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Managing weeds using crop competition in soybean [*Glycine max* (L.) Merr.]

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ABSTRACT

Soybean (*Glycine max* (L.) Merr.) is an important crop worldwide for both protein meal and vegetable oil. Soybean accounts for more than 50% of the global oilseed production. Weed infestation is a complex and regular threat to soybean production all over the world. To combat this threat, chemical, mechanical, and cultural methods are generally used. There has been a revived interest in weed suppression through improved crop competitiveness as an alternative aid in weed management. Different approaches could be utilized to increase crop competitiveness such as adjustment of row spacing, optimum seeding rate, and use of genotypes with high weed-competitive ability. During the past several decades, adoption of narrow row spacing has become increasingly popular among soybean growers primarily because of yield advantage and early canopy closure, which directly provides greater weed suppression. Adoption of narrow rows significantly reduces the density and biomass of late-season emerging weeds and delays the critical time for weed removal compared with wide rows. An increase in seeding density/plant population also suppresses weeds by earlier canopy closure, especially when combined with narrow row spacing. Competitive abilities of different soybean cultivars against different weed species are not consistent. Interseeding cover crops after establishment of soybean also can be a viable option for weed suppression as long as cover crops do not compete with soybean, or act as weeds themselves. Integrated weed management is considered to be the most effective approach for long-term and sustainable management of weeds in soybean. The objective of this article is to provide an overview of currently known cropping practices for improving soybean competitiveness against weeds.

1. Introduction

Soybean (*Glycine max* (L.) Merr.) is one of the most important grain legume and oilseed crops in the world. More than 50% of the world soybean production comes from the US (Zimdahl, 2004). Like all other major crops, prolonged weed interference in soybean can result in significant yield and quality losses, thus requiring early-season weed management to achieve economically acceptable yields (Knezevic et al., 2003a; Hock et al., 2005). Presence of weeds up to beginning of seed stage of soybean (R5) may cause 8–55% reduction in yield (Van Acker et al., 1993a,b). Various types of weed species are commonly found in soybean with differential competitive ability, but most of the work has focused on *Xanthium strumarium* L., *Abutilon theophrasti* Medik., *Ipomoea lacunosa* L., *Amaranthus retroflexus* L., *Sorghum halepense* L., and *Senna obtusifolia* L. (Zimdahl, 2004).

Weeds are managed in soybean primarily by traditional means based on chemical and mechanical tools. Cultural and alternative methods (e.g., flaming) are also utilized, but not as much as the traditional methods (Pester et al., 1999; Ulloa et al., 2010a,b; 2012). All these methods are effective in different situations and help in increasing crop productivity. However, a number of challenges restrict their efficiency in modern agriculture (Jabran et al., 2015). The major challenges associated with hand weeding are decreasing

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availability and higher cost of labour, and inconsistent weed control (Kruidhof et al., 2008; Carballido et al., 2013; Gianessi, 2013; Jabran et al., 2015). Mechanical methods cause soil disturbance, prevent the build-up and/or the maintenance of a stable soil structure, and increase the chance for soil erosion that negatively affect soil fertility (Hiltbrunner et al., 2007; Wszelaki et al., 2007). The increase in the number of herbicide-resistant weeds, the increase in herbicide cost, and environmental concerns due to the movement of herbicides into surface and ground water have sparked public awareness and restrictions on herbicide use (Rifai et al., 2002; Wszelaki et al., 2007; Annett et al., 2014), necessitating the need for alternative methods of weed control.

Cultural practices such as narrow row spacing, high seeding density, and selection of appropriate crop varieties with ability of rapid canopy closure affect weed dynamics (Bussan et al., 1997; Grichar et al., 2004). Cultivation of cover crops could be an efficient method of weed control. Cover crops suppress weed growth through competition for growth-limiting resources such as light (Teasdale and Mohler, 2000), soil nutrients and moisture (Barberi, 2002), and by producing allelopathic compounds (White et al., 1989; Reberg-Horton et al., 2005). However, adverse effects of cover crop on the main crop due to competition for light (Hooks and Johnson, 2001), water (Box et al., 1980), and nutrients (Feil et al., 1997; Garibay et al., 1997) have also been reported. Such type of competition, under certain situations, could be avoided or minimized through interseeding of cover crop into established vegetation of the main crop (Scott et al., 1987; Abdin et al., 1998, 2000). den Hollander et al. (2007) reported a reduction in yield while cultivating leek (*Allium porrum* L.) as the main crop and various *Trifolium* species as interseeded crops.

