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Western United States and Canada perspective: are herbicide-resistant crops the solution to herbicide-resistant weeds?

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Review

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Abstract

Herbicide-resistant (HR) crops are widely grown throughout the United States and Canada. These crop-trait technologies can enhance weed management and therefore can be an important component of integrated weed management (IWM) programs. Concomitantly, evolution of HR weed populations has become ubiquitous in agricultural areas where HR crops are grown. Nevertheless, crop cultivars with new or combined (stacked) HR traits continue to be developed and commercialized. This review, based on a symposium held at the Western Society of Weed Science annual meeting in 2021, examines the impact of HR crops on HR weed management in the U.S. Great Plains, U.S. Pacific Northwest, and the Canadian Prairies over the past 25 yr and their past and future contributions to IWM. We also provide an industry perspective on the future of HR crop development and the role of HR crops in resistance management. Expanded options for HR traits in both major and minor crops are expected. With proper stewardship, HR crops can reduce herbicide-use intensity and help reduce selection pressure on weed populations. However, their proper deployment in cropping systems must be carefully planned by considering a diverse crop rotation sequence with multiple HR and non-HR crops and maximizing crop competition to effectively manage HR weed populations. Based on past experiences in the cultivation of HR crops and associated herbicide use in the western United States and Canada, HR crops have been important determinants of both the selection and management of HR weeds.

Introduction

Modern weed control is primarily performed with herbicides, especially when extensive cropping and non-cropping areas have to be managed. Globally, herbicide use has increased steadily, and chemistries with reduced toxicity have replaced more hazardous herbicides over the last few decades (Kniss 2017). Broad acreage, agronomic crops with herbicide-resistance traits (herbicide-resistant [HR] crops have become a central tool in weed management programs throughout the world since the mid-1990s, with the United States and Canada ranked first and fourth in adoption, respectively; ISAAA 2021). These crop-trait technologies bring many benefits to cropping systems, such as better and more consistent weed control and greater crop safety, soil and moisture conservation by facilitating adoption of no-tillage (NT) practices, and often enhanced yield because of overall reduction in weed interference (Green 2012). The economic benefits associated with HR crops have motivated the farming community to readily embrace these crop cultivars.

New HR crop cultivars continue to be developed and commercialized using both conventional breeding (e.g., quizalofop-resistant wheat [*Triticum aestivum* L.] through mutagenesis) and genetic engineering (e.g., dicamba-resistant soybean [*Glycine max* (L.) Merr.]) techniques. The importance of this technology for weed control can be illustrated by the area of crops grown in the United States (71.5 million ha) and Canada (12.5 million ha) containing HR traits produced via transgenic techniques (ISAAA 2019; Figure 1). Soybean best exemplifies the diversity of commercialized HR traits, initially single traits and now increasingly stacked traits primarily to aid HR (particularly glyphosate-resistant [GR]) weed management (Table 1). For wheat, canola (*Brassica napus* L.), and lentil (*Lens culinaris* Medik), the non-transgenic imidazolinone (IMI) trait is common. Moreover, non-transgenic cultivars of wheat resistant to quizalofop, an acetyl-CoA carboxylase (ACCase) inhibitor, have also been introduced in the U.S. Great Plains (GP) and the Pacific Northwest (PNW) regions. For canola, other traits endow resistance

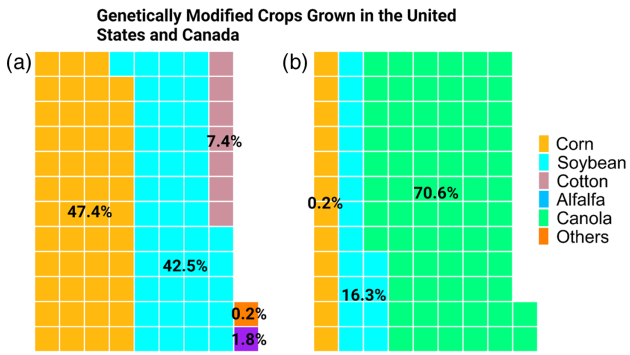

Figure 1. Percentage of each crop species grown in (A) the United States and (B) Canada (adapted from ISAAA 2019).

to glyphosate, glufosinate, and triazine herbicides. The popularity of HR crops continues to increase (ISAAA 2021), and numerous petitions for deregulation of genetically engineered crop cultivars are submitted each year (USDA-APHIS 2021).

Cultivars of HR corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), and soybean occupy the largest area in the United States (Figure 1) and are primarily grown in the Midwest and southern regions. As a result of the broad adoption of these HR crops, weed control programs in early 2000s were drastically simplified and consisted of single or few herbicide sites of action (SOAs). Consequently, there was strong herbicide selection pressure on prevalent weed populations. Over 500 unique cases (species by mechanism of action) of HR weed species have been documented around the world, totaling more than 1,600 individual reports (Heap 2021). The United States and Canada currently rank first and third in the number of reported HR weed biotypes, with a combined 402 weed populations identified in corn, cotton, and soybean (Heap 2021). Currently, HR weeds are ubiquitous in most input-intensive agronomic cropping systems and broadly recognized by farmers as a critical problem lacking efficient solutions (Schroeder et al. 2018). Herbicide resistance in weeds poses a serious challenge to conventional agricultural systems, particularly for farmers who use HR crops as part of their weed management strategy. The herbicides associated with the HR traits may no longer provide effective control (e.g., GR crop cultivars in fields infested with GR Palmer amaranth [*Amaranthus palmeri* S. Watson]). Consequently, alternative chemistries need to be utilized, and many of the benefits of adopting HR crops, such as reduced herbicide use and cost, crop safety, flexibility of application, and weed control efficacy, are lost. In areas where herbicide options to control HR weeds are severely limited, farmers may choose to adopt mechanical options such as tillage, oftentimes in areas with a long history of NT practices (Dentzmann and Burke 2021).

Herbicide resistance in weeds has been further complicated because of widespread multiple or cross-resistance, particularly metabolic resistance. These non–target site based resistance mechanisms are poorly understood, and the resultant resistance patterns usually are unpredictable, impacting herbicides with different SOAs (Busi and Powles 2016). Some weed populations exhibit resistance to four or more SOAs, such as Italian ryegrass [*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] in California and Oregon, and kochia [*Bassia scoparia* (L.) A.J. Scott] and *A. palmeri* in Kansas (Bobadilla et al. 2021; Brunharo and Hanson 2018; Kumar et al. 2019, 2021; Matzrafi et al. 2021). Therefore, weed scientists spend considerable resources to further our understanding on how to efficiently manage these HR weed populations. The investment in herbicide discovery was reduced in the 2000s because of widespread adoption of GR crops, the consolidation of agrochemical companies, and the rising costs associated with developing and commercializing new active ingredients (US $340 million; McDougall 2014). Increasing prevalence of cross- or multiple resistance in weed populations has renewed interest and efforts in the discovery of new active ingredients and the revisiting the use of older chemistries (Qu et al. 2021). Additionally, recent advances in gene editing (e.g., CRISPR; Chen et al. 2019) and the trend of regulatory agencies in many countries to reduce the regulatory burden surrounding products developed by modern biotechnology (Hoffman 2021) may provide further incentives for the development and commercialization of new HR crops.

The literature on HR soybean, corn, and cotton in the Americas is extensive (e.g., Green 2018; Green and Owen 2011; Nandula 2019). In contrast, the experiences with cultivation of HR crops common to agricultural regions of the GP, the PNW, and the Prairie provinces of Canada are much less documented. The PNW includes the states of Idaho, Oregon, and Washington, whereas the U.S. GP is an extensive area ranging from northern Mexico to western Canada and occupying most of the central United States (Figure 2). The Canadian Prairies comprise the provinces of Alberta, Saskatchewan, and Manitoba, where the majority of agronomic crops in the country are grown. Major HR crops in these three geographic regions include alfalfa (*Medicago sativa* L.), canola, grain sorghum [*Sorghum bicolor* (L.) Moench ssp. *bicolor*], lentil, sugar beet (*Beta vulgaris* L.), and wheat.

There are many unique characteristics of cropping systems across these regions. The western United States and Canada are broadly dominated by winter crops in more southerly areas, transitioning to spring crops in more northerly areas. Crop rotations typically include non-HR crops and can be diverse depending upon the environment. For example, in the PNW where sugar beet is grown for sugar, crops such as onion (*Allium cepa* L.), corn, field pea (*Pisum sativum* L.), dry bean (*Phaseolus vulgaris* L.), and alfalfa may be part of a voluntary 3- to 5-yr rotation scheme if irrigation is available. Where sugar beet seed is produced in the region, seed certification standards require that this crop be grown in a minimum 5-yr rotation (OSU Seed Certification 2021). In some semiarid regions, IMI-resistant wheat may dominate the crop area. In certain regions of the GP, barley (*Hordeum vulgare* L.), grain sorghum, sugar beet, and sunflower (*Helianthus annuus* L.) may be added to a 3-yr crop rotation.

A symposium with the focus of this review was held at the Western Society of Weed Science annual meeting in 2021. Based on presentations and discussion at the symposium, we address the general questions of whether HR crops can substantially contribute to IWM programs, and whether HR crops in the semiarid agricultural regions of the U.S. GP, the PNW, and the Canadian Prairies have a place in the weed management toolbox in managing HR weeds.

Can HR Crops Contribute to Successful IWM?

The concept of IWM means different things to different people—IWM versus herbicide-resistance management versus integrated herbicide management. At the conclusion of many scientific papers investigating various aspects of HR weeds, authors stress the importance of implementing IWM (concepts reviewed by Ehler 2006; Harker and O'Donovan 2013; Norris et al. 2003) but do not elaborate further.

Table 1. Herbicide-resistance traits in cultivars of major agronomic crops globally.[a]

	Soybean	Corn	Cotton	Rice	Canola	Wheat	Barley	Lentil
ACCase inhibitor		X		X		X		
ALS inhibitor		X		X	X	X	X	X
Glyphosate	X	X	X		X			
Glufosinate	X	X	X		X			
Glyphosate + glufosinate	X	X	X		X			
Glyphosate + triazine					X			
Glyphosate + dicamba	X		X					
Glyphosate + glufosinate + 2,4D + ACCase		X						
Glyphosate + isoxaflutole	X							
Glyphosate + glufosinate + dicamba	X		X					
Glyphosate + glufosinate + 2,4-D	X		X					
Glyphosate + isoxaflutole + glufosinate	X							

[a]Abbreviations: ACCase, acetyl-CoA carboxylase; ALS, acetolactate synthase.

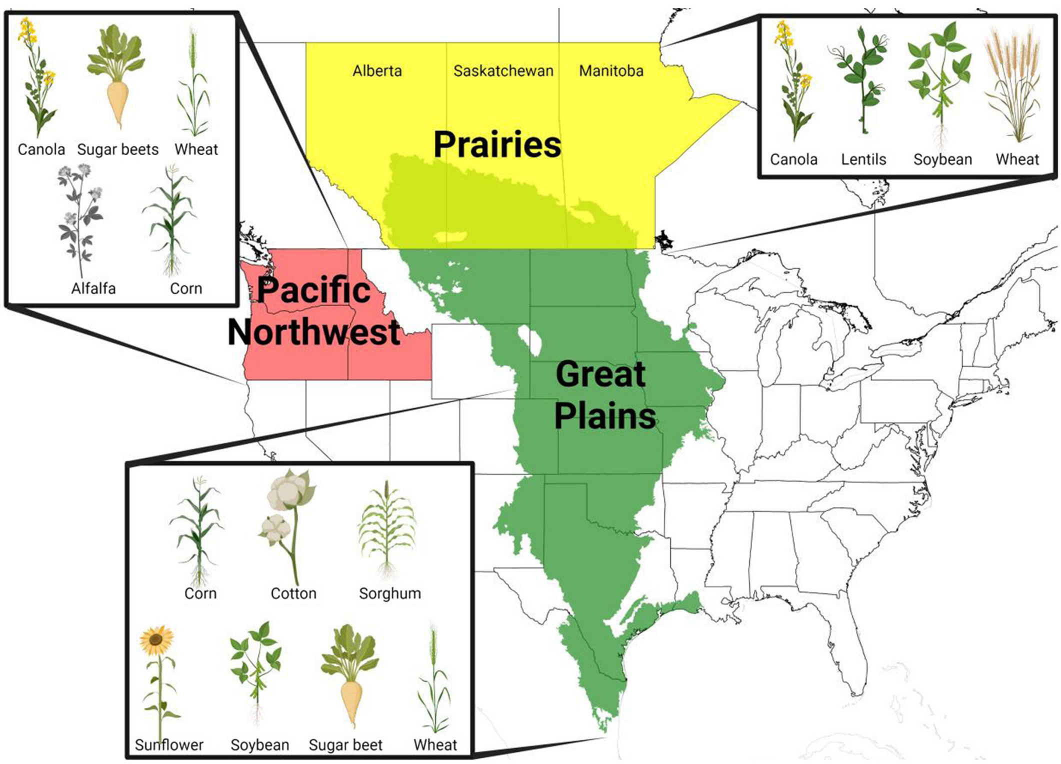

Figure 2. Regions of the United States and Canada where herbicide-resistant (HR) crops are grown and HR crops or components of the rotation.

