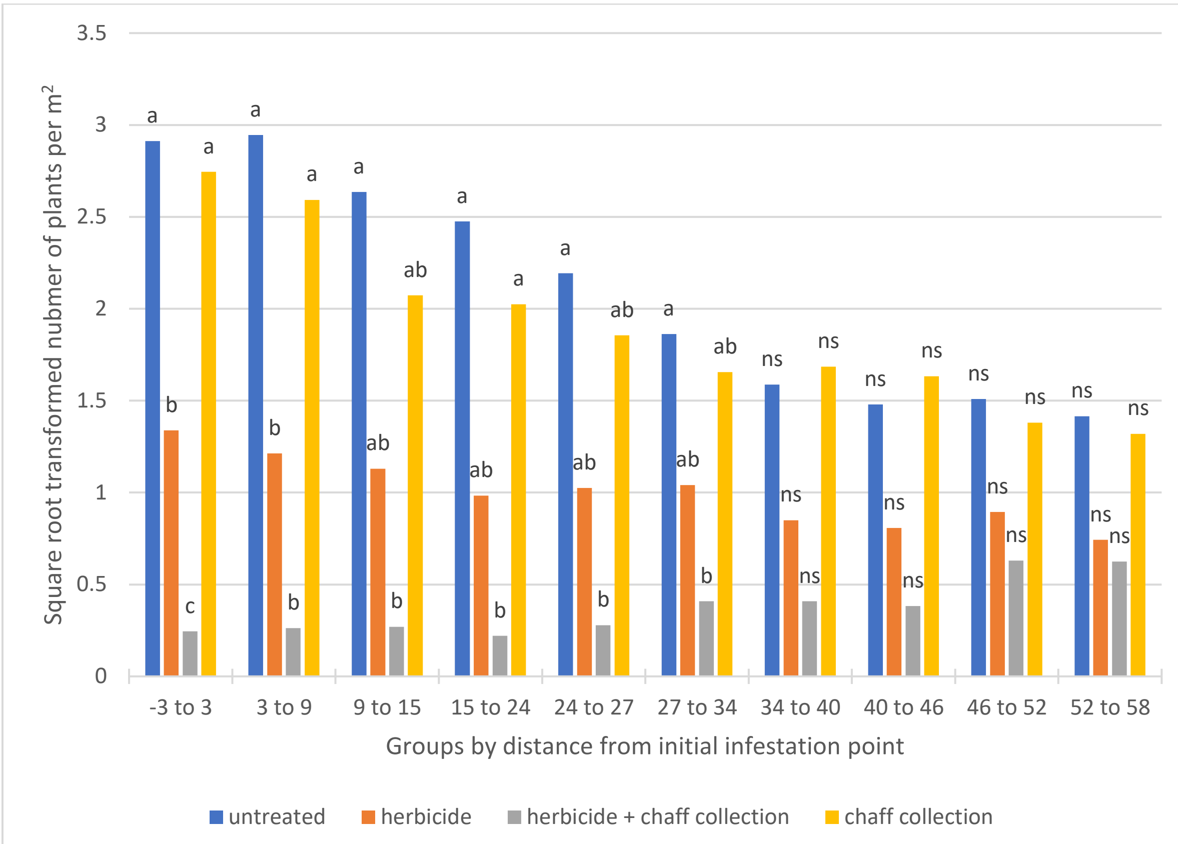

Figure 5. Square root transformed Italian ryegrass density in each treatment separated into ten groups by distance from the initial infestation. Means within a distance group followed by the same letter do not significantly differ (at p-value 0.05). N=4

