Indian Journal of Weed Science **48**(2): 112–116, 2016
DOI: 10.5958/0974-8164.2016.00030.7

Herbicide resistance in cereal production systems of the US Great Plains: A review

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Received: 18 March 2016; Revised: 22 April 2016

ABSTRACT

The US Great Plains comprise the major cereal producing states in the country. In the US, wheat (winter and spring wheat) was grown in 45 million acres in 2014, with a total production of 55 M metric tons. Wheat after chemical fallow (W-F) dominates > 90% of the dryland cropping systems of the Northern Great Plains of the US, where soil moisture (< 300 mm of average annual precipitation) is often the limiting factor for continuous cropping. In the Central Great Plains of the US, wheat–corn/grain sorghum–fallow (W-C/G-F) is a common dryland rotation. An over-reliance on herbicides for weed control in these no-till cropping systems has resulted in weed shifts and escalated cases of resistance evolution in weed populations to single or multiple site-of-action herbicides. Early detection, increased awareness of socio-economic implications of herbicide-resistant weeds, and adoption of diversified weed control tactics would mitigate the further evolution of multiple herbicide-resistant weed biotypes in cereal production systems.

Key words: Cereals, Herbicide resistance, Weed control diversity

The US Great Plains include semi-arid regions bounded by the Mississippi river tall grass prairie on the East and the Rocky Mountains on the West, extending from the Canadian border on the north to Texas on the South. The Great Plains is characterized by hot summer days, an annual precipitation of 300 to 500 mm mostly during the summer, and cold and dry winter (Lenssen *et al.* 2007). The high level of temporal and spatial climate variability, with prolonged and severe drought periods are the major challenges to crop production in this region. This region is dominated by dryland crop production, with wheat being the major crop (Hansen *et al.* 2012). Growers have adopted no–tillage practices for soil moisture conservation in the dryland cropping systems of the region. In the Northern Great Plains, winter wheat after chemical fallow is the major no-till, dryland crop rotation. The purpose of the no-till, chemical fallow in the rotation is to prevent soil erosion, soil nutrient depletion, and more importantly, conserve soil moisture from winter precipitation for successful establishment of the winter wheat crop (Lenssen *et al.* 2007). However, growers in the Central and Southern Great Plains have adopted a relatively more diverse 3-year rotation of winter wheat–corn/grain sorghum–fallow (Hansen *et al.* 2012).

In these no-till systems, there is often a sole reliance on chemical weed control, with multiple post-emergence (PoE) applications of broad-spectrum herbicides, predominantly glyphosate, to obtain season-long weed control in the absence of crop and/or tillage (Fenster and Wicks 1982, Moyer *et al.* 1994). In the wheat–fallow rotation, glyphosate has been widely used to control weeds not only in fallow, but also, prior to crop planting (burndown) and post-harvest (Mickelson *et al.* 2004, Lloyd *et al.* 2011). Each field typically receives three to four applications of glyphosate each year (Kumar *et al.* 2014). Furthermore, this continuous no-till, wheat-based cropping system has resulted in build-up of specialized weed complex, such as wild oat (*Avena fatua* L.), downy brome (*Bromus tectorum* L.), foxtail species (*Setaria* spp.), kochia [*Kochia scoparia* (L.) Schrad], prickly lettuce (*Lactuca serriola* L.) and Russian thistle (*Salsola tragus* L.). Nevertheless, populations of these weed species have evolved resistance to one or more herbicide families (Heap 2016).

Globally, the maximum number of cases of herbicide-resistant weeds have been reported in wheat among all crops (Heap 2016). Glyphosate (burndown), acetyl-COA-carboxylase (ACCase)-inhibitors, acetolactate synthase (ALS)-inhibitors, and synthetic auxins (2,4-D, dicamba, fluroxypyr, MCPA) are the most common herbicide chemistries used in cereal production. This paper, presents specific cases of resistance evolution in the key grass

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This article was presented at the Symposium on "Herbicide Resistance: Current Status and Future Challenges Globally" held as part of the 25th APWSS Conference, Hyderabad, India during 13-16 October, 2015.

and broad-leaved weed species to these site-of-action herbicides in the US Great Plains cereal production systems, and implications for long-term weed management.