Individual weed control methods generally do not provide complete control of weeds (Datta and Knezevic, 2013) and, therefore, integrated weed management (IWM) is often considered to be the most effective approach. IWM comprises combination of different weed control measures such as mechanical, chemical, biological, cultural, and genetic methods (Swanton and Weise, 1991; Knezevic et al., 1994; Knezevic and Cassman, 2003). IWM includes (i) prevention of weeds before start through different agronomic practices, (ii) increasing the ability of crops to compete against weeds, (iii) stopping weeds from adapting, (iv) taking appropriate weed control decision, and (v) proper documentation and maintenance of record (Knezevic, 2014). IWM is not a fixed process and needs to be adjusted depending on crop type, farming operation, and seasonal condition (Knezevic, 2014). The primary goal of IWM is to manage weeds (reduce their population to an extent where these do not offer competition to crop) as total weed eradication is not possible due to many environmental and economic reasons (Knezevic, 2014).

Crop competition, a component of a cultural weed management, is an effective way to suppress weed growth. It is also an important component of an IWM program. Another alternative to these methods might be the development of competitive crop cultivars (Callaway, 1992), which would be helpful in achieving better weed control and higher yields at much lower cost (Lemerle et al., 1996). Crop competitive abilities are generally expressed in two ways: (i) ability to compete with weeds and reducing dry matter and seed production of weeds and (ii) ability to tolerate weed competition without much effect on yield (Callaway, 1992).

In this article, the research on weed management in soybean has been reviewed and the concept of competitive index has been discussed.

2. Competitive ability and factors affecting crop-weed competition

Weed competitiveness can be quantified utilizing the concept of competitive index (CI), which is a relative measure of weed competitiveness (Coble and Mortensen, 1992; Hock et al., 2006a,b). CI is a good tool to quantify the competitiveness of weeds where larger CI values indicate more competitive weeds (Hock et al., 2006a). For example, a plant with a CI of 1 is 1/10 as competitive as a plant with a CI of 10.

Jannink et al. (2000) reported that soybean is not a strong competitor with weeds in early growth stages and weeds outgrow soybean in the absence of proper weed management. If the crop is not kept weed-free during this stage, competition for light starts after four weeks when weeds grow taller than soybean and intercept photosynthetically active radiation (PAR). Table 1 summarizes various factors that influence competitive ability of soybean cultivars.

Competition between soybean and weeds is influenced by certain soil and environmental factors such as nutrient, light, water, and temperature (Zimdahl, 2004). Weed competitiveness is affected by various factors such as location, emergence time, and density of weed species (Hock et al., 2006a). For soybean, weeds emerged at VE (emergence) crop stage produced more total dry matter and plant volume than V1 (first node) stage.

Competitiveness for broadleaf weeds was generally higher than grassy weeds based on total dry matter and plant volume. *Helianthus annuus* L. was reported to be the most competitive weed species (Hock et al., 2006a). Mortensen and Coble (1989) reported that *X. strumarium* reduced soybean yield by 12 and 29% when subjected to water stressed and well-watered conditions, respectively. Another study reported that water stress caused more growth reduction in soybean than *S. obtusifolia* and competition from *S. obtusifolia* decreased the crop leaf area duration with adequate water, but competition from the crop decreased the weed leaf area duration and net assimilation rate (Patterson, 1986). Munger et al. (1987) found that at leaf water potential less than −2.5 MPa, net photosynthetic rate, stomatal conductance, and transpiration rate were greater in *A. theophrasti* than soybean. Under prolonged water stress, all these attributes declined rapidly for *A. theophrasti* than soybean suggesting that soybean is a more effective competitor than *A. theophrasti* under poor soil moisture conditions. The important role of water was also demonstrated in another study where interference from *Ipomoea hederacea* var. *integriscula* Jacq., *X. strumarium*, or both caused 21, 57, or 64% yield reduction in soybean with irrigation and 12, 60, and 76% without irrigation, respectively (Mosier and Oliver, 1995).

