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# Weed management using crop competition in the United States: A review

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## A B S T R A C T

Exploiting the competitive ability of crops is essential to develop cost-effective and sustainable weed management practices. Reduced row spacing, increased seeding rates, and selection of competitive cultivars can potentially manage crop–weed competition in cotton, soybean, wheat, and corn. These cultural weed management practices facilitate a more rapid development of crop canopy that adversely affect the emergence, density, growth, biomass, and subsequently the seed production of weeds during a growing season. These cultural practices can also favour the weed suppressive ability of the crop by influencing the canopy architecture traits (plant height, canopy density, leaf area index, rate of leaf area development, and leaf distribution). These crop-competition attributes can potentially reduce the risk of crop yield losses due to interference from weed cohorts that escape an early- or a late-season post-emergence herbicide application. Furthermore, reduced row spacing, increased seeding rates, and weed-competitive cultivars are effective in reducing reliance on a single site-of-action herbicides, thereby reducing the selection pressure for development of herbicide-resistant weed populations in a cropping system.

## 1. Introduction

Weeds adversely affect the crop growth and yield by competing with crops for limiting resources such as light, water, and nutrients (Harper, 1977; Swanton et al., 2015). The intensity and duration of the crop-weed competition determines the magnitude of crop yield losses (Swanton et al., 2015). Avoiding or reducing crop yield losses due to weed competition requires the utilization of diverse and effective weed management programs (Chauhan and Opeña, 2013; Swanton et al., 2015). Herbicides are the dominant tools used for weed control in global agriculture, and an annual worldwide herbicide sale is estimated to be US \$27 billion (Kraehmer, 2012). As an outcome, the over reliance on the same-site-of-action herbicide in a cropping system has resulted in an increased development of herbicide-resistant (HR) weed populations worldwide (Heap, 2016). Globally, the US ranks first, with more than 150 unique

cases of HR weed evolution, followed by Europe and Australia (Heap, 2016). Commercialization of glyphosate-resistant (GR) trait in soybean [(*Glycine max* (L.) Merr.) (1996), cotton (*Gossypium* spp.) (1997), and corn (*Zea mays* L.) (1998) in the US, and its increasing use for weed management in these GR crops (Duke and Powles, 2009) has resulted in evolution of 15 GR weed species over the last 20 years in the North America (Johnson et al., 2009; Beckie et al., 2014; Kumar et al., 2014, 2015; Heap, 2016). In addition, HR weed populations have also been reported in wheat (*Triticum aestivum* L.) grown in the US (Heap, 2016). Insurgent reports on HR weed populations pose a serious threat to the sustainability of the US cropping systems. Moreover, an increasing cost of managing HR weeds in the absence of any new site-of-action herbicide discovery over the last two decades further exacerbates the problem (Duke, 2012). Current data and future projections on HR weeds strongly suggest the need for development and implementation of integrated weed management (IWM) strategies in cotton, corn, soybean, and wheat to curb the resistance problem (Norsworthy et al., 2012; Vencill et al., 2012).

Developing cost-effective and sustainable weed management strategies further necessitates the in-depth understanding of

concepts and factors involved in crop-weed competitive interactions (Blackshaw et al., 2000; Swanton et al., 2015). The competitive ability of a crop depends on various physiological and morphological attributes that allow the crop to utilize light, water, nutrients, and other limited resources effectively in the presence of the weed pressure. A variety of cultural practices such as crop planting dates, competitive cultivars, seeding rates, row widths, cover crops, nutrient management, and irrigation strategies can manage crop-weed competition and favour the crop competitiveness against weeds (Chauhan and Opeña, 2013; Swanton et al., 2015). Furthermore, the use of reduced crop row spacing, increased seeding rates, and competitive cultivars in a cropping system can potentially minimize reliance on herbicides with the same site of action and manage HR weed seed banks (Norsworthy et al., 2012; Vencill et al., 2012). In the U.S., soybean, cotton, corn, and wheat account for more than 70% of all crop acres planted annually (Price et al., 2011). Therefore, the aim of this review article is to highlight the importance of weed management using crop competition through manipulations in crop row spacing and seeding rates and use of competitive cultivars in these crops grown in the US.