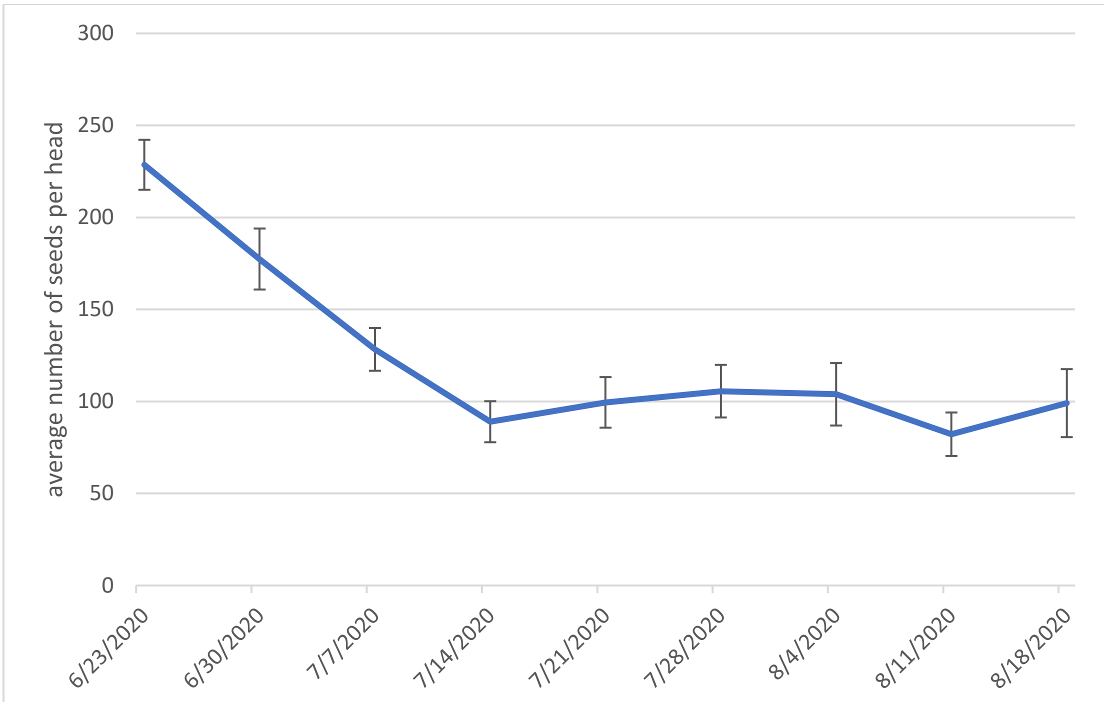

Figure 6. The average number of Italian ryegrass seeds retained on ten heads over time in 2020 (SE, N=10). These data give a rough estimate of 40% of seed remaining at the initiation of winter wheat harvest and that the number of seeds per head remains fairly stable for several weeks into harvest. The start of wheat harvest in 2020 was approximately 7/21/2020.

Table 1. Model of seed deposition during harvest in the seed transport experiment based on 300-650 meters, $Y=30.0e^{-0.003726X}$, $R^2=0.365$, N=5

Meters Traveled	Seeds/ha
1000	7270
1500	1131
2000	176
2500	27
3000	4.27
3500	0.66
4000	0.10

Table 2. The effect of herbicide application and chaff collection on crop yield chaff collection, seed bank study. Means within a year followed by the same letter do not significantly differ (at p-value 0.05).

		Italian ryegrass													
	Rate	2013		2014		2015		2016		2017		2018		2019	
	g ai/ha	plants/m2													
untreated		110	-	211	a	733	a	291	a	3568	ab	0	-	15	-
propoxycarbazone	31.4	98	-	105	b	570	bc	209	b	1001	c	0	-	8	-
OR sethoxydim	314.0														
propoxycarbazone	31.4	83	-	76	b	436	c	173	b	1386	bc	0	-	9	-
OR sethoxydim	314.0														
+ chaff collection															
chaff collection		106	-	88	b	635	ab	220	ab	4311	a	0	-	12	-
LSD P=0.05		26		58		159		70		2443		-		9	

Table 3. Crop yield by year in the seed bank study. Means within a year followed by the same letter do not significantly differ (at p-value 0.05).

		------------------winter wheat------------------						-----red clover seed-----				winter wheat	
Treatment	Rate	2013		2014		2015		2016		2017		2018	
	lb ai/a	--kg/ha--											
untreated		1762	b	3753	b	1385	c	487	-	745	-	8864	-
propoxycarbazone	31.4	3517	a	6053	a	2582	b	493	-	617	-	8938	-
OR sethoxydim	314.0												
propoxycarbazone	31.4	3571	a	6456	a	3410	a	657	-	573	-	8770	-
OR sethoxydim	314.0												
+ chaff collection													
chaff collection		1823	b	4143	b	1412	c	551	-	625	-	9032	-
LSD P=0.05		383		565		756		406		199		806	

Table 4. Crop yield by year in the seed distribution study. Means within a year followed by the same letter do not significantly differ (at p-value 0.05).