The consensus view should be that the most successful IWM programs from a long-term environmental and HR weed management standpoint are synonymous with reduced herbicide use, that is, a key metric of reduced dependency on herbicides while maintaining good weed control (Norris et al. 2003). In turn, a critical metric for good weed control is minimal weed seedbank replenishment (Geddes and Davis 2021). There has been a shift in philosophy from herbicide application decisions based on weed economic thresholds (Jones and Medd 2000) to low or zero tolerance for weed seedbank replenishment (Norris 1999; Norsworthy et al. 2014). This paradigm shift reflects the reality that the majority of weed populations in areas where input-intensive agriculture is practiced are resistant to one or more SOA herbicides. Consequently, the goal of minimizing or preventing weed seedbank replenishment puts even more pressure on growers and, in turn, herbicides to produce clean fields.

Herbicide use was summarized for six major crops (corn, soybean, cotton, rice [*Oryza sativa* L.], spring wheat, winter wheat) in the United States from 1990 to 2015 (Kniss 2018). Herbicide use was quantified by herbicide area treatments (HAT, 0 to 4) to standardize for varying annual crop area and herbicide application rates: 1 HAT is defined as the number of times one herbicide is applied to one field. In corn, soybean, and cotton with high adoption of GR cultivars, glyphosate use increased from near-zero HAT in 1990 to about 1 (corn) to 2 (soybean, cotton) HAT in 2015. There was a marked increase in glyphosate use after 2000 when the patent expired. The rise in glyphosate use coincided with an initial decline in use of non-glyphosate herbicides, which subsequently rebounded after 2005 with the increasing incidence of GR weeds. Total herbicide use increased from about 2 HAT in 1990 to more than 3 HAT in corn and soybean and to nearly 4 HAT in cotton by 2015. In contrast, glyphosate use (mainly applied as a burndown preemergence treatment) in the non-GR crops (rice, spring wheat, winter wheat) increased only gradually over the 15-yr period (<1 HAT in 2015). However, total herbicide use increased substantially in rice and spring wheat (from 2 to nearly 4 HAT). In winter wheat, however, total herbicide use remained below 2 HAT over the 15-yr period. In spring wheat, application of acetolactate synthase (ALS) inhibitors (in both IMI and non-IMI cultivars) increased by the greatest amount over time. In winter wheat, ALS inhibitors make up the largest SOA group, reflecting much greater adoption of IMI-resistant cultivars in this crop than in spring wheat (Baenziger et al. 2016; Nakka et al. 2019). Other SOA groups were auxinic herbicides, glyphosate, and photosystem II (PSII) inhibitors, with little ACCase inhibitor use up to 2015. However, quizalofop-resistant cultivars introduced in 2018 will likely increase use of this ACCase-inhibiting herbicide. The utility of ACCase-inhibiting herbicide is to control the increasing incidence of ALS-inhibitor HR grasses or improving the level of control of a number of important grass weeds such as feral rye (cereal rye, *Secale cereale* L.), downy brome (*Bromus tectorum* L.), and volunteer wheat or barley. In summary, among all the crops evaluated, only winter wheat can be considered a relatively low herbicide use intensity crop in the United States, although herbicide use has doubled over the 15-yr period. With the continual increase of weed resistance, the reality of reducing overall herbicide use in HR and non-HR crops gets more difficult to achieve as supplemental herbicide SOAs (preemergence or postemergence applications) are often needed to control HR weed populations.

In a review of the status of IWM in Europe, Moss (2018, p. 1205) stated that "non-chemical methods are often adopted as a means of compensating for reduced herbicide efficacy due to increasing resistance, rather than as alternatives to herbicides." We would largely agree with that statement, unless growers are mandated to reduce herbicide use because of government policies (e.g., European Union), or key herbicides are no longer commercially available due to a variety of reasons. Significant adoption of IWM usually occurs after a problem with HR weeds not adequately solved by using a different herbicide, as supported by data from Australia and elsewhere (Llewellyn et al. 2004).

Overall, the primary goal should be to reduce herbicide selection pressure in weed populations wherever and whenever possible. Most importantly, it is necessary to simultaneously reduce herbicide SOA-use intensity and weed species population abundance through diverse IWM tactics (Beckie 2006; Owen 2016). Therefore, we need to reduce the frequency of herbicides always doing the heavy lifting and use effective combinations of non-herbicidal practices that aid both herbicide performance and crop competition to suppress weed growth and fecundity (Blackshaw et al. 2005; Liebman and Gallandt 1997).

In a review of IWM in the United States and Canada, Owen et al. (2015) listed the benefits, risks, relative effectiveness, and adoption rate of IWM tactics. For the tactic of HR crops, the benefits listed were the ability to use specific herbicides, no crop injury, and control of existing cross- or multiple HR weeds. Risks included lack of crop and management diversity, increased selection pressure, concerns for injury to non-target crops, volunteers in subsequent crops, and possible limited weed spectrum. Effectiveness of HR crops as a tactic to help manage HR weeds was rated as fair to excellent, with adoption rate assessed as medium to high.

HR crops can potentially contribute directly or indirectly to IWM by: (1) reducing herbicide-use intensity versus non-HR cultivars; (2) improving control of existing HR weeds or troublesome species and reducing weed seedbank replenishment; (3) causing little to no crop injury over a wide application window of growth stages; (4) allowing use of different herbicide SOA groups in cropping systems to diversify herbicide SOA usage; (5) facilitating conservation tillage (minimum-tillage or NT), which creates an unfavorable microclimate for many weed species and aids crop growth and weed competitiveness in water-limited environments; (6) allowing greater flexibility in planting dates, such as early seeding, which may optimize crop yield and weed-suppression potential; and (7) utilizing better crop germplasm (e.g., genetics, seed quality), resulting in greater seed germination, seedling vigor, growth, pest tolerance, and yield potential, all of which culminate in a healthier, more competitive crop (Beckie et al. 2006; Green 2012; Owen et al. 2015).

The seven contributions of HR crops to IWM are best exemplified by HR canola. Herbicide-use intensity and environmental impact of herbicide use are reduced in HR versus non-HR canola systems (Beckie et al. 2006; Brimner et al. 2005; Brookes and Barfoot 2005; O'Donovan et al. 2006). Control of HR and troublesome weed species is markedly greater in HR versus non-HR canola (Devine and Buth 2001; Harker et al. 2000). Before the introduction of HR canola in the mid-1990s, herbicide options were limited. Soil-applied herbicides, such as trifluralin and ethalfluralin, have narrow weed spectrum activity, and efficacy was considered relatively low and variable. The few available postemergence herbicides, such as ethametsulfuron, controlled only a few broadleaf weed species. Because weed competition resulted in significant yield loss, growers planted canola only in fields with low weed densities. After the introduction and adoption of HR canola, the risk and frequency of crop injury became minimal when compared with that of non-HR canola herbicide regimes (O'Donovan et al. 2006). For example, glyphosate could now be applied up to first flower of canola (TruFlex™ cultivars, Bayer CropScience LP, St. Louis, MO, USA), although the critical period of weed control is between the 2- and 4-leaf stage (Harker et al. 2000) to minimize loss in yield potential. Moreover, there are no re-cropping (plant-back) restrictions for GR and glufosinate-resistant canola systems. GR and glufosinate-resistant canola are keeping many grain growers in business as they enable the use of different SOA herbicides to control the many ACCase- and ALS-inhibitor HR weeds, such as wild oat (*Avena fatua* L.) and false cleavers (*Galium aparine* L.) (Beckie et al. 2020). Most importantly, these canola systems have not selected for GR weeds as has been the experience in most other cropping systems with this HR trait in the Americas. The key to that achievement is crop rotation interval (grown every 2 to 4 yr) and moderate adoption rate of the GR trait (<50%). Many growers typically plant canola with different herbicide-resistance traits on their farm each year (Figure 3). Because HR canola, similar to other HR crops, facilitated the adoption of conservation tillage without the necessity of traditionally incorporating preemergence herbicides into the soil, yield potential and profitability are significantly enhanced in the semiarid environment where the crop is grown (Devine and Buth 2001). As a consequence of high adoption of conservation tillage and postemergence versus preemergence herbicide applications in HR canola, delayed seeding to control the first flush of weeds or apply and activate preemergence soil-residual herbicides (stale seedbed technique) is no longer routinely practiced because of the adverse impact on canola emergence uniformity and yield potential. Early seeding results in greater stand establishment,

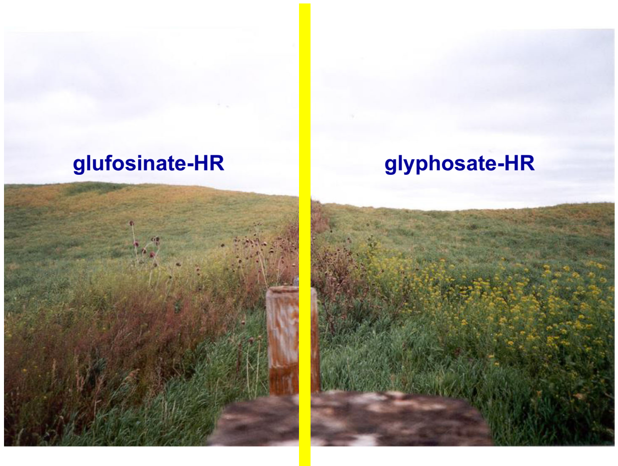

Figure 3. Adjacent commercial fields of transgenic glufosinate- and glyphosate-resistant canola in Saskatchewan, Canada, in the late 1990s (adapted from Beckie et al. 2003).

water-use efficiency, and yield (Kirkland and Johnson 2000). Large, sustained investment in canola breeding by the private sector since the 1990s has resulted in markedly improved germplasm (Harker et al. 2003). Currently, hybrid cultivars dominate the market, characterized by significantly greater seedling vigor, weed competitiveness, and seed yield compared with non-HR cultivars (Canola Council of Canada 2021; Zand and Beckie 2002).

HR canola, therefore, has been an enduring success story over the past 25 yr. The same assessment cannot be made for other HR crops, particularly HR soybean and cotton, which are characterized by cultivars with ever-increasing stacked traits to keep up with the increasing incidence and complexity of cross- and multiple HR weeds (Green and Owen 2011). In HR crops grown in western North America, substantial progress is needed to reduce the gap between actual and potential HR crop contribution to IWM. The main obstacle to closing this divide is the limited non-transgenic HR traits deployed in these crops—to date, traits largely limited to ACCase- and ALS-inhibitor resistance. Even before their introduction, there was high incidence of weed populations resistant to one or both SOA groups because of the popularity of these herbicides, which have been used in multiple non-HR crop cultivars since the late 1970s and early 1980s (Heap 2021). The cultivation of these HR cultivars has only increased the selection pressure further and increasingly requires supplemental SOA herbicides if they are even available. In general, HR crops are widely viewed as a short- to medium-term solution for HR weed management and IWM. With the current herbicide-use practices (i.e., overreliance on a herbicide-only strategy for weed management), HR crops tend to accelerate the selection of multiple HR weed populations (Beckie 2016).