Herbicide-resistant weeds in cereals in the US Great Plains

Wild oat: Wild oat biotypes resistant to difenzoquat (thiocarbamate) and triallate (cell elongation inhibitor) have been reported in cereal production fields in Montana, USA in 1990 (Heap 2016). Wild oat resistance to imazamethabenz-methyl (ALS inhibitor) was first reported in North Dakota and Montana in 1996 (Heap 2016). Resistance to mesosulfuron-methyl (ALS-inhibitor) was subsequently documented in South Dakota wheat fields in 2012 (Heap 2016). Wild oat resistance to ACCase inhibitors (graminicides) is widespread across the US Great Plains wheat belt, especially, against diclofop-methyl, clodinafop-propargyl, fenoxaprop-p-ethyl, and tralkoxydim herbicides used in cereals (Heap 2016). Furthermore, wild oat strains with evolved multiple resistance to difenzoquat, imazamethabenz-methyl, flucarbazone (ALS inhibitor), and tralkoxydim is a concern for wheat producers in Montana (Lehnhoff *et al.* 2013). Two of those multiple herbicide-resistant biotypes from Montana were also found to be 17.5- to 18.1-fold more resistant to triallate, 3.6- to 3.7-fold more resistant to pinoxaden, and 3.2-fold more resistant to paraquat compared with the susceptible biotypes (Keith *et al.* 2015). This seriously limits the herbicide options for wild oat control in wheat. Target-site mutations encompassing the ACC gene are known to confer resistance to ACCase-inhibitors. Also, a non-target-site based enhanced metabolism mediated by cytochrome P450 monooxygenases (P450s) conferred resistance to both ACCase- and ALS-inhibitor-resistant wild oat biotypes (Beckie *et al.* 2012, Keith *et al.* 2015).

Green foxtail: Green foxtail resistance to ACCase inhibitors used in cereals including diclofop-methyl, fenoxaprop-P-ethyl, fluazifop-P-butyl, pinoxaden, and also to sethoxydim has been reported in Montana (Heap 2016). There has been an increase in the occurrence of green foxtail populations with resistance to this site-of-action herbicides in wheat fields of this region. An isoleucine–leucine substitution in chloroplastic ACCase conferred resistance to sethoxydim in green foxtail (Délye *et al.* 2002).

Downy brome: Although not documented in wheat, downy brome populations with resistance to imazamox, primisulfuron-methyl, sulfosulfuron, and propoxycarbazone-sodium (ALS inhibitors) have been reported from Oregon, USA (Mallory-Smith *et al.* 1999, Park and Mallory-Smith 2004). Downy brome biotypes with resistance to clethodim, fluazifop-P-butyl, quazalofop-P-ethyl, and sethoxydim have also been documented (Ball *et al.* 2007). Resistance evolution in downy brome to ALS inhibitors used in winter wheat would be a serious concern for growers in this region. A single point mutation at the Pro197 (amino acid substitution from proline to serine) conferred cross-resistance to sulfonylurea and sulfonylaminocarbonyltriazolinone (SCT) herbicides in downy brome biotypes from Oregon (Park and Mallory-Smith 2004).

Prickly lettuce: Prickly lettuce biotypes resistant to chlorsulfuron, imazethapyr, metsulfuron-methyl, thifensulfuron-methyl, triasulfuron, and tribenuron-methyl have been reported in Idaho, Washington, and Oregon wheat fields; first case documented in 1987. Biotypes cross-resistant to synthetic auxins including 2,4-D, dicamba, and MCPA have also been reported in cereal production fields in Washington (Riar *et al.* 2011, Heap 2016). Reduced absorption and translocation of 2,4-D conferred resistance to the herbicide in a prickly lettuce biotype from Washington, USA (Riar *et al.* 2011).