Early season low temperature was found helpful in reducing competition between soybean and *Sesbania herbacea* (*exaltata*) and competition was almost negligible at 3 or 6 plants m^{-2} densities of the weed (King and Purcell, 1997). A day/night temperature of 30/20 °C was found more congenial for the growth of both the crop and the weed compared with a day/night temperature of 25/15 °C; however, warmer temperatures help stimulate better weed growth than the crop (King and Purcell, 1997). Soybean, *X. strumarium*, and *A. hybridus* L. had a better assimilation rate at 29/20 °C day/night temperature and a significant increase in height, leaf area, and dry weight occurred when day/night temperatures ranged from 26/17, 29/20, and 32/23 °C, respectively. *A. hybridus* was found less competitive than soybean and *X. strumarium* with increasing temperature (Flint and Patterson, 1983).

Light affects interference between soybean and weed. Shading lower leaves of *X. strumarium* and *A. theophrasti* to only 5% of full light for 12 days, increased the upper leaf area at 3 and 6 days after shading for *A. theophrasti* and *X. strumarium*, respectively (Regnier

Table 1
Competitive ability of different soybean cultivars.

Cultivars compared	Major findings	References
SC00–883, Hartz 6255, Delta and Pineland 6299, Asgrow 6202, Northrup King S60-E4, Pioneer 96B21	Competitive ranking was not affected by row spacing with the exception of Pioneer 96B21; and SC00–883 was found highly competitive across all row widths	Norsworthy and Shipe, 2006
One glyphosate-tolerant and three conventional cultivars	There was a greater *Senna obtusifolia* control and yield when soybean was growing in 19 and 38 cm rows compared with 76 cm row spacing	Buehring et al., 2002
Glyphosate tolerant (GT) and non-GT sister lines against high yield, non-herbicide tolerant cultivars	Non-GT sisters yielded 5% more than GT sister lines. Plant height of GT sister lines was 2 cm more than non-GT sisters. Non-herbicide tolerant cultivars yielded 5% and 10% higher than non-GT and GT sister lines, respectively	Elmore et al., 2001
A total of 16 different cultivars	The yield and ranking of soybean genotypes varied with the weed species. Grass weed species reduced higher yield than small-seeded broadleaf weeds	Bussan et al., 1997
Three Group V cultivars	Hutcheson (one of the three cultivars) was found more competitive against *S. obtusifolia*	Shaw et al., 1997
Centennial or Biloxi (tall cultivars) against Tracy M (short cultivar)	*S. obtusifolia* was tallest when grown with Centennial or Biloxi and shortest with Tracy M. *S. obtusifolia* biomass reductions ranged from 30 to 50% depending on cultivar and was directly related to soybean height	Shilling et al., 1995
Maple Glen	Development of cultivars with early branching and the use of narrower rows would be efficient weed management techniques	Van Acker et al., 1993b
Semi-dwarf determinate and indeterminate cultivars	Path analysis of crop-weed interference was recommended to breed crop varieties that suppress weed growth	Jordan, 1992
A total of 12 different cultivars against *Senna obtusifolia*	No relation was found between *S. obtusifolia* interference and soybean cultivar date of introduction or maturity group	James et al., 1988
Forrest and Centennial cultivars against mixed weed species	Soybean cultivar influenced the level and duration of competitiveness depending on the weed species present	Monks and Oliver, 1988
Amsoy 71 against Beeson	Amson 71 was found more competitive than Beeson to both early and late emerging weeds	Burnside, 1979

and Harrison, 1993). There was no reduction in total dry weight due to shading in *A. theophrasti* 12 days after shading, but it was reduced by 10% in *X. strumarium* indicating that *A. theophrasti* has a greater shade tolerance than *X. strumarium*.