		------------------winter wheat-------------------						----red clover seed----				winter wheat	
Treatment	Rate	2015		2016		2017		2018		2019		2020	
	g ai/ha	-----kg/ha-----											
untreated		7373	-	5881	-	5787	ab	724	-	445	-	7218	b
propoxycarbazone	31.4	7118	-	5948	-	5343	b	668	-	310	-	8307	ab
+ sethoxydim	314.0												
propoxycarbazone	31.4	7313	-	5800	-	5303	b	610	-	395	-	8657	a
OR sethoxydim	341.0												
+ chaff collection													
chaff collection		7185	-	5592	-	6083	a	597	-	524	-	7548	ab
LSD P=0.05		810		513		721		141		276		1340	

Chapter 5

Discussion

Weed flow through combines

The flow of material through a combine is much less like a conveyor belt and much more like a turbulent mountain stream, with eddies and backwaters where the rate of flow is greatly reduced, or material is temporarily stalled. Cousens and Mortimer (1995) suggested two 'populations' of seed traveling through a combine; one which travels quickly and is dispersed within several meters of its origin and another which becomes lodged or accumulates within the combine and is dispersed in an exponential decay manner. The data from this experiment support that model of weed seed flow in the combine. When modeling numerous factors, Woolcock and Cousens (2000) indicated that good estimates of dispersal are needed to predict the rate of spread. Italian ryegrass seeds in this study were observed up to 862 meters from the starting point. Presumably, if the experiment had been carried to a greater distance additional seeds would have been observed beyond 862 meters.

Weed management implications

Weeds in isolated patches and weeds that are widespread across a field require different management approaches. For many species, including Italian ryegrass, natural dispersal is limited to short distances. Dispersal by tillage is generally limited and is not substantially greater than dispersal by seed shatter (Barroso et al. 2006 and Rew and Cussans 1997). There may be several methods to effectively prevent weed seeds in the chaff from infesting a field, including windrow burning, chaff carts, seed destruction, direct baling, and others (for example: Lyon et al. 2016; Shirtliffe and Entz 2005; Walsh et al. 2017). Even with a seven-fold reduction in the number of wild oat seeds discharged from the combine, Shirtliffe and Entz (2005) reported that there were more wild oat seeds in the chaff row than outside the chaff row. These results suggest that improvement in historical chaff collection methods would improve the efficacy of chaff collection as a weed management tool.

Weed seeds are often moved between fields (Donald and Ogg, 1991, Horne 1953). Seeds moved by combines between fields would be either inside the machine in some part of the internal threshing mechanism or on the exterior of the machine. Since it is significantly easier to clean the exterior of a combine than the internal components, harvest weed seed management techniques could play an important role in reducing inter-field transport of weed seeds, in addition to intra-field transport.

HWSC and population density

The results of these studies suggest that a field with a high population of Italian ryegrass distributed throughout the field is not as likely to significantly benefit from HWSC as a field were herbicide resistance is developing or a new infestation is moving in in a patchy manner. In the situations evaluated in these studies, HWSC is most likely to be effective when viewed as a preventative measure. The use of HWSC to prevent the spread of infestations newly exhibiting herbicide resistance or of weed species that are new to a field could have a significant benefit in preventing the establishment of new problem species or new herbicide resistance traits. One challenge in implementing these strategies is that they are mostly likely to be effective before a weed problem reaches detectible levels. As the need becomes more apparent, this type of strategy becomes less effective.

Herbicide resistance

Herbicide resistance is important to consider in the context of weed seed movement, since weeds resistant to herbicides are more likely to be present during harvest than those that are susceptible and were controlled prior to harvest. Italian ryegrass has developed resistance to at least six different herbicide modes of action in the United States (Heap 2020). In western Oregon, there is documented resistance to herbicides from seven modes of action representing nearly all herbicides that control Italian ryegrass, with the notable exception of pyroxasulfone (Bobadilla et al 2018, Kunjo 1992). History suggests that Italian ryegrass resistance to pyroxasulfone is all but inevitable. This situation underscores the importance of this data. In a field where pyroxasulfone resistance develops, the plants will mature and produce seed and a combine has the capacity to move some portion of those seed great distances, facilitating the rapid spread across a field. If implemented, methods such as those listed previously in this paper, could mitigate the spread of herbicide resistant weeds.