Russian thistle: Russian thistle has developed resistance to ALS inhibitors used in wheat. Chlorsulfuron-resistant Russian thistle was first identified in Montana in 1987. Russian thistle is one of the predominant broad-leaved weeds in the no-till, wheat–fallow system. At maturity, the plant develops into a globose-elliptical shape, referred to as “tumbleweed” (Young *et al.* 2008). Glyphosate and 2,4-D were effective for Russian thistle control (Young *et al.* 2008), however, there is an enhanced selection pressure for resistance development in this weed species due to repeated use of these herbicides in wheat-based cropping systems of this region. The first global case of glyphosate-resistant Russian thistle has recently been reported in Montana from a wheat–chemical fallow field in Choteau County (Heap 2016, Jha and Kumar, unpublished data); the biotypes were also found resistant to ALS inhibitors. Glyphosate-resistant Russian thistle has also been found in Washington, USA in 2015 (Drew Lyon, personal communication). Two target-site mutations: $Trp_{574}Leu$ and $Pro_{197}Gln$ endowed resistance to ALS inhibitors in Russian thistle biotypes from the western Canada cereal production region (Warwick *et al.* 2010).

Kochia: Increased occurrence of kochia populations resistant to multiple herbicide chemistries is a serious challenge for cereal producers in the US Great Plains (Jha *et al.* 2015). Resistance of kochia to atrazine (PS II inhibitor) was first confirmed in 1976 in Kansas, USA, and it was subsequently reported in other Great Plains' states, including Montana (Heap 2016). Since 1989, there has been a widespread occurrence of kochia biotypes resistant to sulfonylurea herbicides, predominantly in the cereal-based cropping systems of this region (Heap 2016). Dicamba-resistant kochia was first found in 1994 in northern Montana wheat fields, and it now occurs in North Dakota, Idaho, Nebraska, and Colorado, USA (Jha *et al.* 2015, Heap 2016). The problem is further exacerbated because of the evolution of glyphosate-resistant kochia, first reported in western Kansas in 2007, and recently in ten other states; a potential threat to the no-till, cereal production in the US Great Plains (Kumar *et al.* 2014, Heap 2016). Kochia with evolved multiple resistance to four herbicide sites of action (glyphosate, dicamba, atrazine, and ALS inhibitors), reported in Kansas, seriously limits herbicide options to control this weed (Varanasi *et al.* 2015). A novel mechanism of glyphosate resistance *i.e.,* 5-enolypyruvyl-shikimate-3-phosphate synthase (EPSPS) gene amplification (2- to 14-folds increase in EPSPS: ALS gene copies in resistant relative to a single copy of the gene in the susceptible biotypes) confers resistance to glyphosate in kochia (Kumar *et al.* 2015a). Target-site mutations at Pro_{197}, Asp_{376}, and Trp_{574} loci of the *ALS* gene confers resistance to ALS inhibitors in kochia (Warwick *et al.* 2008, Kumar *et al.* 2015)

Herbicide resistance management in cereals

The best management practices (BMPs) for herbicide resistance (HR) management in weeds are established on the concept of 'diversity'. Norsworthy *et al.* (2012) stated – "Reducing herbicide selection pressure by adopting diversified weed control tactics, reducing the spread of resistance alleles by pollen or seed, and preventing weed seed bank additions are the key strategies to mitigate HR". Producers are often reluctant to adopt proactive HR management programs because they are more interested in short-term economic gains and lack awareness or education on the economic risks of HR until it evolves in their production fields (Beckie 2006). Although herbicides will continue to be the dominant weed control tool in the US cereal production, farmers should not anticipate many new site-of-action herbicides to be commercialized in the near future (Duke 2012).