3. Row spacing

It has been reported that row spacing and emergence time significantly impact CI values of weeds. For example, Hock et al. (2006a) observed that three common soybean weeds, *H. annuus*, *X. strumarium*, and *A. theophrasti* had CI values of 10, 4.53, and 2.08, respectively, on the basis of total dry matter in 76 cm row spacing; however, these values were 7.33, 2.99, and 1.27, respectively, in case of 19 cm row spacing. Similarly, emergence time also significantly affects CI values. The CI values for the same weed species were 10, 3.59, and 0.54 when emerged at the VE (emergence) stage in 76 cm rows whereas the values were 3.74, 1.17, and 0.34, respectively, when emerged at the V1 (first node) stage.

Proper row width not only provides optimum conditions to plants for better growth and yield but also leads to efficient weed control. Extensive work in soybean revealed higher yield and better weed control with narrow row spacing than wider ones (Bradley, 2006). Row spacing of less than 76 cm was found better than wider row spacing. The important driving factor for the adoption of narrow row spacing is its potential of higher yield compared with wider row spacing (Mickelson and Renner, 1997).

Controlling early emerging weeds and reducing row spacing could be an effective strategy for weed management in soybean (Hock et al., 2009). Narrow spacing provides better weed management by obstructing the amount of light reaching the soil surface and by reducing the time required for soybean to attain full canopy closure (Bradley, 2006). Soybeans cultivated in narrow rows close the canopy earlier and adversely affect the penetration of light to soil and thereby influencing weed emergence and growth compared with wider row spacing (Yelverton and Coble, 1991; Knezevic et al., 1999). Weed resurgence increases with increasing row width as it allows more amount of light to penetrate to the soil surface (Yelverton and Coble, 1991). A closed canopy can even suppress weeds that escaped herbicide application or that emerged late in the growing season (Mickelson and Renner, 1997). Puricelli et al. (2003) reported a significant reduction in light penetration to the soil surface for soybean grown in narrow rows during the most part of the growing season compared with wider rows. Similar results were also reported by Dalley et al. (2004). Many of the earlier studies also revealed that soybean reaches early canopy closure when grown in narrow rows (Shibles and Weber, 1965, 1966; Wax and Pendleton, 1968). Burnside and Colville (1964) reported that soybean grown in 25 cm wide rows completely shaded the ground 22 days earlier than soybean grown in 76 cm wide rows.

Hock et al. (2009) reported significant reduction in leaf area and total dry matter production of *A. theophrasti* in soybean cultivated in 19 cm row spacing. *Senna obtusifolia* and *Sorghum halepense* were better controlled when soybean was planted at 25 cm row spacing compared with 76 and 97 cm row spacing (Bendixen, 1988; Shaw et al., 1991).

Planting soybean in narrow rows improved early season tolerance against weeds and delayed the critical time for weed removal (CTWR) than wider rows (Knezevic et al., 2003a). An inverse relationship has been observed between row spacing and weed top growth suggesting that weeds occurring in narrow rows of crops shifted their canopy growth more to the upper parts of the plant (Burnside, 1979). Schultz et al. (2015) reported a greater control of *Amaranthus rudis* Sauer in glufosinate-resistant soybean grown in narrow row spacing (19 and 38 cm) and high seeding rate (240,000 to 315,000 seeds ha^{-1}). Buehring et al. (2002), in a study with one glyphosate-tolerant (GT) and three conventional cultivars of soybean, obtained greater control of *S. obtusifolia* and increase in yield with 19 and 38 cm wide rows compared with 76 cm row spacing. Knezevic et al. (2003a) reported that an increase in row spacing from 19 to 76 cm reduced early-season tolerance of soybean to weeds and required earlier weed management in wider rows than in narrower rows.