Italian ryegrass competition can reduce wheat yields well below economically viable thresholds, has a history of repeatedly developing resistance to new herbicide modes of action, and little ability of seed to move on their own. This data demonstrates that combines can greatly facilitate the movement of Italian ryegrass seeds and results underscore the value of harvest weed seed control as a preventive measure in slowing the spread of herbicide resistance weeds, such as Italian ryegrass.

These data provide some insight into the effect combines have on the spread of Italian ryegrass in wheat and what effect chaff collection might have in reducing that spread. There are numerous other weeds that are spread by combines in other crops. In perennial grasses grown for seed, which are the dominant cropping system in the region where this study was conducted, grass weed seeds and volunteer crop are significant issues. Volunteer crop and grass weeds germinate between the crop rows and compete for resources and contaminate seed lots. These weeds and volunteer plants are found concentrated in the chaff rows left by combines during harvest. HWSC has the potential to offer significant gains in the battle against contaminating seeds from grass weeds, including grass weeds resistant to herbicides, and volunteer crop. Evaluation of HWSC in grass grown for seed could demonstrate whether these systems have value in that regionally important crop. There is also a growing number of HWSC methods that have not been evaluated herein. Additional research involving difference combines, HWSC methods, crops, and weeds would greatly expand the understanding of the interactions between weeds seeds, crop harvest, and machinery.

Literature cited

Albeke, WE (1963) The influence on winter wheat yields of competitive weed species. MS Thesis, Oregon State University

Anderson NP, personal communication. 2020

Appleby AP, Olsen PD, Colbert DR (1976) Winter wheat yield reductions from interference by Italian ryegrass. Argon. J. 68:463-466

Appleby AP, Brewster BD (1992) Seeding arrangement on winter wheat (*Triticum aestivum*) grain yield and interaction with Italian ryegrass (*Lolium multiflorum*). Weed Technol 6:820–823

Ashworth MB, Walsh MJ, Flower KC, Vila-Aiub MM, Powles SB (2016) Directional selection for flowering time leads to adaptive evolution in *Raphanus raphanistrum* (wild radish). Evol Appl 9:619–629

Avila-Garcia WV, Mallory-Smith C (2011) Glyphosate-resistant Italian ryegrass (*Lolium perenne*) populations also exhibit resistance to glufosinate. Weed Sci 59:305–309

Bailey WA and Wilson HP (2003) Control of Italian ryegrass (*Lolium multiflorum*) in wheat (*Triticum aestivum*) with postemergence herbicides. Weed Technol. 17:534-542.

Ball DA, Klepper B, and Rydrych DJ (1995) Comparative above-ground developmental rates for several annual grass weeds and cereal grains. Weed Sci. 43:410-416.

Ballare, CL, Scopel AL, Ghersa CM, Sainchez RA (1987) The population ecology of *Datura ferox* in soybean crops. A simulation approach incorporating seed dispersal. Agric. Ecosyst. Environ. 19:177-188.

Barroso J, Navarrete L, Sanchez del Arco MJ, Fernandez-Quintanilla C, Lutman PJW, Perry NH, Hull RI (2006) Dispersal of *Avena fatua* and *Avena sterilis* patches by natural dissemination, soil tillage and combine harvesters. Weed Res. 46:118-128

Beam SC, Mirsky S, Cahoon C, Haak D, Flessner M (2019) Harvest weed seed control of Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], common ragweed (*Ambrosia artemisiifolia* L.), and Palmer amaranth (*Amaranthus palmeri* S. Watson) Weed Technol 33:627–632c

Blanco-Moreno JM, Chamorro L, Masalles RM, Recasens J, Sans FX (2004) Spatial distribution of *Lolium rigidum* seedlings following seed dispersal by combine harvesters. Weed Res 44:375–387

Bobadilla LK, Berry PA, Hulting AG, Mallory-Smith CA (2018) Distribution and frequency of Italian ryegrass herbicide resistance in the Willamette Valley. 2018 Seed Production Research at Oregon State University Ext/CrS p.1-4

Brewster BD, Appleby AP, Spinney RL (1977) Control of Italian ryegrass and wild oats in winter wheat with HOE 23408. Agron. J. 69:911-913.