Multiple, effective modes of action and pre-emergence (PRE) soil-residual herbicides will serve as a foundation for the HR weed management programs in cereals (Kumar and Jha 2015a). However, it should be noted that the persistence of soil-residual herbicides in high pH and low organic matter soils is the major constraint for diversifying crop rotations in the semi-arid US Great Plains. Although limited PRE herbicide options are available in wheat, growers should utilize products such as sulfentrazone or metribuzin, labelled in pulse crops such as pea, chickpea, or lentil, to obtain effective residual control of herbicide-resistant populations of kochia and Russian thistle in wheat–pulse rotation (Kumar and Jha 2015a). Glyphosate-resistant kochia seed bank in the fallow should be proactively managed in the rotational wheat crop with alternative, effective modes of action (applied as tank mixtures), such as bromoxynil + MCPA, pyrasulfotole + bromoxynil, dicamba + fluroxypyr, fluroxypyr + bromoxynil. The objective of the HR management programs should be to prevent seed set and replenishment of the weed seedbank. Paraquat + atrazine, linuron, or metribuzin, and saflufenacil + 2,4-D could be effective, alternative postharvest herbicides (multiple modes of action) in wheat for late-season control and seed prevention of glyphosate-resistant kochia (Kumar and Jha 2015b). It is to be further noted that using multiple, effective site-of-action herbicides is more effective than herbicide rotation in mitigating HR evolution in weed species through herbicide selection (Beckie and Rebound 2009).

An integrated weed management (IWM) approach for mitigating HR needs to be implemented in cereal production systems. For instance, integration of pulse crops into the wheat-fallow rotation would add weed control diversity in dryland cropping systems of the US Great Plains. The ACCase-resistant populations of grass weeds (wild oat and green foxtail) in wheat could be controlled by herbicides not selective in wheat, but labelled for use in the pulse crops grown in rotation. Nonselective herbicides, such as glyphosate or glufosinate, could potentially manage grass weed populations with metabolism-based resistance to ACCase and/or ALS-inhibitors (Beckie *et al.* 2012).

Tillage is an important component of IWM programs (Norsworthy *et al.* 2012). A shallow tillage using wide blades or sweeps can be used to control weeds during summer fallow, with minimum soil disturbance. Also, a shallow burial through minimum tillage can potentially reduce the seed-bank of smallseeded weed species, such as kochia, which cannot emerge from soil depths below 10 mm and exhibits low seed dormancy and persistence in the soil (seed persistence of 1 to 2 years) (Anderson and Nielsen 1996, Schwinghamer and Van Acker 2008). Additionally, legume green manures or cover crop mixtures have recently been investigated in the semi-arid dryland cereal production regions of the Western US as a fallow substitute (wheat–cover crop), for increased soil health and productivity (Miller *et al.* 2015). This can also reduce reliance on multiple applications of burndown herbicides such as glyphosate and 2,4-D in fallow, thereby, minimizing the selection pressure for HR development in weed species.

Successfully managing HR would require collaboration and information from multiple disciplines, including applied weed science, evolutionary biology, population genetics, molecular biology and biochemistry, physiology, and ecology. Additionally, economics, sociology and other social sciences would play an important role on growers' decision making and adoption of integrated HR weed management programs and changed farming practices at a community level (Ervin and Jussaume 2014). There needs to be an active, strong linkage between innovation, adoption, and diffusion of new weed control technologies and changed farming practices. Switching to new HR-stacked-trait crop technologies may not be the ultimate, long-term weed management solution, unless 'holistic approaches' for innovation, adoption, and diffusion of these new technologies are adopted. Precision weed control technologies using advanced optics such as light-activated sensor-controlled (LASC) sprayers (Weed Seeker) and hyperspectral imaging to differentiate plants, unmanned aerial vehicle (UAV)-automated sprayers and robotics, would play a crucial role in weed management in the near future.

In conclusion, less-frequent selective herbicide use, non-herbicidal tactics, and weed control diversity at a cropping systems level, can mitigate the evolution, spread, and economic impact of HR weeds in cereal production systems.

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