To enhance the contribution of HR crops to IWM, new SOA HR traits are urgently needed. New SOA herbicides associated with such HR traits should only be registered in one major crop (or multiple minor HR crops) in an agroregion to limit recurrent usage and overall herbicide-use intensity and reduce the risk of selecting for HR weeds. Expanding HR trait technologies to minor crops would improve HR and non-HR weed control in agroregions where major HR crops (i.e., soybean, cotton, corn, canola) are not commonly grown. As outlined previously, conservation tillage and early seeding are critical components of semiarid IWM cropping systems in the western United States and Canada. Therefore, new HR traits and associated registered herbicides need to be compatible with these cropping system requirements.

HR Crops and Their Role in Resistance Management in the U.S. GP

The GP region mainly represents the central portions of the continental United States; it extends from western Canada in the north to Texas in the south and is bordered by the Mississippi River in the east and the Rocky Mountains in the west, encompassing a semiarid agroecosystem where NT cropping systems dominate (Kumar et al. 2020c; Lenssen et al. 2007; Paulsen and Shroyer 2008; Unger and Baumhardt 2001; Figure 2). The GP region is divided into three subregions: the Northern Great Plains (NGP), which include the agricultural areas of Alberta, Saskatchewan, and Manitoba, Canada, and portions of Montana, Wyoming, North Dakota, and South Dakota in the United States; the Central Great Plains (CGP), which include portions of Nebraska, Colorado, and Kansas; and the Southern Great Plains (SGP), which includes portions of New Mexico, Oklahoma, and Texas. This section only covers the U.S. portion of the GP (see later section on the Canadian Prairies). The GP region is characterized by shallow soils (low to moderate in organic matter content) with irregular and generally deficient annual rainfall (<380 mm in the west to >760 mm in the east) (Nielsen 2018; Peterson and Westfall 2004). Due to these soil and agroclimatic constraints, growers in this region have adopted soil conservation practices, including a fallow phase in many crop rotations (Nielsen 2018; Peterson and Westfall 2004; Shafer et al. 2014). The NT fallow-based production system in the region has been adopted mainly to prevent wind and water erosion and to conserve soil moisture from the winter precipitation. The successful adoption of soil conservation practices was only possible due to the ease of chemical weed control during fallow periods (Lenssen et al. 2007). Winter wheat–fallow is an important crop rotation in the NGP and CGP regions, whereas winter wheat–summer crop–fallow is more common in the SGP and CGP regions. Summer crops in a typical 3-yr rotation include corn, cotton, grain sorghum, soybean, or sunflower. In addition to these rotations, corn–sugar beet or barley–sugar beet are two other common rotations followed in some states in the southern part of the NGP region.

Major problematic broadleaf weed species in this region include horseweed [*Conyza canadensis* (L.) Cronquist], *B. scoparia*, *A. palmeri*, Russian thistle (*Salsola tragus* L.), common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and wild buckwheat [*Fallopia convolvulus* (L.) Á. Löve], while major troublesome grass weed species include *B. tectorum*, Japanese brome (*Bromus japonicus* Thunb.), *S. cereale*, *L. perenne* ssp. *multiflorum*, *A. fatua*, foxtail species (*Setaria* spp.), and tumble windmill grass (*Chloris verticillata* Nutt.) (Buhler and Oplinger 1990; Jha et al. 2016; Nichols et al. 2015). The majority of these grass weed species are winter annuals and infest winter or spring wheat. In contrast, the broadleaf weed species are mainly summer annuals and infest summer row crops. Similar to other agroecosystems, the GP region is facing the ever-increasing challenge of HR weeds. The NT fallow production system was originally introduced in the semiarid GP with the help of chemical weed control. However, the repeated use of herbicides with the same SOA led to the evolution of herbicide resistance in several weed populations (Table 2).

IMI-resistant winter wheat introduced in 2003 allowed growers to use imazamox for selective control of grass weed species.

Table 2. Most troublesome herbicide-resistant (HR) weeds and resistance by site of action (SOA) reported in the U.S. Great Plains (GP).

Species	Common name	Resistance by SOA group[a]
Amaranthus palmeri	Palmer amaranth	2, **4**, 5, 6, **9**, 27
Avena fatua	Wild oat	**1**, **2**, 8
Bassia scoparia[b]	Kochia	**2**, **4**, 5, 6, **9**
Bromus tectorum	Downy brome	**1**, **2**
Conyza canadensis (L.) Cronquist	Horseweed	**2**, **9**
Salsola tragus	Russian thistle	**2**, **9**

[a]Numbers are WSSA groups. Bolded group letters represent group resistance traits available in HR crops grown in the U.S. GP.
[b]Indicates multiple-resistant populations have been reported in the region.

Growers in the GP region have utilized IMI-resistant wheat to control annual grass weeds, including *B. tectorum* and jointed goatgrass (*Aegilops cylindrica* Host), and suppress *L. perenne* ssp. *multiflorum* and *S. cereale* as well as some broadleaf weed species (Geier et al. 2004; Kniss et al. 2011; Pester et al. 2001). Due to widespread evolution of resistance to ALS-inhibiting herbicides in grass weed species and inconsistent activity of imazamox on *S. cereale*, winter wheat cultivars resistant to quizalofop have recently been developed and commercialized (Ostlie et al. 2015). These wheat cultivars allow growers to use postemergence applications of quizalofop for selective control of grass weed species, including ALS inhibitor–resistant weed biotypes (Anonymous 2017a). Quizalofop provides improved control of *S. cereale* (Kumar et al. 2020a). Because of limited ACCase inhibitor–resistant weed populations in the region, widespread adoption of quizalofop-resistant wheat cultivars is expected.

It is also important to note that grain sorghum (rotational crop with winter wheat in CGP and SGP regions) with resistance to quizalofop (Double Team™ sorghum, S&W Seed Company, Longmont, CO, USA) will also be available for commercial use. Repeated applications of quizalofop for grass control in areas with wheat–sorghum rotations will exert significant selection pressure for resistance to ACCase-inhibiting herbicides. Therefore, proper stewardship guidelines (proper herbicide rate, time of application, crop growth stage, plant-back restrictions, rotational restrictions, etc.) in HR wheat production systems are warranted.

Grain sorghum is a major summer crop grown in the south-central GP (eastern Colorado, western Nebraska, western Kansas, western Oklahoma). Due to limited herbicide options, selective control of grass weed species is a major challenge. In recent years, grain sorghum hybrids with tolerance to ALS- and ACCase-inhibiting herbicides have been developed, allowing growers to use postemergence applications of herbicides such as nicosulfuron, imazamox, and quizalofop (Lancaster and Currie 2020). It is important to steward these newly available HR crop technologies (both grain sorghum and wheat) for long-term use and to prevent widespread evolution of ALS and ACCase inhibitor–resistant weeds, because a common rotation in the CGP and SGP is grain sorghum–wheat. It should be noted that close relatives to grain sorghum, such as shattercane [*Sorghum bicolor* (L.) Moench ssp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb.] and johnsongrass [*Sorghum halepense* (L.) Pers.], may hybridize with the crop, resulting in weedy populations with IMI- and quizalofop-resistant alleles (Schmidt et al. 2013).

As in other agroregions, the introduction of GR crops revolutionized weed control practices in the GP. Sugar beet is one of the predominant GR crops in the NGP, whereas corn, cotton, and soybean are major GR crops grown in the south-central parts of the GP. In addition, GR alfalfa and GR canola are also grown in the region. Before the use of GR crops, growers relied heavily on preemergence or postemergence applications of ALS- and PSII-inhibiting herbicides that resulted in selection of ALS and PSII inhibitor–resistant weed populations. The use of glyphosate in GR crops helped to control these HR weed biotypes.

GR sugar beet was commercially introduced in 2008 and was rapidly adopted by growers, mainly due to ease of weed control with this technology (Morishita 2018). Before the availability of GR sugar beet, growers relied on combination of three to five herbicide applications, cultivation, and hand weeding for season-long weed control in sugar beet (Kniss 2018; Morishita 2018). In addition, none of the registered herbicides in sugar beet were very effective without risking crop injury (Kniss 2018; Morishita 2018). However, the ease of weed control with glyphosate use resulted in reduced reliance on soil-residual herbicides and preplant tillage. Subsequently, the sole reliance on glyphosate in GR crops and fallow fields selected GR weed biotypes in the region. The repeated use of glyphosate in GR sugar beet fields resulted in evolution of GR *B. scoparia* in Colorado, Wyoming, Nebraska, Montana, Idaho and Oregon (Gaines et al. 2016; Kumar et al. 2018).

Difficulty in managing GR weeds has led to the development of crop technologies with stacked traits (two- or three-way resistance). For instance, soybean cultivars with resistance to glyphosate and dicamba, or glyphosate, dicamba, and glufosinate have been developed and commercialized (Anonymous 2017b). These systems allow postemergence applications of dicamba for in-season control of GR weeds (Kumar et al. 2020b; Yadav et al. 2020). Similarly, crops with resistance to glyphosate and glufosinate, glufosinate and hydroxyphenolpyruvate dioxygenase (HPPD) inhibitors, and glyphosate, 2,4-D, and glufosinate have recently been commercialized (Shyam et al. 2021; Smith et al. 2019). In the CGP and SGP regions, these newly available row crop cultivars (corn, cotton, or soybean) are mainly grown in 3-yr rotations (winter wheat–summer crop–fallow). Adoption of these new stacked-trait crop technologies in corn, cotton, and soybean in the south-central GP has helped to provide effective control of GR weed biotypes, including *B. scoparia*, *C. canadensis*, and *A. palmeri* (Kumar et al. 2020b; Shyam et al. 2021; Yadav et al. 2020). These stacked-trait technologies allow growers to use two or three herbicide SOAs in combination for in-season control of GR or ALS inhibitor–resistant weed biotypes. These newly available crop technologies can serve as an important component of IWM for managing herbicide resistance. However, increasing cases of dicamba-resistant *B. scoparia* and recent evolution of 2,4-D–resistant *A. palmeri* in the CGP are serious threats to these stacked-trait crop cultivars (Kumar et al. 2019). Therefore, it is important to use these crop-trait technologies in combination with other IWM practices, such as cover crops, strategic tillage, harvest weed seed control such as chaff lining and weed seed destruction (see review by Walsh et al. 2017), precision tools, and others, for their sustainable use in HR weed management in the region. The adoption of proper stewardship and use of these stacked-trait technologies as a component of IWM systems are needed for sustainable weed control in the semiarid region of the GP.