Buhler DD (2002) Challenges and opportunities for integrated weed management. Weed Sci 50:273–280

Burrill LC, Appleby AP (1978) Influence of Italian ryegrass density on efficacy of diuron herbicide. Agron. J. 70:505-5

Busi R, Gaines TA, Walsh MJ, Powles SB (2012) Understanding the potential for resistance evolution to the new herbicide pyroxasulfone: field selection at high doses versus recurrent selection at low doses. Weed Res 52:489–499

Carson KH, Cralle NT, Chandler JM, Miller TD, Bovey RW, Senseman SA, Stone MJ (1999) *Triticum aestivum* and *Lolium multiflorum* interaction during drought. Weed Sci. 47:440-445

Chauhan BS, Gill G, Preston C. (2006a) Influence of tillage systems on vertical distribution, seedling recruitment and persistence of rigid ryegrass (*Lolium rigidum*) seed bank. Weed Sci 54:669–676

Chauhan BS, Gill G, Preston C (2006b) Influence of environmental factors on seed germination and seedling emergence of rigid ryegrass (*Lolium rigidum*). Weed Sci 54:1004–1012

Cousens R and Mortimer M (1995) Dispersal within and between populations. Pages 79- 81 *in* Dynamics of weed populations. Great Britain: Cambridge Press

Cousens RD, Mokhtari S (1998) Seasonal and site variability in the tolerance of wheat cultivars to interference from *Lolium rigidum*. Weed Research, July 1998, Vol.38(4), pp.301-307

Donald WW and Ogg AG (1991) Biology of Jointed Goatgrass (*Aegilops cylindrical*), a Review. Weed Technol. 5:3-17

Duke SO (2012) Why have no new herbicide modes of action appeared in recent years? Pest Management Science 68:505–512.

Ellis AT, Morgan GD, Mueller TC (2008) Mesosulfuron-resistant Italian ryegrass (*Lolium multiflorum*) biotype from Texas. Weed Technol. 22:431-434.

Ellis AT, Steckel LE, Main CL, de Melo MSC, West DR, Mueller TC (2010) A survey for diclofop-methyl resistance in Italian ryegrass from Tennessee and how to manage resistance in wheat. Weed Technol. 24:303-309

Fogelfors H (1982) Collection of chaff, awns and straw when combining and its influence on the seed bank and the composition of the weed flora. Pages 339-345 in Weeds and Weed Control: 23rd Swedish Weed Conference. Uppsala, Sweden: Department of Plant Husbandry and Research Information Centre, Swedish University of Agricultural

Forcella F (1984) Wheat and ryegrass competition for pulses of mineral nitrogen. Aust. J. Exp. Agric. Anim. Husb. 24:421

Ghersa CM, Martinez-Ghersa MA, Satorre EH, Van Esso ML, and Chichotky G (1993) Seed dispersal, distribution and recruitment of seedlings of *Sorghum halepense* (L.) Pers. Weed Res. 33:79-88

Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide-resistant Lolium rigidum. Pestic. Sci. 51:352-358

González-Andujar JL, Fernández-Quintanilla C (2004) Modelling the population dynamics of annual ryegrass (*Lolium rigidum*) under various weed management systems. Crop Prot. 23:723-729.

Gressel J (1978) The paucity of plants evolving genetic resistance to herbicides: possible reasonsand implications. Journal of Theoretical Biology 75, 349–371.

Griffin JL (1986) Ryegrass (*Lolium multiflorum*) control in winter wheat (*Triticum aestivum*). Weed Sci. 34:98-100.

Hashem A, Radosevich SR, Roush ML (1998) Effect of proximity factors on competition between winter wheat (*Triticum aestivum*) and Italian ryegrass (*Lolium multiflorum*). Weed Sci. 46:181-190.