Weed removal time is as important as the extent of weed control (Jackson et al., 1985). With adequate amount of soil moisture, weed interference up to four weeks from emergence posed no significant adverse effect on soybean yield. However, yield was reduced with four weeks of interference with high weed density or soil moisture deficiency and there was no difference in the competitive effect of annual grasses or annual broadleaf weed species (Jackson et al., 1985).

Understanding the interaction between crop and weeds is the key to successful weed management. Soybean may not suffer from presence of weeds during initial stages of growth, but with increasing growth of weeds, competition for resources affects growth and yield of soybean. The critical period for weed control (CPWC) is an interval of time during crop growth period when it is required to maintain weed-free conditions to avoid unacceptable yield loss. Several factors affect the CPWC such as weed emergence time and weed morphology, planting density, row spacing, competitive ability of crop, environmental variables, and management practices (Teasdale, 1995). For soybean, the CPWC can range from the first trifoliate stage to the beginning of the pod stage (sixth trifoliate stage) depending on crop geometry, environmental condition, and management (Van Acker et al., 1993a; Mulugeta and Boerboom, 2000; Knezevic et al., 2003b). Several other factors also influence the CPWC and the CTWR. Defoliation of soybean by insects in the early crop growth season significantly affected the CTWR where the CTWR was reported to be as third, second, and first trifoliate stages for 0, 30, and 60% defoliation levels, respectively (Gustafson et al., 2006). Mulugeta and Boerboom (2000) reported that application time of glyphosate was more important than the dose for weed competition efficiency and yield of crop. Under favourable growing conditions, single application of glyphosate was able to prevent yield loss in GT soybean planted in narrow rows, whereas the CPWC occurred earlier in soybean planted in wider rows and necessitated a second application of glyphosate for the control of late emerging weeds. The CTWR varied with tillage operation and time, and was generally different for no- and reduced-tillage practices (Mulugeta and Boerboom, 2000).

Though a general trend of better weed management for crops growing in narrow rows was found (Table 2), the response varied depending on the types of weed species. Some weeds such as *X. strumarium*, *Chenopodium album* L., *Ambrosia artemisiifolia* L., *Solanum ptycanthum* Dunal., *Setaria faberi* Herrm., *Amaranthus retroflexus*, *I. lacunosa*, and *Abutilon theophrasti* were better controlled in narrow row compared with wide row spacing in some studies, but did not respond to row spacing in other experiments (Table 2). In contrast, other weeds such as *Echinochloa crus-galli* (L.) Beauv., *A. rudis*, *S. herbacea* (Mill.) McVaugh, *Digitaria sanguinali* (L.) Scop., and *Anoda cristata* L. were better controlled in narrow compared with wide row spacing. The second group of weeds generally emerge late in the season. Narrow rows cultivation resulted in rapid canopy closure and consequently reduced the germination of these late emerging weeds compared with wide row spacing.

4. Seeding density

Narrow row spacing and high seeding rate help the crop compete with weeds for essential resources (Grichar et al., 2004), and high plant populations cause a complete weed suppression due to an increase in plant biomass (Weiner et al., 2001). Many studies support the concept of high seeding density/plant population as one of the best options for weed management in soybean (Table 3).

Sarver (2009) observed that seeding density of soybean failed to influence the critical time for weed control. Similarly, DeWerff et al. (2014) observed no difference in density or size of weeds in a field infested with mixed weed flora with an increase in seeding rate of soybean. However, Norsworthy and Oliver (2002) observed that an increase in soybean population from 247,000 to 729,000 plants ha^{-1} increased the weed control efficiency from 60 to 91%. Better control of *S. obtusifolia* and 21% higher yield of conventional soybean cultivars with medium population (455,375 plants ha^{-1}) was obtained with 19 cm row spacing than 38 cm row spacing, whereas with lower plant population (241,000 plants ha^{-1}), row spacing of 38 cm resulted in 21 and 64% higher yield than 19 and 76 cm row spacing, respectively (Buehring et al., 2002).