HR Crops and Their Role in Resistance Management in the PNW

Cropping systems in the PNW are diverse because of the number of agronomic zones across the region (Hagerty et al. 2019; Kaur et al. 2017). The agricultural region west of the Cascade

Table 3. Most troublesome herbicide-resistant (HR) weeds and resistance by site of action (SOA) reported in the Pacific Northwest (PNW).[a]

Species	Common name	Resistance by SOA group[b]
Aegilops cylindrica	Jointed goatgrass	**2**
Agrostis stolonifera[c]	Creeping bentgrass	**9**
Amaranthus powellii	Powell amaranth	5
Amaranthus retroflexus	Redroot pigweed	5
Anthemus cotula	Mayweed chamomile	**2**
Avena fatua	Wild oat	**1**, **2**, 3, 8, 26
Bassia scoparia	Kochia	2, 4, 5, **9**
Bromus tectorum	Downy brome	**1**, **2**, **9**
Camelina microcarpa	Small seeded false flax	2
Capsella bursa-pastoris	Shepherd's-purse	5, 6
Centaurea solstitialis	Yellow starthistle	4
Chenopodium album	Common lambsquarters	5, 6, **9**
Lactuca serriola	Prickly lettuce	**2**, 4
Lolium perenne ssp. *multiflorum*	Italian ryegrass	**1**, **2**, **3**, **9**, **10**, 15, 22
Poa annua	Annual bluegrass	5, 7, 8, 16
Salsola tragus	Russian thistle	**2**, **9**
Senecio vulgaris	Common groundsel	6
Sonchus asper	Spiny sowthistle	**2**

[a]Data from Heap (2021) and Campbell et al. (2011); CACG Brunharo, personal observations; I Burke, J Campbell, and D Lyon, personal communications.
[b]Numbers are WSSA/HRAC groups. Bolded group letters represent group resistance traits available in HR crops grown in the PNW.
[c]GE Roundup Ready®.

Mountain range in Oregon and Washington receives more precipitation than the inland PNW. In this region, the major crops produced are nursery stock, grass and vegetable seed, fruit, and vegetables (Figure 2). As expected, HR crops vary within the agronomic zones. Very few hectares of HR crops are grown in the western region of the PNW, so this region will not be discussed.

Weeds have evolved resistance to many classes of herbicides, including the traits introduced into HR crops in the PNW (Table 3). Many of the weed populations display cross- and multiple HR and occur not only in the year when HR crops are grown, but also in non-HR crops grown in rotation. In addition to weed resistance to glyphosate, glufosinate, and imazamox, weed populations have evolved resistance to microtubule assembly, PSII, very-long-chain fatty-acid inhibitors, and auxinic herbicides, which are used in non-HR crops rotated with the HR crops (Bobadilla et al. 2021; Rauch et al. 2010). The number and widespread occurrence of HR weed populations is a challenge when designing a management program. The HR crops could, in theory, increase opportunities to control HR weed populations.

The HR crops grown in the PNW include GR alfalfa, IMI-, glyphosate-, and glufosinate-resistant canola and corn, GR sugar beet, and quizalofop- and IMI-resistant wheat. Corn with both glyphosate and glufosinate resistance traits is also available. Data for area planted for each of the crops are difficult to obtain. Therefore, the estimates provided are based on data published from U.S. Department of Agriculture reports, estimates from experts, and grower commissions in the PNW.

GR alfalfa was fully deregulated in 2011, and its adoption appears to be slower than for other crops. In 2013, 13% of the alfalfa area was GR (Fernandez-Cornejo et al. 2016). In 2019, this number increased to about 19% (ISAAA 2019). The apparent slower adoption is partly due to alfalfa being a perennial crop, so each year only a portion of the hectares are seeded (Undersander et al. 2011). It is possible that in the future, GR alfalfa may represent a greater proportion of the area. In the PNW, adoption of GR alfalfa is not reported; however, 19% of the 0.75 million ha planted nationally would be equivalent to more than 141,000 ha. One of the reasons for low adoption in some states that export hay, such as Washington, is lack of market acceptance in importing countries (S Norberg, personal communication). GR alfalfa has been adopted by dairy producers in Oregon and Idaho to control weeds that might taint the flavor of milk (J Felix, personal communication) and has the potential to be a valuable tool to manage non-GR weed populations. As a perennial crop, alfalfa is often grown in a field for at least 4yr and is a competitive crop once established. In areas where alfalfa is grown or could potentially be grown, HR alfalfa would be an excellent tool for reducing the evolution of HR weeds, especially if grown in rotation with non-HR crops or where the system is not heavily dependent on glyphosate for weed control in rotational crops. In addition, there are herbicide options for use in alfalfa to which there are few or no reported weed resistance cases in the PNW, including 2,4-DB, bromoxynil, flumioxazin, hexazinone, pendimethalin, and trifluralin. Planting GR alfalfa and applying glyphosate plus herbicides with alternative SOAs would reduce selection pressure of glyphosate and could provide control of both resistant grass and broadleaf weeds and slow the evolution of additional HR populations.

Canola has been introduced into wheat rotations across the PNW, with 2020 production at 18,800 ha in Idaho, 1,500 ha in Oregon, and 32,000 ha in Washington (USDA-NASS 2020). Based on estimates from seed suppliers and growers, an estimated 66% of the area in the PNW is planted to spring canola and 34% to winter canola, where the majority of the crop grown in Idaho and Washington is spring canola, and about 58% in Oregon is winter canola (PNW Canola Association 2021).

It is estimated that 75% of the spring canola and 10% of the winter canola have a GR trait (J Davis, personal communication). Conversely, the number of hectares planted to glufosinate-resistant canola is only 5% and is all spring canola. ALS-resistant canola is also available in the region and was introduced to prevent injury from soil residual activity of ALS inhibitors used in the rotation. For winter canola, 60% of the hectares are planted to conventional canola. Some growers have indicated that the only reason that they grow HR canola is to improve weed control. More specifically, growers may take advantage of the GR trait in canola in rotation with wheat to control ALS- and ACCase-resistant weed populations, notably multiple-resistant *L. perenne* ssp. *multiflorum*. The wheat rotation systems are heavily dependent on glyphosate preplant and postharvest; therefore, special consideration should be given on how to use the traits most effectively in the rotation.

The GR trait in sugar beet was considered to be one of most valuable tools compared with other GR crops, because few effective herbicides are registered for use in sugar beet and they often cause crop injury (Morishita 2018). In addition, before the advent of GR sugar beet, tillage was required for adequate weed control, which also caused crop injury and increased the cost of weed control. In the United States, it is estimated that >99% of sugar beet production contains the GR trait.

In 2020, approximately 74,000 ha of sugar beet (16% of U.S. production) were grown in the PNW, with 99% of the PNW production in the irrigated areas of southeastern Oregon (approximately 3,600 ha) and southern Idaho (70,000 ha)

(USDA-NASS 2021). Common rotations include sugar beet–cereal–potato (*Solanum tuberosum* L.), sugar beet–onion–wheat or corn–dry bean, or a shorter rotation of sugar beet–corn or cereal–sugar beet. Sugar beet and corn are often grown in rotation, both containing a GR trait. It is not surprising that GR *B. scoparia* populations were identified in southern Idaho and southeastern Oregon sugar beet fields in 2014, considering this overreliance on GR crops and glyphosate (Kumar et al. 2018). The fields had been in a corn–sugar beet rotation, both with GR traits, for more than 7 yr, and the fields received multiple glyphosate applications per year. Growers in this area often used glyphosate preplant or postharvest for weed control. GR *B. scoparia* threatens the utility and advantage that the GR trait added to sugar beet for weed management, including control of non-GR weeds. In fields where GR *B. scoparia* is not present, growers have the option to use conventional or glufosinate-resistant corn in the rotation to delay the evolution of GR *B. scoparia* or to use a longer rotation that includes additional conventional crops. Because growers also plant cereals, dry bean, onion, and potato, there is the potential for control of HR *B. scoparia* in those crops. Many herbicides are available for such a cropping system, including inhibitors of microtubule assembly, PSII, protoporphyrinogen oxidase, and auxinic herbicides depending on the crop (Peachey 2021). ALS inhibitor–resistant *B. scoparia* populations are widespread across the PNW, including southern Idaho and southeastern Oregon (Heap 2021; Mallory-Smith et al. 1993). Therefore, it is unlikely that herbicides from this SOA will be effective due to multiple resistance. This is an example of a lost opportunity to use GR sugar beet or corn to manage HR weeds such as ALS inhibitor–resistant *B. scoparia*. Sugar beet with stacked HR traits for glyphosate, glufosinate, and dicamba is under development, but not yet on the market. The addition of glufosinate and dicamba could be beneficial for HR weed control in the PNW, because only *L. perenne* ssp. *multiflorum* has been identified with resistance to glufosinate, and only *B. scoparia* and prickly lettuce (*Lactuca serriola* L.) have been confirmed to be resistant to dicamba (Heap 2021).

Wheat was grown on approximately 1.7 million ha in 2020, more area than any other crop in the PNW (USDA-NASS 2021). There are approximately 1.3 million ha of winter wheat and 0.4 million ha of spring wheat produced each year in the region. Most of the spring wheat production is in Idaho and Washington, as production systems across agronomic zones are driven mainly by precipitation and temperature (Hagerty et al. 2019; Kirby et al. 2017). In zones with the least precipitation, a winter wheat–fallow rotation is common, whereas in areas with more precipitation or irrigation, annual cropping is practiced with rotation mostly to other cereals or legumes. In the irrigated areas of southeastern Oregon and southern Idaho, the rotations may include malting barley, corn, dry bean, potato, and sugar beet.

The first widely grown IMI-resistant wheat cultivars in the PNW were released in 2003. The wheat is resistant to imazamox, and the initial development of IMI-resistant wheat cultivars was targeted at controlling *A. cylindrica* (Mallory-Smith et al. 2018). In the 2019–2020 crop year, 74% of the more than 0.4 million ha of winter wheat grown in Oregon were IMI-resistant (Flowers et al. 2008; Oregon Wheat Commission n.d.), whereas in Washington the adoption is approximately 40% for winter wheat (Washington Wheat Commission 2021) and less than 1% for spring wheat. In Idaho, the number of IMI-resistant wheat hectares is difficult to discern but appears to be much less than in neighboring states in the PNW (Idaho Wheat Commission 2021).

There has only been one confirmed case of imazamox-resistant *A. cylindrica* reported in IMI-resistant wheat (Rodriguez et al. 2021). The authors reported that IMI-resistant wheat was first planted in 2007 and then each successive year; by 2012, the grower observed that control of *A. cylindrica* had declined but did not report the suspected resistance until 2015. Because resistance to ALS-inhibiting herbicides is so prevalent, many researchers predicted that resistance would occur quickly. Therefore, it is unusual that this is the only confirmed case to date. However, other weed populations resistant to this SOA are common in the dryland wheat production area of the PNW.

In the PNW, quizalofop-resistant hard red winter wheat was planted on 26,000 ha in 2020 and soft white winter wheat will be launched in 2022 (C Shelton, personal communication). Resistance to ACCase-inhibiting herbicides is widespread in the PNW, and it remains to be seen how valuable this technology will be in the dryland regions (Bobadilla et al. 2021; Rauch et al. 2010). Given widespread resistance to ALS-inhibiting herbicides, as in populations of *L. perenne* ssp. *multiflorum*, *B. tectorum*, and *A. fatua*, quizalofop-resistant wheat may be a useful tool where these HR biotypes occur. On the other hand, it may result in the selection of other ACCase inhibitor–resistant grasses not previously reported, for example *S. cereale* or *A. cylindrica*. Quizalofop-resistant wheat could become an important resistance management tool for grass weeds in rotations in southeastern Oregon and southern Idaho, because ACCase inhibitor–resistant grasses are not common in those areas and therefore could provide an herbicide with a different SOA in the rotation. Volunteer quizalofop-resistant wheat could be controlled by glyphosate in the GR crop year and by other chemistries, such as EPTC, in the potato year. Because quizalofop only controls grass weed species, this technology will not play a role in reducing the evolution of GR broadleaf weeds. IMI-resistant wheat has not been widely planted in southeastern Oregon or southern Idaho. The reasons for this lack of adoption have not been well quantified but could be either because of plant-back restrictions for sensitive crops such as barley, mustard (*Brassica*/*Sinapis*) species, sugar beet, the cost of the seed, or widespread ALS inhibitor–resistant weeds in the region.