## 2. Row spacing

### 2.1. Cotton

Traditionally, cotton in the US is grown in wide rows spaced 76- to 102-cm apart. The concept of Ultra Narrow Row (UNR) spacing originated in 1990s, with cultivation of cotton in narrow rows (twin rows) with a spacing of 19–38 cm (Reddy, 2001; Wilson et al., 2007). The UNR system allows the use of higher seeding rates of cotton per unit area. The major goals of adopting the UNR cotton system are to reduce production cost, improve weed control, and increase yield as well as economic return by increasing the plant population (Parvin et al., 2000; Nichols et al., 2004). Early and rapid canopy closure under the UNR cotton system also helps conserve soil moisture and suppress weeds early in the season (Reddy, 2001; Molin et al., 2004). Several studies conducted in the US have shown a mixed response on weed control under the UNR vs. the traditional wide row (76–102 cm) cotton production system (Parvin et al., 2000; Bryson et al., 2003; Molin et al., 2004). Rogers et al. (1976) reported that only 6 weeks of weed-free period was needed to obtain high yields in cotton grown in narrow rows (53 cm); whereas, 10–14 weeks of weed-free period was required to obtain similar yields in wide rows (79–106 cm). A four-year study showed that *Sida spinosa* L. under the UNR cotton system had 74–82% less total dry weight, and 71–90% less number of capsules per plant, compared with the wide row cotton system (Molin et al., 2004). The study also reported a 67–85% decline in the total dry weight plant<sup>-1</sup> of *Euphorbia hyssopifolia* L. under the UNR vs. the wide row cotton system (Molin et al., 2004). Stephenson and Brecke (2010) found that cotton planted in 19-cm twin rows, with each set of twin rows being 76-cm apart, had greater control of *Commelina benghalensis* L., *Senna obtusifolia* L. Irwin & Barneby, and *Jacquemontia tamnifolia* L. compared with the single-row (76 cm apart) planting pattern of cotton. In addition, the end-season total weed dry biomass was reduced by 35% in the twin-row (two rows 38 cm apart on 102-cm beds) compared to the single-row (on 102-cm beds) cotton planting system (Reddy and Boykin, 2010). Aulakh et al. (2011) observed that sequential post-emergence applications of pyriithiobac at 2- to 4-leaf stages of conventional cotton increased the *S. obtusifolia* control in 38-cm compared to 102-cm wide rows. In contrast, Miller et al. (1983) observed no differences in total density of grass or broadleaf weed species with tillage plus trifluralin and prometryn, and tillage plus trifluralin and

fluometuron treatments, in cotton grown under narrow (51 cm) vs. wide (102 cm) rows. Similarly, a minimal effect on annual grass and broadleaf weed control was observed with various pre-emergence followed by post-emergence herbicide programs in glufosinate-resistant cotton planted in 38-cm vs. 97-cm rows (Wilson et al., 2007).

### 2.2. Soybean

Numerous studies conducted in the US have reported the potential benefits of the narrow-row spacing on weed management in soybean. The benefits are mainly attributed to the early canopy closure in the soybean planted in narrow (19- or 38-cm wide) that enhances the competitive ability of the crop against weeds, compared to wide (76 cm or more) rows (Steckel and Sprague, 2004; Jha et al., 2008; Jha and Norsworthy, 2009). Shibles and Weber (1966) reported that the 95% solar light interception occurred 17 d earlier in the 25-cm wide rows compared to the 102-cm wide rows. In addition, soybean canopy closure occurred 40 d earlier in soybean planted in 25-cm vs. 76-cm wide rows (Mickelson and Renner, 1997). Reducing soybean row spacing from 76 to 19 cm delayed the critical timing of weed control (CTWR) from the first-trifoliolate to the third-trifoliolate stage of soybean, indicating enhanced weed competitive ability of the narrow-row soybean (Knezevic et al., 2003). Reducing the soybean row spacing from 91 to 23 cm reduced the weed density from 16 to 2 plants m<sup>-2</sup> and the aboveground biomass from 141 to 33 g m<sup>-2</sup> (Yelverton and Coble, 1991). There was a greater control of *Setaria faberi* Herrm. and *Amaranthus rudis* Sauer., and an increase in soybean yield in the GR soybean planted in narrow (19- or 38-cm) vs. wide (78-cm) rows (Young et al., 2001). Similar results on the suppressive effect of the narrow-row soybean on weed density and biomass were evident for several other weeds including, other *Amaranthus* species, *Chenopodium album* L., *S. obtusifolia*, *Ipomoea* species, *Xanthium strumarium* L., and *Ambrosia artemisiifolia* L. which are predominant in the US soybean production (Legere and Schreiber, 1989; Mickelson and Renner, 1997; Buehring et al., 2002; Steckel and Sprague, 2004; Hock et al., 2006; Harder et al., 2007). A single application of glyphosate at the V3 stage of soybean eliminated seed production from *Amaranthus palmeri* S. Wats plants in 19-cm soybean rows, compared with 600 seeds m<sup>-2</sup> produced by plants grown in 97-cm soybean rows (Jha et al., 2008). Furthermore, in majority of these studies, soybean yields were greater in narrow compared to wide rows.