The interaction of four density levels of *I. lacunosa* (3.3, 10, 20, and 40 plants m^{-2}) with soybean grown under conventional (1 m spacing) and narrow (20 cm spacing) rows at 23 and 50 plants m^{-2} revealed that interference of *I. lacunosa* at initial stages of crop growth was more significant in conventional-row soybean compared with narrow-row soybean due to a rapid increase in leaf area index and biomass from 4 to 8 weeks after emergence (Howe and Oliver, 1987). Effect of *I. lacunosa* on yield of soybean was more prominent in conventional-row soybean with higher plant density.

Table 2
Effects of different row spacings on weed control in soybean.

Weed species	Soybean cultivar	Major findings	References
Amaranthus palmeri S.Wats.	Glufosinate tolerant	Influence of herbicide program was found more prominent on *A. palmeri* control than row spacing or seeding rate of soybean	Bell et al., 2015
Mixed species	Sachiyutakke A1 (short-stem cultivar)	Weed suppression at 20 cm row width was 60% higher than 75 cm row width. Early planting with narrow row spacing (20 cm) was recommended for higher yield, effective weed suppression, and less lodging of the plant	Matsuo et al., 2015
Mixed species	Glyphosate tolerant	Leaf area index of soybean was highest for 19 cm row spacing compared with 38 and 76 cm row spacings. Canopy closure was delayed by two weeks in 76 cm rows, yield was also highest in 19 cm row spacing with no significant difference between 38 and 76 cm rows	Harder et al., 2007
Amaranthus rudis J.D.Sauer	Conventional	Narrow row spacing (19 cm) reduced weed density and biomass greater than wide-row soybean (76 cm)	Steckel and Sprague, 2004
*Sesbania herbacea (*Mill.) McVaugh, *Ipomoea lacunosa* L., *Senna obtusifolia* (L.) H.S.Irwin & Barneby	Glufosiante tolerant	Weed control was increased in narrow rows (38 cm) compared with wide rows (76 cm). There were no differences in yield due to row spacing	Norris et al., 2002
Sicyos angulatus L.	Glyphosate-tolerant	Narrow row spacing (38 cm) was found non-significant for weed control (emergence or biomass production) compared with wide row spacing (76 cm)	Esbenshade et al., 2001
Amaranthus rudis	Glyphosate-tolerant	Weed control was increased with deceasing row spacing (from 76 cm rows to 38 and 19 cm row spacing)	Young et al., 2001
Ambrosia artemisiifolia L., *Amaranthus retroflexus* L., *Chenopodium album* L., *Abutilon theophrasti* Medik.,	Conventional	Efficacy of three post emergence herbicides were evaluated in wide (76 cm) and narrow row (19 cm) soybean, and it was concluded that post-emergence herbicide application resulted in greater weed control and higher greater soybean yield in narrow compared with wider rows	Nelson and Renner, 1998
Senna obtusifolia, *Xanthium strumarium* L.	Conventional	Weed biomass increased and soybean biomass decreased as soybean row spacing increased. Soybean biomass and yield were unaffected by row spacing when weeds were absent	Patterson et al., 1988

Table 3
Effects of different seeding densities on weed control in soybean.