HR Crops and Their Role in Resistance Management in the Canadian Prairies

The Canadian Prairies represent a large and diverse region comprising the provinces of Alberta, Saskatchewan, and Manitoba and accounting for approximately 85% of Canada's arable land (May et al. 2020; Figure 2). The soils are very diverse, both between and within the provinces. There are significant differences in soils throughout the Prairies, ranging from brown chernozemic soils to gray-wooded luvisols and some solenetzic soils (Soil Classification Working Group 2001). Precipitation across the Prairies ranges from a yearly average of 300 to 500 mm (McGinn 2010). The majority of the precipitation is received as rain, with June and July accounting for the greater part of the precipitation received during the growing season (McGinn 2010). There is temperature and precipitation variation across the provinces, with Saskatchewan being the driest of the three. As a result, there is wide variation in cropping systems in terms of crops grown (Agriculture and Agri-Food Canada 2021), cropping practices (Statistics Canada 2016) as well as crop yield and profitability (Statistics Canada 2019).

The predominant HR crop varies by province, as does the most popular HR trait in each crop (Table 4). There are other HR crops

Table 4. Herbicide-resistant (HR) crop market share as a percent of insured acres, by trait, in Alberta, Saskatchewan, and Manitoba, Canada, as well as averaged across provinces, based on 2020 crop insurance data compiled by the Canadian Grain Commission (2020).

Crop or (HR) trait	Alberta	Saskatchewan	Manitoba	Prairie Province average
		— % —		
Canola				
Glyphosate	42	26	16	28
Glufosinate	55	58	77	61
Imidazolinone	0.9	2	5	3
Sulfonyl-urea	0.02	0.04	0.1	0.05
Glyphosate + glufosinate	0.7	0.2	0.8	0.4
Conventional	0.1	0.02	0.09	0.06
Not specified	0.9	14	0.2	8
Soybean				
Glyphosate	0	88	56	59
Glyphosate + dicamba	0	9	37	35
Glyphosate + 2,4-D	0	3	2	2
Glufosinate	0	0	0.2	0.2
Conventional	0	0	0.05	0.04
Not specified	100	0	4	4
Lentil				
Imidazolinone	90	65	66	68
Conventional	9	15	13	14
Not specified	0.4	20	21	18
Canadian western red spring wheat				
Imidazolinone	4	0.8	0.3	2
Conventional	96	99	99	98

Figure 4. Field-scale evaluation (e.g., acetolactate synthase inhibitor herbicide usage/application, pollen-mediated gene flow, yield, quality) of non-transgenic imidazolinone-resistant (Clearfield™) wheat compared with non–herbicide resistant (conventional) wheat in Saskatchewan, Canada, in the early 2000s (adapted from Beckie et al. 2011).

grown in the Prairies in minor acreages, such as chick pea (*Cicer arietinum* L.) and sugar beet, but for the purposes of this review, the focus will be on large-acreage HR crops. Canola is the most commonly grown HR crop in Alberta. Saskatchewan's most common HR crops are canola and lentil, and soybean and canola are most dominant in Manitoba.

Across the Prairies, more than 8.4 million ha of canola were seeded in 2020 (Statistics Canada 2021). Data on insured acreage are collated by the Canadian Grain Commission (2020) for all the HR crops discussed in this section and were used to determine percent market share allocated to each HR trait in each crop (Table 4). In Alberta, where canola is the most dominant HR crop, glufosinate resistance is the most dominant trait at about 55% of the planted area, followed by glyphosate resistance at about 42% of the area. All other resistance traits make up less than 1% of the crop area.

There is more diversity in the cropping areas in Saskatchewan for HR crops, with canola and lentil both making up significant portions of the cropping system. Canola was seeded on approximately 4.6 million ha in Saskatchewan, while lentil was seeded on 1.5 million ha (Statistics Canada 2021). Glufosinate resistance was the dominant HR trait being used in canola, at 58% market share of insured hectares, with glyphosate resistance being only 26% (Table 4). It is possible that many of the "not specified" cropping areas were seeded to a GR cultivar. IMI resistance accounted for 2% of the market share in Saskatchewan, with other traits accounting for <0.5%. For lentil, approximately 66% of the market share is accounted for by IMI-resistant cultivars, with conventional cultivars accounting for only 15%. It is likely that some of the unspecified cropping areas (20%) are also HR cultivars, thus leaving that share above 66%. There were approximately 50,000 ha of soybean grown, primarily in the southeast area of the province. The soybean market is dominated by GR cultivars either as a single trait (88%) or stacked with either dicamba (9%) or 2,4-D (3%).

The Manitoba canola market share (approximately 1.4 million ha) (Statistics Canada 2021) is dominated by glufosinate-resistant cultivars (77%) (Table 4). There are also larger percentages sown with IMI-resistant canola cultivars than in the other provinces (5%). The soybean area (465,000 ha) is dominated by either GR (56%) or glyphosate plus an additional HR-trait (>37%) cultivar, suggesting a heavy use of glyphosate in these systems (93% of insured hectares). There has been adoption by farmers of different traits in the canola and soybean components of the rotation to allow for management of volunteers and rotation of herbicide SOA. Glufosinate-resistant canola volunteers can be relatively easily controlled by glyphosate in the soybean phase of the rotation, and any soybean volunteers (less common) controlled in the canola phase. The ability to control volunteers has led to a relatively compatible rotation between HR traits and crops in the province.

While wheat is grown on a large scale across the Prairie provinces (primarily spring wheat), with nearly 9.5 million ha of wheat seeded in 2020 (Statistics Canada 2021), use of HR cultivars is limited. IMI resistance is the only HR trait available in western Canada. While IMI-resistant cultivars were registered in 2004 (Harker et al. 2007; Figure 4), they have not had the same rate of adoption as is evident in the insured areas of other crops. Areas with IMI-resistant wheat only account for 2% of the land across the Prairies. This low adoption is likely the result of high use of IMI chemistry in pulse crops, other effective chemicals with different SOAs being available in wheat crops to provide high levels of weed control, and presence of ALS inhibitor–resistant weeds on the Prairies.

HR crops in western Canada have provided an excellent management tool for difficult to control weeds. In particular, the use of nonselective herbicides in HR canola allowed management of weeds in a crop that is typically very challenging (Beckie et al. 2006). The presence of multiple HR traits in canola and soybean, as well as multiple HR crops, has kept selection for herbicide resistance relatively low, aside from HR crops as volunteer weeds. In comparison to other cropping systems in the Prairies, such as corn–soybean rotations in Ontario, where high reliance on glyphosate exists and has resulted in the selection of glyphosate resistance in populations of six weed species (Heap 2021), the Prairie provinces only have two reports of GR weed populations to date. Overall, glyphosate resistance is still of limited concern, and the diversity of HR crops and traits has played a part in keeping the frequency of glyphosate resistance low.

It is interesting to compare use of the HR traits among provinces. For example, in Manitoba, where there is reliance on the GR trait in soybean, there is a more dominant use of glufosinate-resistant canola compared with Alberta; other HR traits in canola are more closely balanced in the latter province (Table 4). The rotational use of the traits in different crops in Manitoba especially helps with management of volunteer crops; the balanced use of traits in Alberta helps to manage weeds that are better controlled by one trait over another and thereby not strongly selecting for resistance. Because of the multiple options in traits and crops, farms can design a cropping system best suited to the climate, region, growing degree days, and problematic weeds.

HR crops in the Prairie provinces have allowed control of HR weeds. Resistance to ACCase- and ALS-inhibiting herbicides is most predominant in populations of *A. fatua* (single and multiple resistance) and a number of broadleaf weeds (Beckie et al. 2020; Heap 2021). Auxinic-resistant populations of *B. scoparia* are also increasing (Beckie et al. 2019; Heap 2021). Therefore, the utility of the nonselective herbicides that can be used in canola and soybean for resistance management. Adoption of IMI resistance has been higher in lentil than in wheat, likely because there is more utility to the trait in a noncompetitive crop (i.e., lentil) with few other effective herbicide options. However, in the more competitive wheat crop with far more herbicide options, the trait does not provide as much benefit due to already existing resistance. The addition of nonselective HR traits essentially allowed Prairie farmers to grow a crop in place of chemical fallow or summer fallow, resulting in an overall increase in productivity. The diversity of traits and crops with herbicide resistance also has allowed for development of a relatively diverse cropping system on the Prairies.

Initial studies indicated higher net returns in GR canola than in non-HR, conventional canola, particularly with only a single pass of glyphosate (O'Donovan et al. 2006). Within 10 yr of introduction, the highest-yielding cultivars also tended to be those with HR traits (Harker et al. 2007). This association is very likely still the case, as most agricultural companies have focused breeding efforts on HR cultivars, although a recent comparison of yields has not been performed. In the past, GR canola cultivars provided profitable returns more often than those with other HR traits (Upadhyay et al. 2006). However, recent measures of these yield differences have not been reported. In addition, within the first 5 yr of adoption (by 2000), Brimner et al. (2005) found that cultivation of HR canola reduced total herbicide inputs by 43%. The reduction was a result of lower herbicide application rates and number of applications. O'Donovan et al. (2006) also found fewer herbicide active ingredients applied in GR canola than with conventional cultivars. It is unclear whether this still holds true in the Prairies, or whether the evolution of herbicide resistance, increased tank mixing, and multiple HR crops has led to an increase in the herbicide active ingredient applications per hectare since that time.

As discussed previously, one of the biggest concerns around the use of HR crops is selection and evolution of HR weeds. While this has certainly been an issue in other cropping systems with a reliance on glyphosate, HR weed evolution to any specific herbicide has not been a significant issue in the Prairies. This is likely due to the variety of HR traits available in the various crops for incorporation in a cropping system. From a glyphosate-resistance perspective, only GR *B. scoparia* populations occur on the Prairies (Heap 2021). GR *B. scoparia* was likely selected in Prairie chemical-fallow systems (Beckie et al. 2013, 2015; Hall et al. 2014). Volunteer GR canola has become a significant issue in soybean in Manitoba, and it has increased in prevalence across the Prairies since the 1970s (Leeson 2016; Leeson et al. 2017, 2019), with most volunteers likely to possess an HR trait based on dominance of these cultivars in the marketplace. This phenomenon is not surprising, given that harvest losses from canola can be more than 6,000 seeds m^{-2} (Cavalieri et al. 2016); the majority of those losses originate in an HR canola field because of the widespread adoption of cultivars with HR traits (Table 4). GR waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] was introduced into Manitoba from the United States via equipment, water, or other anthropogenic means, but is currently not considered established. There is significant concern about the potential for additional *A. tuberculatus* introductions as well as introductions of *A. palmeri*, which could significantly increase weed management problems, particularly if the populations are HR. Weed populations resistant to ALS-inhibiting herbicides are a significant problem, especially in lentil, where weed control relies on those chemistries. While there are options for managing these weeds in other phases of a crop rotation, resistance to ALS-inhibiting herbicides can be a challenge in cereal crops as well.

Other issues surrounding weed management problems in HR crops are demonstrable with volunteer canola. Multiple HR populations of volunteer canola have been identified as a result of gene flow from GR and glufosinate-resistant cultivars (Beckie et al. 2003). With the high level of seedbank inputs from harvest losses of canola, there is higher likelihood of gene flow to allow for the development of volunteer canola with resistance to multiple SOAs. There is also a risk of movement of HR traits to weedy relatives. This has been reported in Quebec, Canada, with movement of the transgene to weedy rape (*Brassica rapa* L.; Laforest et al. 2021) but has not yet been reported in western Canada.

Shifts in weed communities have also been documented, particularly linked with GR cropping systems, albeit not systems that are specific to the Prairies (Harker et al. 2005; Hilgenfeld et al. 2004; Owen 2008; Reddy 2004). The diversity in HR crops within Prairie cropping systems has likely limited this to an extent. As indicated by Harker et al. (2007), this is a concern when the weed spectrum shifts to those that are more difficult to control. There have been some changes in weed distributions that are likely correlated with the expansion in HR crop area. For example, *G. spurium* has increased in abundance throughout Alberta since the 1970s (Leeson et al. 2019). When the areas where *G. spurium* were mapped, they were concentrated in the areas where HR canola area has expanded or canola in the rotation has increased in frequency. *Galium aparine* is known to be problematic in canola, as it can emerge as a winter annual and is difficult to remove from canola seed, and not all herbicide options are equally effective for its management. Thus, there is a logical potential correlation between the expansion and concentration of HR canola and the expansion and concentration of *G. spurium* as an abundant weed. However, these types of shifts also increase the frequency and risk of resistance evolution in "new" problem weeds as a result of repeated herbicide use in the HR crops.