Heap I (2020) The International Survey of Herbicide Resistant Weeds http://www.weedscience.org/Summary/Species.aspx. Accessed January 10, 2020

Hitchcock, A. S. 1971. Manual of the Grasses of the United States. 2nd ed., revised by A. Chase. Washington, DC: United States Department of Agriculture Misc. Pub. 200. pp. 274-276.

Horn FR (1953) The significance of weed seeds in relation to crop production. Page 384 in Proceedings of the British Weed Control Conference. Margate England; British Weed Control Conference

Hulting AG, Dauer JT, Hinds-Cook B, Curtis D, Koepke-Hill RM, Mallory-Smith C (2012) Management of Italian ryegrass *(Lolium perenne* ssp. *multiflorum*) in western Oregon with preemergence applications of pyroxasulfone in winter wheat. Weed Technol 26:230–235

Justice GG, Peeper TF, Solie JB, Epplin FM (1994) Net returns from Italian ryegrass (*Lolium multiflorum*) control in winter wheat (*Triticum aestivum*). Weed Technol 8:317–323

Khodayari, K, Frans RE, Collins FC (1983) Diclofop-a selective herbicide for Italian ryegrass *(Lolium multiflorum*) control in winter wheat (*Triticum aestivum*). Weed Sci. 31:436-438

Kuk YI, Burgos NR (2007) Cross-resistance profile of mesosulfuron methyl-resistant Italian ryegrass in the southern United States. Pest Manag. Sci. 63:349-357.

Kunjo EM (1992) Emergence and growth of nine accessions of diclofop-resistant Italian ryegrass (*Lolium multiflorum* L.) and multiple resistance to other herbicides MS thesis Corvallis, OR. Oregon State University 36 p

Liebl R, Worsham AD (1987) Interference of Italian ryegrass (*Lolium multiflorum*) in wheat (*Triticum aestivum*). Weed Sci 35:819–823

Liu M, Hulting AG, Mallory-Smith CA (2014) Characterization of multiple-herbicide-resistant Italian ryegrass (*Lolium perenne* spp. *multiflorum*). Pest Manag Sci 70:1145–1150

Liu M, Hulting AG, Mallory-Smith C (2016) Characterization of multiple herbicide-resistant Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) populations from winter wheat fields in Oregon. Weed Science 2016 64:331–338

Lyon DJ, Huggins DR, Spring JF. (2016) Windrow burning eliminates Italian ryegrass (*Lolium perenne* ssp. *multiflorum*) seed viability. Weed Technol 30:279-283

Mallory-Smith C, Hulting AG, Thill D, Morishita D, Krenz J (2007) Herbicide-resistant weeds and their management. Moscow, ID: University of Idaho, Pacific Northwest Extension Publication No. 437

Mallory-Smith C. Unpublished data.

Matthews JM, Llewellyn R, Powles S, Reeves T (1996) Integrated weed management for the control of herbicide resistant annual ryegrass. Toowoomba, Australia: Australian Society of Agronomy. Pp 417–420

Matthews J, Llewellyn R, Jaeschke R, Powles S. (1996) Catching weed seeds at harvest: a method to reduce annual weed populations. Australian Soc of Agronomy/et al Proc ofthe 8th Australian Agronomy Conf 1996, Toowoomba, Queensland, Australia, Jan 30, 1996, p.684

McCanny SJ, Cavers PB (1988) Spread of proso millet (*Panicum miliaceum* L.) in Ontario, Canada. II. Dispersal by combines. Weed Res. 28:67-72

Medd, RW, Auld BA, Kemp DR, Murison RD (1985) The influence of wheat density and spatial arrangement on annual ryegrass, Lolium rigidum, competition. Aust. J. Agric. Res. 36:361-371.

Norris RF (2007) Weed fecundity: Current status and future needs. Crop Prot. 26:182–188. doi:10.1016/j.cropro.2005.07.013

Parker EC (1915) Field Management and Crop Rotation. Pages 71-97, 436-447 Webb Publ. Co., St. Paul, MN.

Pagnoncelli F, Trezzi M, Gonzalez-Andujar J (2020) Modeling the population dynamics and management of Italian ryegrass under two climatic scenarios in Brazil. Plants 9:325

Owen MJ, Walsh MJ, Llewell RS, Powles SB (2007) Widespread evolution of multiple herbicide resistance in annual ryegrass (*Lolium rigidum*) populations within the Western Australian wheat belt. Australian Journal of Agricultural Research 58:711–718.