A dense canopy of soybean when planted in narrow rows (19 cm) resulted in decreased photosynthetic active radiation (PAR) and red/far-red ratio of light available to seed on or near the soil surface under no-tillage conditions (Norsworthy, 2004). This resulted in reduced emergence of *X. strumarium*, *S. obtusifolia*, and *A. palmeri* by 33, 68, and 76%, respectively, in plots in the presence compared to those in the absence of soybean (Norsworthy, 2004; Jha and Norsworthy, 2009). Thus, the early canopy formation trait of narrow-row soybean can potentially reduce weed resurgence and reduce reliance on multiple post-emergence glyphosate applications in GR soybean (Steckel and Sprague, 2004; Jha et al., 2008).

### 2.3. Wheat

There is relatively limited research conducted in the US on assessing the effect of row spacing on crop-weed competition in wheat. Nalewaja and Arnold (1970) reported that reducing the row spacing could enhance the wheat competitiveness against weeds, and improve wheat yields. There was a 12% increase in the yield of hard red winter wheat, with a decrease in the row spacing from 23

to 7.5 cm in a field infested with *Bromus secalinus* L. (Solie et al., 1991). Koscelny et al. (1990) found a 20% increase in wheat yield and a 16% reduction in seed yield of *B. secalinus*, with a decrease in wheat row spacing from 23 to 8 cm. Similarly, reducing the wheat row spacing from 30 to 10 cm decreased *Aegilops cylindrica* Host. spikelet yield from 513 to 391 kg ha<sup>-1</sup> (Kelley, 1998). Increased wheat yield and competitiveness in wheat planted in narrow rows were due to an increase in the number of tillers per unit area (Koscelny et al., 1990). A delayed canopy closure in wheat planted with wider row spacing provides opportunity for emergence of late-season weed cohorts and substantial late-season weed competition, resulting in reduced grain yield (Koscelny et al., 1990; Kelley, 1998). A narrow (11–15 cm) compared to a wide row (23 cm) spacing can result in a more uniform plant distribution, growth, leaf and root architecture of wheat plants, allowing them to more efficiently utilize PAR and available water and nutrients from the soil (Koscelny et al., 1990; Kelley, 1998). In the northeastern Missouri, US, light interception and leaf area index of wheat were greater when planted in 19-cm than in 38-cm wide rows (Sandler et al., 2015).

#### 2.4. Corn

Studies conducted in the US have documented the superior weed suppression ability and yield of corn planted in narrow rows (19 or 38 cm) vs. wide rows (76 cm) (Teasdale, 1995; Murphy et al., 1996; Dalley et al., 2004). Early canopy closure and increased shading of weeds resulted in an increased crop competitiveness and a reduced weed growth in narrow-vs. wide-row corn (Teasdale, 1995; Dalley et al., 2004). In a 3-year field study, Murphy et al. (1996) reported a 20% less weed biomass production in the corn planted in 50-cm compared to 75-cm wide rows, implying a greater competitive ability of corn planted in narrow rows. Up to 60% reductions in weed biomass have been reported in corn planted in 38-cm vs. 76-cm row spacing (Shrestha et al., 2001; Tharp and Kells, 2001). Furthermore, narrow rows (38 cm) coupled with a higher plant population (90,000 to 124,000 plants ha<sup>-1</sup>) resulted in an adequate weed control even at the reduced rates of herbicides in corn (Teasdale, 1995). The risk of yield loss due to weed interference from the delayed post-emergence glyphosate treatment in GR corn was reduced when the corn was planted in 38-cm vs. 76-cm row spacing (Dalley et al., 2004). In a study conducted in Michigan, US, corn row spacing did not affect grain yield; nevertheless, a more efficient utilization of soil moisture by corn plants grown in competition with *C. album* and *S. faberii* was evident in 36-cm compared to 76-cm rows (Dalley et al., 2006). However, a little to no effect of row spacing on corn-velvetleaf competition was reported (Teasdale, 1998). Similarly, the row spacing had no effect on emergence or growth of weeds and the critical period of weed control (CPWC) in corn, especially at high weed densities (Johnson and Hoverstad, 2002; Dalley et al., 2006). Environmental conditions, weed density, species composition, and herbicide application timings can potentially mask the effect of row spacing on crop-weed competition (Hall et al., 1992; Dalley et al., 2006).