HR crops continue to have a place in western Canada agriculture. There is already some limited initial adoption of canola with resistance to both glyphosate and glufosinate (Table 4). While this level is small based on insured cropping area, it will be interesting to see how adoption grows in the coming years, and in particular how adoption may vary across the provinces and their varied cropping systems. We also are seeing adoption of GR and dicamba-resistant soybean, particularly in Manitoba, where 33% of the insured area in 2020 was listed with this trait (Table 4). The impact of these adoptions could be widespread. As an example, the adoption of GR and dicamba-resistant soybean could aid in the management of GR *B. scoparia*. However, dicamba-resistant *B. scoparia* has already been identified in the Prairies, as well as *B. scoparia* with both glyphosate and dicamba resistance (Beckie et al. 2019). The dual-trait canola may result in increased difficulty in managing volunteers, as well as potentially increasing the weediness of the species. However, the impact may be limited where there were already volunteers with both resistance traits due to gene flow compared with areas free of multiple HR volunteer canola. It is also unclear how large of a market share the dual-trait HR crops will occupy in the future. If they become a large share of the market, the impact could be widespread. There are also a number of relatively low-cost alternative herbicides that provide control of volunteer canola (Harker et al. 2007; Rainbolt et al. 2004).

The Canadian Prairies are a concrete example of how having multiple HR traits available within a crop, as well as multiple traits within a cropping system, can aid in weed management and mitigate some of the concerns or complications around the overuse of HR crops and associated herbicides experienced in other regions. This region demonstrates that weed management can be improved with HR traits as the backbone of a weed management program, without necessarily resulting in rapid evolution of HR weeds.

The Future of HR Crops and Their Role in Resistance Management

Numerous HR crop technologies have been developed by private agricultural companies utilizing transgenic and non-transgenic techniques with the purpose of improving the diversity and effectiveness of weed management tools (Green 2018; Liu et al. 2020). A key benefit of HR cropping systems is to increase the spectrum, reliability, and durability of weed control by enabling application of herbicide active ingredients that lack inherent crop tolerance. Many HR crops have been created through genetic modification by introducing or altering genes to express an insensitive form of the target SOA or herbicide-metabolizing enzymes (Green 2018). Non-transgenic approaches include chemical or radiation mutagenesis, somaclonal selection, or wild species selection followed by introgression to create or select for insensitive SOA proteins in crops (Tan et al. 2005; Walter et al. 2013). Initially, companies developed single-trait systems in crops, for example, GR soybean, corn, and cotton, among others. The current industry trend is development of stacked-trait systems of two or more resistance genes to employ multiple SOA herbicide active ingredients to address increasing levels and complexity of herbicide resistance. Due to the high cost and time to develop both herbicides and traits and public acceptance of transgenic crops, typically only major agronomic commodity crops are targeted for transgenic HR crops (CropLife International 2021; ISAAA 2021; Prado et al. 2014).

Future approaches may include introduction of new herbicide SOAs, or a new chemotype of existing herbicide SOAs, and associated resistance traits able to control problematic HR weed populations. Additionally, the rapid increase in genomics technology may allow for parallel discovery of herbicides and transgenic resistance traits, or perhaps non-transgenic approaches. Genome editing tools are evolving rapidly and are being used to design HR crops, among other concepts. Zinc finger nucleases and transcription activator–like effector nucleases have made it possible for plant molecular biologists to target and modify specific genes of interest more precisely (Novak 2019). However, a vast improvement has been achieved through CRISPR/Cas9-mediated genome editing—utilizing the same Cas9 enzyme flexibly using different guide RNAs targeting various specific gene targets, allowing genetic material to be added, removed, or altered at particular locations in the genome (Jaganathan et al. 2018). Application of these techniques has the potential to result in the development of non-transgenic modified crops with the desired trait (Dong et al. 2021; Wang et al. 2021). Having a more economical and faster approach opens the possibility of employment of HR crop technologies into minor or smaller area crops, where fewer traditional herbicide options exist today. Regulations around genome-edited crops are also evolving rapidly, but today are not harmonized among global regulatory agencies and remain a hurdle to commercialization for crops with global distribution (Podevin et al. 2013; Turnbull et al. 2021).

Regardless of the approach used to derive new HR crops, good proactive stewardship is required to protect the long-term durability of HR technologies. Educational programs that include proper use and stewardship are essential. HR crop systems should always be part of an overall integrated approach toward effective and sustainable weed management, including an achievable resistance management plan along with an execution plan complementing the HR technology. Properly employed modern HR crop systems can provide additional tools for weed resistance management and sustainable weed control.

Conclusion

When examining the history of HR crop cultivation globally, it is clear that HR crops have simultaneously been part of the solution and part of the problem of HR weed evolution and management, adoption of IWM practices, and sustainable agriculture in general. Where the needle points on the problem–solution spectrum depends on the HR crop and HR trait, as well as the environment or agricultural region where it is grown. As emphasized in the preceding sections, we need to continually deliver the message of herbicide stewardship, not only in HR crop production, but both HR and non-HR crop production. Herbicides are a finite, nonrenewable resource. It has been stated that the problem is not HR crops per se, but herbicide use associated with HR crops. Many find it hard to separate one from the other.

Going forward, the utility and effectiveness of recently introduced HR traits such as HPPD-inhibitor resistance and other soon-to-be commercialized HR traits, as well as herbicides with new SOAs, need to be sustained or preserved for longer time frames than for those traits and chemistries previously introduced. Achieving that goal will favor the needle pointing more toward part of the solution versus part of the problem in HR weed evolution and management and IWM in general. However, new SOA herbicides introduced either for use in HR or non-HR crops will immediately be put under severe selection pressure because of the urgent need of growers to manage their existing HR weed populations, which are often characterized by multiple SOA resistance.

The addition of single traits to already existing HR crops, particularly if weed populations resistant to one of the traits already exist, is not necessarily the best path forward. This addition only results in rapid evolution of resistance to the new trait or multiple resistance to both traits in a single weed population. This can be illustrated by the selection of weed populations with metabolic herbicide resistance that is nonspecific to herbicides from multiple SOAs (Busi and Powles 2016). Rather, the inclusion of new, diverse traits in the cropping system, particularly if they can aid in the adoption of more minor crops with weed management challenges, would be a more effective and efficient way to continue to expand the HR crop market.

The challenge of the weed science community, crop protection industry, and governments at all levels is incentivizing growers and land managers to practice restraint on the frequency of use of these new tools in their fields. A strictly voluntary approach has not worked thus far. Registration requirements and industry stewardship plans need teeth (Beckie 2016). To avoid a "tragedy of the commons," recommendations for maximum herbicide-use intensity (within and across growing seasons) and HR crop rotation frequency are needed. Comprehensive training for growers in proper stewardship practices is critical for optimizing and prolonging the benefits and minimizing risks of HR crops as they are repeatedly and widely deployed across millions of hectares of cropland annually. Seed retailers and agronomists also require professional development training in this area, as they often advise and influence a grower's decision regarding herbicide options best tailored to specific weed problems. Concomitantly, industry and government financial incentives must expand to improve growers' adoption of best management practices for HR crops to better manage HR weeds sustainably.

As described in this review, there is a consensus across the different regions of the western United States and Canada that new HR traits, in combination with new or established SOA herbicides, can improve proactive and reactive HR weed management. The regulatory environment as well as the application of genome editing techniques are rapidly evolving. It is likely that HR crops will continue to be, or will become, an important component of IWM, including management of HR weed populations in both major and minor crops. Although counterintuitive, this technology still has the long-term potential to reduce herbicide-use intensity and herbicide selection pressure for resistance evolution across this geographic region despite ever-increasing infestations of HR weeds.

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References

Agriculture and Agri-Food Canada (2021) G002—Area, Yield and Production of Canadian Principal Field Crops Report: Provincial. https://aimis-simia.agr.gc.ca/rp/index-eng.cfm?action=pR&r=243&lang=EN. Accessed: June 28, 2021

Anonymous (2017a) Albaugh, LLC Aggressor® label. http://www.coaxiumwps.com/wp-content/uploads/AggressorLabel.pdf. Accessed: September 20, 2021

Anonymous (2017b) XtendiMax® with VaporGrip technology herbicide product label. EPA Reg. No. 524-617. Research Triangle Park, NC: BayerCrop Protection, Inc. 9 p

Baenziger PS, Rose D, Santra D, Guttieri M, Xu L (2016) Improving Wheat Varieties for Nebraska. https://agronomy.unl.edu/documents/Whtann12V8R2.pdf. Accessed: September 17, 2021

Beckie HJ (2006) Herbicide-resistant weeds: management tactics and practices. Weed Technol 20:793–814

Beckie HJ (2016) Herbicide-resistant (HR) crop management: a Canadian perspective. Pages 75–80 *in* Thompson GA, Lipari SE, Hardy RWF, eds. Stewardship for the Sustainability of Genetically Engineered Crops: The Way Forward in Pest Management, Coexistence, and Trade. NABC Report 27. Ithaca, NY: North American Agricultural Biotechnology Council

Beckie HJ, Blackshaw RE, Low R, Hall LM, Sauder CA, Martin S, Brandt RN, Shirriff SW (2013) Glyphosate- and acetolactate synthase inhibitor-resistant kochia (*Kochia scoparia*) in western Canada. Weed Sci 61:310–318

Beckie HJ, Gulden RH, Shaikh N, Johnson EN, Willenborg CJ, Brenzil CA, Shirriff SW, Lozinski C, Ford G (2015) Glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Saskatchewan and Manitoba. Can J Plant Sci 95:345–349

Beckie HJ, Hall LM, Shirriff SW, Martin E, Leeson JY (2019) Triple-resistant kochia [*Kochia scoparia* (L.) Schrad.] in Alberta. Can J Plant Sci 99:281–285

Beckie HJ, Harker KN, Hall LM, Warwick WI, Legere A, Sikkema PH, Clayton GW, Thomas AG, Leeson JY, Seguin-Swartz G, Simard M-J (2006) A decade of herbicide-resistant crops in Canada. Can J Plant Sci 86:1243–1264

Beckie HJ, Shirriff SW, Leeson JY, Hall LM, Harker KN, Dokken-Bouchard F, Brenzil CA (2020) Herbicide-resistant weeds in the Canadian prairies: 2012–2017. Weed Technol 34:461–474

Beckie HJ, Warwick SI, Nair H, Séguin-Swartz G (2003) Gene flow in commercial fields of herbicide-resistant canola (*Brassica napus*). J Ecol Appl 13:1276–1294

Beckie HJ, Warwick SI, Sauder CA, Hall LM, Harker KN, Lozinski C (2011) Pollen-mediated gene flow in commercial fields of spring wheat in western Canada. Crop Sci 51:306–313

Blackshaw RE, Beckie HJ, Molnar LJ, Entz T, Moyer JR (2005) Combining agronomic practices and herbicides improves weed management in wheat–canola rotations within zero-tillage production systems. Weed Sci 53:528–535

Bobadilla LK, Hulting AG, Berry PA, Moretti ML, Mallory-Smith C (2021) Frequency, distribution, and ploidy diversity of herbicide-resistant Italian ryegrass (*Lolium perenne* L. spp. *multiflorum*) populations of western Oregon. Weed Sci 69:177–185

Brimner TA, Gallivan GJ, Stephenson GR (2005) Influence of herbicide-resistant canola on the environmental impact of weed management. Pest Manag Sci 61:47–52

Brookes G, Barfoot P (2005) GM crops: the global economic and environmental impact—the first nine years 1996–2004. AgBioForum 8:187–196