Owen MJ, Martinez NJ, Powles SB (2014) Multiple herbicide-resistant *Lolium rigidum* (annualryegrass) now dominates across the Western Australian grain belt. Weed Res 54:314-324

Owen MJ, Michael PJ, Renton M, Steadman KJ & Powels SB (2011) Towards large-scale prediction of *Lolium rigidum* emergence. II. Correlation between dormancy and herbicide resistance levels suggests an impact of cropping systems. Weed Research 51, 133–141.

Pavlychenlo TK, Harrington JB (1934) Competitive efficiency of weeds and cereal crop. Can. J. Res. 10:77-94.

Pedreros AL (2002) Wild oat (*Avena fatua* L.) and Italian ryegrass (*Lolium multiflorum* Lam.) effect on wheat yield at two locations Agricultura Técnica 61:3

Perez-Jones A, Park KW, Colquhoun J, Mallory-Smith C, Shaner D (2005) Identification of glyphosate-resistant Italian ryegrass (*Lolium multiflorum*) in Oregon. Weed Sci. 53:775-779.

Petzold K (1955) Combine-Harvesting and Weeds. J Agric Eng Res. 1:178-181

Rew LJ, Cussans GW (1997) Horizontal movement of seeds following tine and plough cultivation: implications for spatial dynamics of weed infestations. Weed Research 37:247-256

Roerig KC, Hulting AG, Curtis DW, and Mallory-Smith CA (2015) Management of multiple resistant annual ryegrass with pyroxasulfone. West Soc. Weed Sci. Res. Prog. Rep. p71

Rauch TA, Thill DC, Gersdorf SA, Price WJ (2010) Widespread occurrence of herbicide-resistant Italian ryegrass (*Lolium multiflorum*) in northern Idaho and eastern Washington. Weed Technol 24:281–288

Rerkasem K, Stern WR, Goodchild NA. 1980. Associated growth of wheat and annual ryegrass. I. Effect of varying total density and proportion in mixtures of wheat and annual ryegrass. Australian J of Ag Res, 31:649-58

Schwartz-Lazaro LM, Norsworthy JK, Walsh MJ, Bagavathiannan MV (2017) Efficacy of the Integrated Harrington Seed Destructor on weeds of soybean and rice production systems in the Southern United States. Crop Sci 57:2812–2818

Schweitzer LR (1994) Reducing grass seed field volunteer populations with combine-mounted seed gleaners or recovery system and by selective harvest timing. Seed Prod Res. 19-24

Scursoni JA, Palmano M, De Notta A, Delfino D (2012) Italian ryegrass (*Lolium multiflorum* Lam.) density and N fertilization on wheat (*Triticum aestivum* L.) yield in Argentina. Crop Protection 32:36-40

Shellard JE, Macmillan RH (1978) Aerodynamic properties of threshed wheat material. J. Agric. Engin. Res. 23:273-281

Shirtliffe SJ, Entz MH, Van Acker RC (2000) *Avena fatua* development and seed shatter as related to thermal time. Weed Sci 48:555–560

Shirtliffe SJ, Entz MH (2005) Chaff collection reduces seed dispersal of wild oat (*Avena fatua*) by a combine harvester. Weed Sci. 53:465-470

Somerville GJ, Powles SB, Walsh MJ, Renton M (2018) Modeling the impact of harvest weed seed control on herbicide-resistance evolution. Weed Sci 66:395–403

Soni N, Nissen SJ, Westra P, Norsworthy JK, Walsh MJ, Gaines TA (2020) Seed retention of winter annual grass weeds at winter wheat harvest maturity shows potential for harvest weed seed control. Weed Technol 34:266-271

Stone M J (1994) The influence of ryegrass on vegetative and reproductive growth, yield, and yield components of winter wheat. Ph.D. dissertation. Texas A&M Univ., College Station, TX. 100 p.