### 3. Seeding rate

#### 3.1. Cotton

There is a limited research conducted on the effect of cotton seeding rates on crop-weed competition in the US. In a study conducted in Florida, US, control of *C. benghalensis* and *S. obtusifolia* increased with an increase in the cotton density from 7 to 26 plants m<sup>-2</sup> under low levels of weed management (glyphosate plus S-metolachlor) (Stephenson and Brecke, 2010). However, the effect of

cotton density on weed control was not evident at the medium [glyphosate + S-metolachlor followed by (fb) glyphosate] and high (glyphosate + S-metolachlor fb glyphosate fb MSMA + prometryn) weed management inputs (Stephenson et al., 2011). Total nodes, plant height, and total bolls per plant of cotton decreased with an increase in cotton density from 7 to 15 plants m<sup>-2</sup> (Stephenson et al., 2011); nevertheless, the planting density had a minimal effect on cotton seed and lint yield and on fiber quality (Jones and Wells, 1997; Stephenson et al., 2011). A planting density of 13 plants m<sup>-2</sup> in a single-row planting pattern was needed to obtain similar yield and weed control provided by a twin-row cotton planted at 7 plants m<sup>-2</sup> (Stephenson and Brecke, 2010).

#### 3.2. Soybean

Seeding rate is an important cultural practice that influences the crop-weed competition, thereby influencing weed management (Nice et al., 2001; Arce et al., 2009). Increasing the soybean-seeding rate from 124,000 to 494,000 seeds ha<sup>-1</sup> reduced weed interference and increased soybean yield by 48% (Oplinger and Philbrook, 1992; Harder et al., 2007; Arce et al., 2009). Nice et al. (2001) also reported a reduction in the density and biomass of *S. obtusifolia* and *Solanum ptycanthum* L. with an increase in soybean population from 245,000 to 481,000 or 676,000 plants ha<sup>-1</sup> in the narrow rows. Similar suppressive effects of increased seeding rates on crop-weed competition have been reported for several other problem weed species in soybean, including *Solanum ptycanthum* L., *Ipomoea lacunosa*, *Sesbania exaltata* (Raf.) Cory., *Amaranthus* species, and *S. obtusifolia* (Buehring et al., 2002; Norsworthy and Oliver, 2002a, 2002b; Rich and Renner, 2007; Place et al., 2009).

An early canopy development is an important component of cultural weed control in soybean (Buehring et al., 2002; Norsworthy and Oliver, 2002a, 2002b; Jha et al., 2008). An increase in the seeding rate from 148,200 to 469,300 seeds ha<sup>-1</sup> increased the cumulative intercepted photosynthetic active radiation (CIPAR) during the critical period of weed control (CPWC) in soybean by 76–172% (DeWerff et al., 2014). An early canopy development with an increase in soybean population from 247,000 to 729,000 plants ha<sup>-1</sup> improved *I. lacunosa* and *S. exaltata* control by >30%, with a glyphosate application at the V2 stage of GR soybean (Norsworthy and Oliver, 2002a). Also, a lack of complete canopy formation at the time of an early post-emergence application of glyphosate in GR soybean increased the risk of late-season weeds and consequent crop yield loss; the effect was more pronounced in soybean planted at 240,000 and 300,000 compared to 420,000 seeds ha<sup>-1</sup> (Arce et al., 2009). A greater competitiveness of soybean planted at a high density can not only suppress late-emerging weed cohorts, but also those that survive an early-season post-emergence herbicide treatment (Young et al., 2001). This could potentially improve the consistency of weed management and reduce reliance on post-emergence herbicides for weed control (DeWerff et al., 2014).