Weed species	Soybean cultivars	Major findings	References
Mixed	Herbicide tolerant and non-herbicide tolerant	An increase in seeding rate did not reduce the density or size of weeds exposed to the post-emergence herbicide, and at the end-of-season, weed density and biomass were also not affected. The use of a pre-emergence herbicide reduced total weed density and biomass before post-emergence application	DeWerff et al., 2014
Mixed	Glyphosate tolerant	Seeding density had non-significant effect on the critical time for weed control	Sarver, 2009
Solanum ptychanthum Dunal.	Conventional	Soybean planted in 19 cm row spacing was more competitive irrespective of the seeding density. An increase in soybean seeding rate in 76 cm rows from 185,000 to 432,000 seeds ha^{-1} reduced weed dry weight by three fold	Rich and Renner, 2007
Amaranthus palmeri S.Wats., *Richardia scabra* L.	Glyphosate tolerant drilled seeded with conventional soybean	Mixed cultivation of both types of soybean might be helpful in suppressing early season weeds, but glyphosate should be applied within four weeks of soybean emergence to optimize yield and to prevent interference of the two soybean types	Norsworthy, 2005
Sesbania herbacea (Mill.) McVaugh, *Ipomoea lacunosa* L.	Glyphosate tolerant	An increase in soybean population from 247,000 to 729,000 plants ha^{-1}, weed control efficiency was increased from 60 to 91%, respectively	Norsworthy and Oliver, 2002
Senna obtusifolia (L.) H.S.Irwin & Barneby	Glyphosate-tolerant and conventional	Reducing row spacing (from 76 cm to 38 and 19 cm) and increasing plant population (from 245,000 to 481,000 and 676,000 plants ha^{-1}) suppressed both vegetative and reproductive growth of *S. obtusifolia*	Nice et al., 2001
Ipomoea lacunosa	Conventional	Leaf area index and seed production of *I. lacunosa* was greater in conventional rows (1 m) compared with narrow rows (20 cm). Yield of narrow-row soybean was equal or greater than yield of conventional-row soybean regardless of weed density	Howe and Oliver, 1987

Bensch et al. (2003) examined the effects of three pigweed species (*A. retroflexus*, *A. palmeri*, and *A. rudis*) with seven densities (0.25, 0.50, 1, 2, 4, and 8 plants m^{-1}, and a weed free control) and two weed planting dates (with soybean planting and at cotyledon stage) on soybean yield loss. Soybean yield reduction was greater with early weed emergence time and at high weed density. Yield reductions of 79, 56, and 38% were recorded for *A. palmeri*, *A. rudis*, and *A. retroflexus*, respectively, at the highest density of 8 plants m^{-1}. Harder et al. (2007) observed that increasing soybean population in a row did not influence the growth of late emerging weeds and yield was higher in narrow-row planted crop with moderate or high populations compared with low populations. Reddy (2002) studied the effects of soybean planted in three spacing of 19 cm (narrow) rows/high density (NR–HD), 57 cm (medium) rows/medium density (MR–MD), and 95 cm (wide) rows/low density (WR–LD) on weed control and yield. Total biomass of weeds produced in the NR–HD system was 65 and 78% less and yield was 8 and 27% higher compared with MR–MD and WR–LD, respectively.

Seeding density dependent crop competitiveness is equally important for both conventional and organic soybean production. Demand for organically produced food products and even feed is fast increasing worldwide (Dimitri and Greene, 2002). Organic soybean is mainly used for making a large number of organic food products and feed rations. Weed management in organic soybean is currently carried out by mechanical method (Ulloa et al., 2010b), which is effective for control of weeds between rows (inter-row), but control of such weeds in intra-rows is difficult and leads to competition for resources (Vangessel et al., 1995; Garrett and Dixon, 1998; Datta and Knezevic, 2013). In organic soybean, desirable weed control can be achieved by increased seeding density (Liebman and Gallandt, 1997; Place et al., 2009). A two years study across five sites in North Carolina, USA, with four seeding rates (185,000, 309,000, 432,000, and 556,000 viable seeds ha^{-1}) showed that the rate of 556,000 viable seeds ha^{-1} provided better weed control along with higher yield and increased profits (Place et al., 2009). In another study conducted in Minnesota, USA, Coulter et al. (2011) revealed that early planting of organic soybean was more critical for weed control and yield rather than seeding rate. They observed that increasing seeding rate from 395,400 to 543,600 plants ha^{-1} did not improve weed control or yield, but planting soybean in mid-to late-May than mid-June enhanced both weed control and yield for most of the organically produced soybean cultivars.

Seed size of crop may also influence its competitiveness against weeds. A two-year field study conducted in North Carolina, USA, with three soybean varieties (Hutcheson, NC–Roy, and NC–Raleigh) differing in seed sizes revealed that planting larger seeds improved soybean competitiveness by increasing petiole length and plant height and consequently resulted in superior weed control in organic soybean production (Place et al., 2011). Plant population of GT soybean caused negative impact on weed biomass at soybean harvest with a little effect on weed population during soybean growth period (Arce et al., 2009).