Brunharo CACG, Hanson BD (2018) Multiple herbicide-resistant Italian ryegrass [*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot] in California perennial crops: characterization, mechanism of resistance, and chemical management. Weed Sci 66:696–701

Buhler DD, Oplinger ES (1990) Influence of tillage systems on annual weed densities and control in solid-seeded soybean (*Glycine max*). Weed Sci 38:158–165

Busi R, Powles SB (2016) Cross-resistance to prosulfocarb + *S*-metolachlor and pyroxasulfone selected by either herbicide in *Lolium rigidum*. Pest Manag Sci 72:1664–1672

Campbell J, Mallory-Smith C, Hulting A, Weber C (2011) Herbicide-Resistant Weeds and Their Management. https://catalog.extension.oregonstate.edu/pnw437/html. Accessed: October 2, 2021

Canadian Grain Commission (2020) Grain Varieties by Acreage Insured. https://www.grainscanada.gc.ca/en/grain-research/statistics/varieties-by-acreage. Accessed: June 2, 2021

Canola Council of Canada (2021) Markets and Statistics. http://www.canolacouncil.org. Accessed: May 10, 2021

Cavalieri A, Harker KN, Hall LM, Willenborg CJ, Haile TA, Shirtliffe SJ, Gulden RH (2016) Evaluation of the causes of on-farm harvest losses in canola in the Northern Great Plains. Crop Sci 56:2005–2015

Chen K, Wang Y, Zhang R, Zhang H, Gao C (2019) CRISPR/Cas genome editing and precision plant breeding in agriculture. Annu Rev Plant Biol 70:667–697

CropLife International (2021) Biotradestatus. http://www.biotradestatus.com. Accessed: September 20, 2021

Dentzmann, K, Burke IC (2021) Herbicide resistance, tillage, and community management in the Pacific Northwest. Sustainability 13:e1937

Devine MD, Buth JL (2001) Advantages of genetically modified canola: a Canadian perspective. Pages 367–372 *in* Proceedings Brighton Crop Protection Conference—Weeds. Farnham, Surrey, UK: British Crop Protection Council

Dong H, Huwang Y, Wang K (2021) The development of herbicide resistance crop plants using CRISPR/Cas0-mediated gene editing. Genes 12:e912

Ehler LE (2006) Integrated pest management (IPM): definition, historical development and implementation, and the other IPM. Pest Manag Sci 62:787–789

Fernandez-Cornejo J, Wechsler S, Milkove D (2016) The Adoption of Genetically Engineered Alfalfa, Canola, and Sugar Beets in the United States. Washington, DC: US. Dept of Agriculture–Economic Research Service. 28 p. https://www.ers.usda.gov/publications/pub-details/?pubid=81175. Accessed: April 7, 2022

Flowers M, Peterson CJ, Hulting A, Burns J, Kuehner J (2008) ORCF-102 Clearfield Soft White Winter Wheat. Oregon State University Extension Service EM 8972-E. 11 p

Gaines TA, Barker AL, Patterson EL, Westra P, Westra EP, Wilson RG, Jha P, Kumar V, Kniss AR (2016) EPSPS gene copy number and whole-plant glyphosate resistance level in *Kochia scoparia*. PLoS ONE 11:e0168295

Geddes CM, Davis AS (2021) The critical period for weed seed control: a proposed framework to limit weed seed return. Weed Res 61:282–287

Geier PW, Stahlman PW, White AD, Miller SD, Alford CM, Lyon DJ (2004) Imazamox for winter annual grass control in imidazolinone-tolerant winter wheat. Weed Technol 18:924–930

Green JM (2012) The benefits of herbicide-resistant crops. Pest Manag Sci 68:1323–1331

Green JM (2018) The rise and future of glyphosate and glyphosate-resistant crops. Pest Manag Sci 74:1035–1039

Green JM, Owen MDK (2011) Herbicide-resistant crops: utilities and limitations for herbicide-resistant weed management. J Agric Food Chem 59:5819–5829

Hagerty C, Fickas KC, Wysockie DJ (2019) Agronomic Zones of the Dryland Pacific Northwest. https://catalog.extension.oregonstate.edu/pnw354. Accessed: September 20, 2021

Hall LM, Beckie HJ, Low R, Shirriff SW, Blackshaw RE, Kimmel N, Neeser C (2014) Survey of glyphosate-resistant kochia (*Kochia scoparia* L. Schrad.) in Alberta. Can J Plant Sci 94:127–130

Harker KN, Blackshaw RE, Kirkland KJ, Derksen DA, Wall D (2000) Herbicide-tolerant canola: weed control and yield comparisons in western Canada. Can J Plant Sci 80:647–554

Harker KN, Clayton GW, Beckie HJ (2007) Weed management with herbicide-resistant crops in western Canada. Pages 15–31 *in* Gulden RH, Swanton CJ, eds. The First Decade of Herbicide-Resistant Crops in Canada. Topics in Canadian Weed Science. Sainte Anne de Bellevue, QC: Canadian Weed Science Society

Harker KN, Clayton GW, Blackshaw RE, O'Donovan JT, Lupwayi NZ, Johnson EN, Gan Y, Zentner RP, Lafond GP, Irvine RB (2005) Glyphosate-resistant spring wheat production system effects on weed communities. Weed Sci 53:451–464

Harker KN, Clayton GW, Blackshaw RE, O'Donovan JT, Stevenson RC (2003) Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can J Plant Sci 83:433–440

Harker KN, O'Donovan JT (2013) Recent weed control, weed management and integrated weed management. Weed Technol 27:1–11

Heap I (2021) The International Herbicide-Resistant Weed Database. www.weedscience.org. Accessed: September 6, 2021

Hilgenfeld KL, Martin AR, Mortensen DA, Mason SC (2004) Weed management in a glyphosate resistant soybean system: weed species shifts. Weed Technol 18:284–291

Hoffman, NE (2021) Revisions to USDA biotechnology regulations, the SECURE rule. Proc Natl Acad Sci 118:1–6

Idaho Wheat Commission (2021) Variety Survey Report. https://www.idahowheat.org/?page_id=54201. Accessed: October 2, 2021

[ISAAA] International Service for the Acquisition of Agri-biotech Applications (2019) Global Status of Commercialized Biotech/GM Crops in 2019: Biotech Crops Drive Socio-Economic Development and Sustainable Environment in the New Frontier. ISAAA Brief No 55. Ithaca, NY: ISAAA

[ISAAA] International Service for the Acquisition of Agri-biotech Applications (2021) International Service for the Aquisition of Agri-Biotech Applications GM Approval Database. https://www.isaaa.org/gmapprovaldatabase/default.asp. Accessed: September 20, 2021

Jaganathan D, Ramasamy K, Sellamuthu G, Jayabalan S, Venkataraman G (2018) CRISPR for crop improvement: an update review. Front Plant Sci 9:e985

Jha P, Kumar V, Lim CA (2016) Herbicide resistance in cereal production systems of the US Great Plains: a review. Indian J Weed Sci 48:112–116

Jones RE, Medd RW (2000) Economic thresholds and the case for longer term approaches to population management of weeds. Weed Technol 14:337–350

Kaur H, Huggins DR, Rupp RA, Abatzoglou JT, Stockle CO, Reganold JP (2017) Agro-ecological class stability decreases in response to climate change projections for the Pacific Northwest USA. Front Ecol Evol 5:e74

Kirby, E, Pan W, Huggins D, Painter K, Bista P (2017) Rotational diversification and intensification. Pages 163–236 *in* Yorgey G, Kruger C, eds. Advances in Sustainable Dryland Farming in the Inland Pacific Northwest. Pullman, WA: Washington State University Extension Publication EM108

Kirkland KJ, Johnson EN (2000) Alternative seeding dates (fall and April) affect *Brassica napus* canola yield and quality. Can J Plant Sci 80:713–719

Kniss AR (2017) Long-term trends in the intensity and relative toxicity of herbicide use. Nat Commun 8:e14865

Kniss AR (2018) Genetically engineered herbicide-resistant crops and herbicide-resistant weed evolution in the United States. Weed Sci 66:260–273

Kniss AR, Lyon DJ, Vassios JD, Nissen SJ (2011) MCPA synergizes imazamox control of feral rye (*Secale cereale*). Weed Technol 25:303–309

Kumar V, Felix J, Morishita D, Jha P (2018) Confirmation of glyphosate-resistant kochia (*Kochia scoparia*) from sugar beet fields in Idaho and Oregon. Weed Technol 32:27–33

Kumar V, Liu R, Boyer G, Stahlman PW (2019) Confirmation of 2,4-D resistance and identification of multiple resistance in a Kansas Palmer amaranth (*Amaranthus palmeri*) population. Pest Manag Sci 75:2925–2933

Kumar V, Liu R, Currie RS, Jha P, Morran S, Gaines TA, Stahlman PW (2021) Cross-resistance to atrazine and metribuzin in multiple herbicide-resistant kochia accessions: confirmation, mechanism, and management. Weed Technol 35:539–546

Kumar V, Liu R, Manuchehri MR, Westra EP, Gaines TA, Shelton CW (2020a) Feral rye control in quizalofop-resistant wheat in central Great Plains. Agron J 113:407–418

Kumar V, Liu R, Peterson DE, Stahlman PW (2020b) Effective two-pass herbicide programs to control glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in glyphosate/dicamba-resistant soybean. Weed Technol 35:128–135

Kumar V, Obour A, Jha P, Liu R, Manuchehri MR, Dille JA, Holman J, Stahlman PW (2020c) Integrating cover crops for weed management in the semiarid U.S. Great Plains: opportunities and challenges. Weed Sci 68:311–323

Laforest M, Bisaillon K, Soufiane B, Maheux L, Fortin S, Martin S, James T, Miville D, Marcoux A, Simard M-J (2021) Glyphosate resistant bird rape mustard (*Brassica rapa*) through introgression of a transgenic construct: distribution and genetic characterization. Abstract 40 *in* Proceedings of the Weed Science Society of America Annual Meeting. Arlington, VA: Weed Science Society of America

Lancaster S, Currie RS (2020) Herbicide-Resistant Grain Sorghum Hybrids—Are They Here Yet? https://eupdate.agronomy.ksu.edu/article_new/herbicide-resistant-grain-sorghum-hybrids-are-they-here-yet-414. Accessed: December 28, 2021

Leeson JY (2016) Saskatchewan Weed Survey of Cereal, Oilseed and Pulse Crops in 2014 and 2015. Publication 26-1. Saskatoon, SK: Agriculture and Agri-Food Canada. 356 p

Leeson JY, Gaultier J, Grenkow L (2017) Manitoba Weed Survey of Annual Crops in 2016. Publication 17-2. Saskatoon, SK: Agriculture and Agri-Food Canada. 203 p

Leeson JY, Hall LM, Neeser C, Tidemann B, Harker KN (2019) Alberta Weed Survey of Annual Crops in 2017. Publication 19-1. Saskatoon, SK: Agriculture and Agri-Food Canada. 275 p

Lenssen AW, Johnson GD, Carlson GR (2007) Cropping sequence and tillage system influence annual crop production and water use in semiarid Montana. Field Crops Res 100:32–43

Liebman M, Gallandt ER (1997) Many little hammers: ecological management of crop-weed interactions. Pages 291–343 *in* Jackson LE, ed. Ecology in Agriculture. San Diego, CA: Academic

Liu C, Neve P, Glasgow L, Wuerffel RJ, Owen MDK, Kaundun SS (2020) Modeling the sustainability and economics of stacked herbicide-tolerant traits and early weed management strategy for waterhemp (*Amaranthus tuberculatus*) control. Weed Sci 68:179–185

Llewellyn RS, Lindner RK, Pannell DJ, Powles SB (2004) Grain grower perceptions and use of integrated weed management. Aust J Exp Agric 44:993–1001

Mallory-Smith C, Kniss A, Lyon D, Zemetra R (2018) Jointed goatgrass (*Aegilops cylindrica*): a review. Weed Sci 66:562–573

Mallory-Smith CA, Thill DC, Stallings GP (1993) Survey and gene flow in acetolactate synthase resistant kochia and Russian thistle. Pages 555–558 *in* Brighton Crop Protection Conference—Weeds. Farnham, UK: British Crop Protection Council

Matzrafi M, Preston C, Brunharo CACG (2021) Review: evolutionary drivers of agricultural adaptation in *Lolium* spp. Pest Manag Sci 77:2209–2218

May WE, St Luce M, Gan Y (2020) No-till farming systems in the Canadian Prairies. Pages 601–616 *in* Dang YP, Dalal RC, Menzies NW, eds. No-Till Farming Systems for Sustainable Agriculture: Challenges and Opportunities. Cham, Switzerland: Springer

McDougall P (2014) The Cost of New Agrochemical Product Discovery, Development and Registration in 1995, 2000, 2005-8 and 2010-2014. https://croplife.org/wp-content/uploads/2016/04/Cost-of-CP-report-FINAL.pdf. Accessed: September 17, 2021

McGinn SM (2010) Weather and Climate Patterns in Canada's Prairie Grasslands. Pages 105–119 *in* Shorthouse JD, Floate KD, eds. Arthropods of Canadian Grasslands: Ecology and Interactions in Grassland Habitats. Ottawa, ON: Biological Survey of Canada.