Stone MJ, Cralle HT, Chandler JM, Miller TD, Bovey RW (1999) Wheat yield loss in response to Italian ryegrass in diverse Environments. Journal of Prod. Ag., 12(2):229-231

Stone MJ, Cralle HT, Chandler JM, Miller TD, Carson KH (1998) Above and below ground interference of wheat (*Triticum aestivum*) by Italian ryegrass (*Lolium multiflorum*). Weed Sci. 46:438-441

Stubler H, Busch M, Strek H (2016) Invited plenary presentation: Weed control at the crossroads–which innovations are on the horizon? Pages 8–12 in Proceedings of the 7th International Weed Science Congress. Prague, Czech Republic: International Weed Science Society

Swanton CJ, Weise SF (1991) Integrated weed management: the rationale and approach. Weed Technol 5:657–663

Thill DC, Mallory-Smith CA (1997) The nature and consequence of weed spread in cropping systems. Weed Sci 45, 337–342

Thill DC, Lish JM, Callihan RH, Bechinski EJ (1991) Integrated weed management-a component of integrated pest management: a critical review. Weed Technol 5:648–656

Tidemann BD, Hall LM, Harker KN, Alexander BCS (2016) Identifying critical control points in the wild oat (*Avena fatua*) life cycle and the potential effects of harvest weed-seed control. Weed Sci 64:463–473

Trusler CS, Peeper TF, Stone AE (2007) Italian ryegrass (*Lolium Multiflorum*) management options in winter wheat in Oklahoma. Weed Technol. 21:151-158.

Walker RH, Buchanan GA. (1982) Crop manipulation in integrated weed management systems. Weed Sci (Suppl.)30:17-24

Walsh M (1996) Effectiveness of seed collection systems for collecting ryegrass seed. Page 725 in 8th Australian Agronomy Conference. Toowoomba, Queensland: Australian Society of Agronomy.

Walsh M, Newman P, Powles S (2013) Targeting weed seeds in-crop: a new weed control paradigm for global agriculture. Weed Technol 27: 431–436

Walsh M, Parker W (2002) Wild radish and ryegrass seed collection at harvest: chaff carts and other devices. Pages 37-38 in Agribusiness Crop Updates. Perth, Western Australia: Department of Agriculture Western Australia

Walsh M, Newman P (2007) Burning narrow windrows for weed seed destruction. Field Crops Res 104:24-30

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332–338

Walsh MJ, Broster JC, Aves C, Powles SB (2018). Influence of crop competition and harvest weed seed control on rigid ryegrass (*Lolium rigidum*) seed retention height in wheat crop canopies. Weed Sci 66:627–633

Walsh MJ, Broster JC, Schwartz-Lazaro LM, Norsworthy JK, Davis AS, Tidemann BD, Beckie HJ, Lyon DJ, Soni N, Neve P, Bagavathiannan MV (2018) Opportunities and challenges for harvest weed seed control in global cropping systems. Pest Manag Sci 74:2235–2245

Walsh MJ, Broster JC, Aves C, Powles SB, Randall R (Editor), Lloyd S (Editor), Borger C (Editor) (2016) Influence of annual ryegrass seed retention height on harvest weed seed control (HWSC) and harvest efficiency. 20th Australasian Weeds Conference, Perth, Western Australia, 11-15 September 2016, 2016, pp.42-45

Walsh MJ, Harrington RB, Powles SB (2012) Harrington seed destructor: a new nonchemical weed control tool for global grain crops. Crop Sci 52: 1343–1347

Walsh M, Ouzman M, Newman P, Powles S, Llewellyn R (2017) High levels of adoption indicate that harvest weed seed control is now an established weed control practice in Australian cropping. Weed Technol 31:341–347

Walsh MJ, Powles SB (2007) Management strategies for herbicide-resistant weed populations in Australian dryland crop production systems. Weed Technol 21:332–338

Walsh MJ, Powles SB (2014) High seed retention at maturity of annual weeds infesting crop fields highlights the potential for harvest weed seed control. Weed Technol 28:486–493

Walsh MJ, C Aves, SB Powles (2017) Harvest weed seed control systems are similarly effective on rigid ryegrass. Weed Technol 31:178–183

Walsh MJ, Broster JC, Powles SB (2018). iHSD mill efficacy on the seeds of Australian cropping system weeds. Weed Technol 32:103–108

Woolcock JL, Cousens R (2000) A mathematical analysis of factors affecting the rate of spread of patches of annual weeds in an arable field. Weed Sci 48:27-34