#### 3.3. Wheat

Several researchers in the US have documented the benefits of increasing seeding rate or plant density on increased competitive ability of wheat against weeds. For instance, a four-year study concluded that increasing the seeding rate of wheat from 50 to 300 kg ha<sup>-1</sup> reduced the *Erodium cicutarium* L. biomass by 53% and seed production of *E. cicutarium* by 95%, and increased wheat yields by 56–498% over the four years of the study (Blackshaw et al., 2000). *Avena fatua* and *Aegilops cylindrica* are the most troublesome weeds in wheat production systems in the Great Plains and Pacific Northwest regions of the US (Heap, 2016). In Montana, US,

increasing the spring wheat seeding rate from 175 to 280 plants  $m^{-2}$  increased the wheat grain yield by 12% and reduced the biomass and seed production of *Avena fatua* L. by 20% (Xue and Stougaard, 2002; Stougaard and Xue, 2004). Similarly, Carlson and Hill (1985) observed an increase in competitive ability of wheat against *A. fatua* and up to 23% increase in grain yield, by increasing the wheat density from 175 to 700 plants  $m^{-2}$ . An increase in winter wheat population density from 40 to 60 plants  $m^{-1}$  row also reduced *A. cylindrica* biomass by 27%, weed head density by 37%, and weed spikelet biomass by 47% (Yenish and Young, 2004). In a study conducted in Maine, US, increasing the spring wheat planting density from the standard practice of 400 plants  $m^{-2}$  to 600 plants  $m^{-2}$  reduced *Sinapis alba* L. density by 30%; nevertheless, it reduced the grain protein by 5% (Kolb et al., 2012). Optimizing the wheat seeding rate is, therefore, also important from a grain quality standpoint (Kolb et al., 2012). With a limited information available from the US, some insights can be gained from other countries. In UK and Europe, higher wheat seeding rates enhanced the flag-leaf senescence and negatively affected the grain-filling stage and protein concentration in the wheat kernels (Gooding et al., 2002). In addition, high seeding rates can reduce wheat grain protein due to an increased intraspecific competition for available soil nitrogen (Gooding et al., 2002; Arduini et al., 2006).

#### 3.4. Corn

Several studies conducted in the US demonstrated the importance of seeding rate as a cultural weed management tool in corn production. Increasing the corn seeding rates enhanced the corn leaf area and rate of canopy closure, which further improved the ability of corn plants to suppress *Abutilon theophrasti* Medik., one of the major problem weeds in corn production in the US (Lindquist et al., 1998). Corn planted at a high density (100,000 plants  $ha^{-1}$ ) in 38-cm narrow rows reduced early-season weed interference, and also aided in controlling late-emerging weed cohorts (Shrestha et al., 2001). Weil (1982) observed a negative correlation between corn plant density and total weed biomass accumulation. The greater competitiveness and an early canopy development by increasing the population density of corn reduced the biomass of late-emerging weed cohorts by 41% (Murphy et al., 1996; Williams and Boydston, 2013). Similarly, an increase in corn density reduced canopy-transmitted photosynthetic photon flux density (PPFD), and consequently the total dry matter accumulation (reduced by 89%) of *Amaranthus retroflexus* L. (McLachlan et al., 1993). Furthermore, corn-induced shading caused a relatively greater allocation of dry matter to main stem than to branches of *A. retroflexus*, thereby influencing the weed canopy architecture (McLachlan et al., 1993). Teasdale (1998) observed a 99% reduction in seed production of *A. theophrasti* in corn planted at 128,000 compared to 64,000 plants  $ha^{-1}$  seeding rate. Increasing the corn population from 59,300 to 72,900 plants  $ha^{-1}$  reduced weed seed production by 50% and improved corn yields (Tharp and Kells, 2001). Williams and Boydston (2013) also observed a decline from 72 to 27% in seed production of *Panicum miliaceum* L. with an increase in corn seeding rate from 35,000 to 105,000 seeds  $ha^{-1}$ , respectively.