Morishita D (2018) Impact of glyphosate-resistant sugar beet. Pest Manag Sci 74:1050–1053

Moss S (2018) Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides? Pest Manag Sci 75:1205–1211

Nakka S, Jugulam M, Peterson D, Asif M (2019) Herbicide resistance: development of wheat production systems and current status of resistant weeds in wheat cropping systems. Crop J 7:750–760

Nandula V (2019) Herbicide resistance traits in maize and soybean: current status and future outlook. Plants 9:e337

Nichols V, Verhulst N, Cox R, Govaerts B (2015) Weed dynamics and conservation agriculture principles: a review. Field Crop Res 183:56–68

Nielsen DC (2018) Influence of latitude on the US Great Plains east–west precipitation gradient. Agric Environ Lett 3:1–5

Norris R (1999) Ecological implications of using thresholds for weed management. Pages 31–58 *in* Buhler DD, ed. Expanding the Context of Weed Management. New York: Haworth

Norris R, Caswell-Chen EP, Kogan M (2003) Concepts in Integrated Pest Management. Upper Saddle River, NJ: Prentice Hall. 586 p

Norsworthy JK, Griffith G, Griffin T, Bagavathiannan M, Gbur EE (2014) In-field movement of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) and its impact on cotton lint yield: evidence supporting a zero-threshold strategy. Weed Sci 62:237–249

Novak S (2019) Plant biotechnology applications of zinc finger technology. *In* Kumar S, Barone P, Smith M, eds. Transgenic Plants (Methods in Molecular Biology 1864). New York: Humana. https://doi.org/10.1007/978-1-4939-8778-8_20. Accessed: December 6, 2021

O'Donovan JT, Harker KN, Clayton GW, Blackshaw RE (2006) Comparison of a glyphosate-resistant canola (*Brassica napus* L.) system with traditional herbicide regimes. Weed Technol 20:494–501

[OSU] Oregon State University Seed Certification (2021) Home page. http://www.seedcert.oregonstate.edu. Accessed: September 20, 2021

Oregon Wheat Commission (n.d.) Statistics. http://www.owgl.org. Accessed: September 20, 2021

Ostlie M, Haley SD, Anderson V, Shaner D, Manmathan H, Beil C, Westra P (2015) Development and characterization of mutant winter wheat (*Triticum aestivum* L.) accessions resistant to the herbicide quizalofop. Theor Appl Genet 128:343–351

Owen MDK (2008) Weed species shifts in glyphosate-resistant crops. Pest Manag Sci 64:377–387

Owen MDK (2016) Diverse approaches to herbicide-resistant weed management. Weed Sci 64:570–584

Owen MDK, Beckie HJ, Leeson JY, Norsworthy JK, Steckel LE (2015) Integrated pest management and weed management in the United States and Canada. Pest Manag Sci 71:357–376

Paulsen GM, Shroyer JP (2008) The early history of wheat improvement in the Great Plains. Agron J 100:S70–S78

Pester TA, Westra P, Nissen SJ (2001) Absorption, translocation, and metabolism of imazamox in jointed goatgrass and feral rye. Weed Sci 49:607–612

Peterson GA, Westfall DG (2004) Managing precipitation use in sustainable dryland agroecosystems. Ann Appl Biol 144:127–138

Peachey E (2021) Pacific Northwest Weed Management Handbook. http://www.pnwhandbooks.org. Accessed: September 20, 2021

PNW Canola Association (2021) Where Is Canola Grown? https://pnwcanola.org/for-consumers/where-is-it-grown. Accessed: November 30, 2021

Podevin N, Davies HV, Hartung F, Nogue F, Casacuberta JM (2013) Site-directed nucleases: a paradigm shift in predictable, knowledge-based plant breeding. Trends Biotechnol 31:375–383

Prado JR, Segers G, Voelker T, Carson D, Dobert R, Phillips J, Cook K, Cornejo C, Monken J, Grapes L, Reynolds T, Martino-Catt S (2014) Genetically engineered crops: from idea to product. Annu Rev Plant Biol 65:769–790

Qu R-Y, He B, Yang J-F, Lin H-Y, Yang W-C, Wu Q-Y, Li QX, Yang G-F (2021) Where are the new herbicides? Pest Manag Sci 77:2620–2625

Rainbolt CR, Thill DC, Young FL (2004) Control of volunteer herbicide-resistant wheat and canola. Weed Technol 18:711–718

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

Reddy KN (2004) Weed control and species shift in bromoxynil- and glyphosate-resistant cotton (*Gossypium hirsutum*) rotation systems. Weed Technol 18:131–139

Rodriguez J, Hauvermale A, Carter A, Zuger R, Burke IC (2021) An ALA_{122}THR substitution in the AHAS/ALS gene confers imazamox-resistance in *Aegilops cylindrica*. Pest Manag Sci 77:4583–4592

Schmidt JJ, Pedersen JF, Bernards ML, Lindquist JL (2013) Rate of shattercane x sorghum hybridization in situ. Crop Sci 53:1677–1685

Schroeder J, Barrett M, Shaw DR, Asmus AB, Coble H, Ervin D, Jussaume RA Jr, Owen MDK, Burke I, Creech CF, Culpepper AS, Curran WS, Dodds DM, Gaines TA, Gunsolus JL, *et al.* (2018) Managing wicked herbicide-resistance: lessons from the field. Weed Technol 32:475–488

Shafer M, Ojima D, Antle JM, Kluck D, McPherson R, Peterson S, Scanlon B, Sherman K (2014) Great Plains Climate Change Impacts in the United States. The Third National Climate Assessment. Washington, DC: U.S. Global Change Research Program. Pp 441–461. http://nca2014.globalchange.gov/report/regions/great-plains. Accessed: July 21, 2021

Shyam C, Chahal PS, Jhala AJ, Jugulam M (2021) Management of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*) in 2,4-D-, glufosinate-, and glyphosate-resistant soybean. Weed Technol 35:136–143

Smith A, Soltani N, Kaastra AC, Hooker DC, Robinson D, Sikkema PH (2019) Isoxaflutole and metribuzin interactions in isoxaflutole-resistant soybean. Weed Sci 67:1–12

Soil Classification Working Group (2001) Soils of Canada. Agriculture and Agri-food Canada, Research Branch. https://sis.agr.gc.ca/cansis/publications/maps/soc/all/soils/soc_all_soils_2004en.png. Accessed: July 6, 2021

Statistics Canada (2016) Proportion of Land Prepared for Seeding Using No-Till Seeding. https://www150.statcan.gc.ca/n1/pub/95-634-x/2017001/article/54903/catm-ctra-390-eng.htm. Accessed: July 7, 2021

Statistics Canada (2019) Net Farm Income, by Province. https://www150.statcan.gc.ca/n1/pub/71-607-x/71-607-x2020012-eng.htm. Accessed: July 7, 2021

Statistics Canada (2021) Table 32-10-0359-01: Estimated Areas, Yield, Production, Average Farm Price and Total Farm Value of Principal Field Crops. https://www150.statcan.gc.ca/t1/tbl1/en/tv.action?pid=3210035901. Accessed: June 28, 2021

Tan S, Evans RR, Dahmer ML, Singh BK, Shaner DL (2005) Imidazolinone-tolerant crops: history, current status and future. Pest Manag Sci 61:246–257

Turnbull C, Lillemo M, Hvoslef-Eide TAK (2021) Global regulation of genetically modified crops amid the gene edited crop boom—a review. Front Plant Sci 12:e630396

Undersander D, Cosgrove D, Cullen E, Grau C, Rice ME, Renz M, Sheaffer C, Shewmaker G, Sulc M (2011) Alfalfa Management Guide. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. Pp 23–29

Unger PW, Baumhardt RL (2001) Historical development of conservation tillage in Southern Great Plains. Pages 1–18 *in* Stiegler JH, ed. Proceedings of the 24th Annual Southern Conservation Tillage Conference for Sustainable Agriculture, Oklahoma City, July 9–11, 2001. Oklahoma City: Oklahoma State University

Upadhyay BM, Smith EG, Clayton GW, Harker KN, Blackshaw RE (2006) Economics of integrated weed management in herbicide-resistant canola. Weed Sci 55:138–147

[USDA-APHIS] U.S. Department of Agriculture–Animal and Plant Health Inspection Service (2021) Petitions for Determination of Nonregulated Status. https://www.aphis.usda.gov/aphis/ourfocus/biotechnology/permits-notifications-petitions/petitions/petition-status. Accessed: July 9, 2021

[USDA-NASS] U.S. Department of Agriculture–National Statistics Service (2020) Statistics by State. https://www.nass.usda.gov/Statistics_by_State/Oregon/Publications/Field_Crop_Report/crop%20reports/2020/CE12_01.pdf. Accessed: September 20, 2021

[USDA-NASS] U.S. Department of Agriculture–National Statistics Service (2021) Acreage. https://www.nass.usda.gov/Publications/Todays_Reports/reports/acrg0621.pdf. Accessed: September 20, 2021

Walter KL, Strachan SD, Ferry NM, Albert HH, Castle LA, Sebastian SA (2013) Molecular and phenotypic characterization of *Als1* and *Als2* mutations conferring tolerance to acetolactate synthase herbicides in soybean. Pest Manag Sci 70:1831–1839

Walsh MJ, Broster JC, Schwartz-Lazaro LM, Norsworthy JK, Davis AS, Tidemann BD, Beckie HJ, Lyon DJ, Soni N, Neve P, Bagavathiannan MV (2017) Opportunities and challenges for harvest weed seed control in global cropping systems. Pest Manag Sci 74:2235–2245

Wang F, Xu Y, Li W, Chen Z, Wang J, Fan F, Tao Y, Jiang Y, Q-H Zhu, Yang J (2021) Creating a novel herbicide-tolerance *OsALS* allele using CRISPR/Cas9-meidated gene editing. Crop J 9:305–312

Washington Wheat Commission (2021) Washington Wheat Variety Survey. https://wagrains.org/wp-content/uploads/2020/09/2020-WA-Wheat-Variety-Survey.pdf. Accessed: October 2, 2021

Yadav R, Kumar V, Jha P (2020) Herbicide programs to manage glyphosate/dicamba-resistant kochia (*Bassia scoparia*) in glyphosate/dicamba-resistant soybean. Weed Technol 34:1–22

Zand E, Beckie HJ (2002) Competitive ability of hybrid and open-pollinated canola (*Brassica napus*) with wild oat (*Avena fatua*). Can J Plant Sci 82:473–480