### 4. Competitive cultivars

#### 4.1. Cotton

Only a few field studies have been conducted in the US to test the weed competitive ability of cotton cultivars. Like corn and soybean, the differential competitive ability of cotton cultivars is associated with differences in canopy development characteristics

and time of maturity (Andries et al., 1974; Chandler and Merredith, 1983). Andries et al. (1974) evaluated three near-isogenic strains of cotton including okra-, super okra-, and normal-leaf type, under three different row spacings (25-, 50-, and 100-cm rows), and with various combinations of trifluralin and flumeturon for weed control and observed that okra or normal-leaf type cotton had a better late-season weed control than the super okra-leaf strain. Chandler and Merredith (1983) found that the early-maturing cotton cultivar ('DES 21326-04') was less tolerant to early-season competition from *Anoda cristata* (L.) Schlecht than the late-maturing cultivar (Deltapine 16 or Stoneville 213). However, Bridges and Chandler (1987) reported no differences in the weed competitive ability between three cotton cultivars ('1209-619-7', 'TAMCOT SP37-H', and 'Stoneville 213') with different plant heights, when grown in competition with *Sorghum halepense* (L.) Pers. at increasing densities.

#### 4.2. Soybean

Soybean cultivars grown in the US are divided into different maturity groups, from Group 0, best adapted to region north of 46°N, to Group IX, best adapted to southern regions like southern Florida and Texas (Zhang et al., 2007). Soybean cultivars can differ in their ability to compete with annual grass and broadleaf weeds, and can adapt to different environments by changes in plant morphology, canopy architecture, and yield variables (Burnside, 1972; McWhorter and Hartwig, 1972). Bussan et al. (1997) observed differences in weed competitive abilities between 16 soybean genotypes that were mostly associated with the differences in canopy architecture, height, and volume of the plants. For instance, a greater biomass reduction in *S. obtusifolia* occurred in the presence of taller soybean cultivars (maturity Group VI) (Shilling et al., 1995). Similarly, the tall soybean cultivars being more competitive, reduced seed production and seed weight of *I. lacunosa* by 48 and 38%, respectively, compared to the short cultivars (Bennett and Shaw, 2000). Jordan (1992) found that the short-statured soybean cultivars reduced *X. strumarium* growth early in the season, while the tall cultivars had a greater suppressive effect on the weed growth late in the season. Late-maturing soybean cultivars had earlier emergence, greater seedling vigour, more rapid canopy development, and a greater competitive ability against *A. theophrasti* and *Setaria italica* (L.) Beauv. compared with the early-maturing cultivars (Rose et al., 1984; Nordby et al., 2007). In contrast, early-maturing soybean cultivars reduced seed production and seed weight of *I. lacunosa* by 76 and 49%, respectively, compared with the late-maturing cultivars by allowing harvest before the physiological maturity of the weed (Bennett and Shaw, 2000). However, James et al. (1988) observed a lack of consistent effect of cultivar selection on *S. obtusifolia* interference in soybean. Similarly, Monks and Oliver (1988) did not find differences in grain yield or weed biomass between the soybean cultivars, 'Forrest' (Group V cultivar) and 'Centennial' (Group VI cultivar). Rose et al. (1984) proposed that soybean cultivars with a weed suppressive ability through allelopathy would be an added advantage to growers.

#### 4.3. Wheat

Competitive cultivars apparently offer a cheap tool to consider in IWM programs. The efficiency of light interception by a particular crop cultivar contributes to its competitive ability against weeds (Holt, 1995). Crop cultivars that rapidly shade the soil surface are more competitive in suppressing the weed growth than the slow growing cultivars (Holt, 1995). Plant height, tiller number, early vigour, and leaf size strongly correlate with the suppressive

ability of a wheat cultivar against weeds (Blackshaw et al., 1981; Mason et al., 2007). Tall spring wheat cultivars ( $\geq 83$  cm in height) were found to have a more pronounced suppressive effect on weeds than the shorter cultivars (73–78 cm) (Blackshaw et al., 1981; Wicks et al., 1986). Tall, hard red winter wheat cultivar ‘Turkey’ ( $>90$  cm tall with higher number of stems/tillers  $m^{-2}$ ) was found to be the most competitive wheat cultivar for suppressing annual grasses including *Bromus tectorum* L. in wheat production in Nebraska, US (Challaiah et al., 1986; Wicks et al., 2004). Similarly, taller, soft winter wheat cultivars had a greater grain yield and a lower seed production of *A. cylindrica*, when grown in competition (Ogg and Seefeldt, 1999). Among the eight different winter wheat cultivars tested in competition with *A. cylindrica* and *B. secalinus*, the two shorter cultivars (‘TAM 107’ and ‘2180’) were the least competitive (Kelley et al., 1999). The greater weed suppressive ability of the taller cultivars was due to their greater ability to intercept PAR (Kelley et al., 1999). In contrast, 14–30% more grain yield reductions in shorter compared to taller winter wheat cultivars occurred in the presence of the season-long interference from *B. tectorum* (Blackshaw, 1994). There was also a negative relationship between wheat plant height and *B. tectorum* seed yield (Challaiah et al., 1986). In addition, the ability of competitive cultivars to reduce the fecundity of a weed species should be an important consideration for managing weed seed banks and reducing reliance on herbicides.

#### 4.4. Corn

Differences in weed suppression ability among genotypes is an important trait exploited both in conventional and modern corn cultivars. Plant height, canopy density, leaf area index, leaf uprightiness, rate of leaf area development, and leaf distribution are the important canopy architecture traits that can determine the crop tolerance to weed interference (Lindquist et al., 1998; Lindquist and Mortensen, 1998; Sankula et al., 2004). So et al. (2009) tested 25 commercial sweet corn hybrids in the presence of *P. miliaceum* competition, and revealed that the canopy architecture was positively associated with the competitive ability of the hybrids. On the other hand, Staniforth (1961) found an early-maturing corn hybrid to be more tolerant to a high density of *Setaria glauca* (L.) Beauv compared with a late-maturing hybrid. Begna et al. (2001) also observed that early-maturing, leafy reduced stature (LRS) and conventional Pioneer (‘P3979’) corn hybrids, had 29–44% less total weed biomass compared with the late-maturing, big leaf (LMBL) corn hybrids, when grown under a high weed pressure. Furthermore, the differential yield loss in response to a high weed density of a modern vs. old corn hybrid was due to the differences in leaf area index, late-season PPFD, and nitrogen-use efficiency between the two hybrids (Tollenaar et al., 1994). Concerning reductions in weed biomass and fecundity, the corn hybrid ‘GH2547’ was 25–31% and 70–91% more competitive than the ‘Spirit’ hybrid against *P. miliaceum* in trials conducted in Washington and Illinois, respectively (Williams et al., 2008). Lindquist and Mortensen (1998) observed a greater reduction in the number of capsules of *A. theophrasti* by old-corn compared to modern-corn hybrids. In another study, it was reported that the ‘Pioneer 3260’ corn hybrid with a horizontal leaf architecture, had lower weed density, weed biomass, intercepted PAR, and weed seed production, compared to the ‘Pioneer 3394’ corn hybrid, with an upright leaf architecture (Sankula et al., 2004).

#### 5. Conclusions

The high rate of adoption of transgenic GR soybean, cotton, and corn in the US since 1996, has meant unprecedented and often an

exclusive use of this relatively simple, reliable, and cost-effective glyphosate-based weed control in these crops. Consequently, there are now evolved GR populations of *A. palmeri*, *A. artemissifolia* L., *Ambrosia trifida* L., *Amaranthus rudis* JD Sauer, and various *Conyza* and *Lolium* spp. in the US corn, soybean, and cotton production (Heap, 2016). As GR-crop technology will dominate and remain popular with growers, it is anticipated that other GR weeds will evolve in the near future, posing a greater risk to the sustainability and continued success of glyphosate and GR crops. It is to be noted that GR weeds are not yet a problem in many parts of the world, and lessons can be learnt to add weed control diversity by adopting ecological weed management approaches, thereby, maintaining the sustainability of glyphosate and GR crops for future harvests.

Ecological weed management strategies including reduced row spacing, higher seeding rates, and competitive cultivars can provide an early-season competitive advantage to the crop, facilitate an early crop canopy development, and maximize the resource utilization by the crop to reduce weed density, biomass, and seed bank additions. These strategies can potentially manage crop-weed competition in cotton, soybean, wheat, and corn. These crop competition variables can be used as an integral component of the best management practices to reduce herbicide usage and minimize herbicide selection pressure for the evolution of HR weed populations in farm fields. Reduced row spacing, increased seeding rates, and competitive cultivars can be potentially integrated into the current glyphosate resistance management programs to reduce survival and fecundity of GR weeds in GR corn, soybean, or cotton production systems; however, there is a limited research on understanding how these cultural weed control strategies relate to management of GR weeds. Future research efforts should also explore the allelopathic potential of competitive cultivars to suppress weeds in an agroecosystem.

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