5. Cultivars

A competitive species is the one that can out-compete its neighbour for nutrients, water, light, and space. It is suggested that if different weed species or weed pressure has little impact on the competitive rank of soybean genotypes, then the highest yielding genotypes under weed-free conditions will also produce the highest yield and be the best competitor against weeds (Grime, 2001). Another hypothesis states that a high yielding genotype in weed-free conditions could be a poor competitor, while a competitive genotype could yield less under weed-free conditions. The tradeoff theory of competition also supports this hypothesis (Tilman, 1990). This theory has been developed to describe differences in competitive ability among species, and is based on variability among different species in their resources allocation leading to a tradeoff in competition. For example, soybean requires a low N and high K supply for survival as it allocates energy to nodule development making it a strong competitor under low N soils and a poor competitor in low K soils. The same theory may be applied to define differences in competitive ability among crop genotypes.

Soybean cultivars/genotypes vary in their competitiveness against different weeds (Zimdahl, 2004). Differences in weed biomass production up to 45% due to cultivation of different cultivars of soybean have been reported (Rose et al., 1984). Rezvani et al. (2013) tested six soybean varieties for weed suppression ability and CI by recording relative biomass total, competitive balance index, and relative crowding coefficient. Weeds caused a reduction in the height, yield, and yield components of all soybean varieties, but the weed suppressive ability and CI values showed variations in competitiveness among the tested varieties. The factors that determine the competitive ability of soybean cultivars include: (i) emergence rate compared with competing weeds, (ii) vigour of seedling, (iii) rate of canopy closure, and (iv) allelopathic properties (Rose et al., 1984). The competitiveness could be linked to some complex or at least difficult to measure traits, or combinations of traits (Norsworthy and Shipe, 2006). Breeding crops with increased weed suppression ability would be a better approach for improving soybean weed management for which genetic variation in the soybean-weed interaction is required (Vollmann et al., 2010).

Amson 71 was found more competitive than Beeson to both early and late emerging weeds (Burnside, 1979) (Table 1). An evaluation of 16 genotypes revealed differences in yield and ranking of soybean genotypes with the weed species (Bussan et al., 1997). Grass weed species reduced higher yield than small-seeded broadleaf weeds (Bussan et al., 1997). Norsworthy and Shipe (2006) reported greater competitive ability of cultivars Pioneer 96B21 and SC00–883 across all row widths. Tracy M, a short cultivar of soybean, caused greater reduction in plant height and biomass of *S. obtusifolia* than tall growing cultivars Centennial or Biloxi (Shilling et al., 1995). Of the three cultivars, Hutcheson was found more competitive against *S. obtusifolia* (Shaw et al., 1997). However, James et al. (1988) observed no relation between *S. obtusifolia* interference and date of introduction or maturity of 12 soybean cultivars.

Most of the work to identify morphological traits associated with competitiveness of soybean genotypes was focused on wide rows (76 cm) of soybean (Jordan, 1992). Since the last two decades, there has been an increase in narrow-row soybean production over wide rows because of associated yield advantages and availability of narrow-row planters (Frederick et al., 1998). Use of glyphosate in GT soybean is another contributing factor for the large scale adoption of narrow row spacing in soybean. The requirement of glyphosate could be minimized if genotypes are selected based on competitive ability. Glyphosate has no residual weed control activity and competitiveness could be maximized through equidistant spacing that can more accurately be maintained in narrow rows (Norsworthy and Shipe, 2006).

Soybean competitiveness intensifies with a decrease in row width (Legere and Schreiber, 1989) and an increase in plant population (Norsworthy and Oliver, 2002). Mostly competitive genotypes are selected by plant breeders under non-weedy conditions. In rice (*Oryza sativa* L.), weed suppression during the early stages of crop growth is related to leaf area (Gibson et al., 2003), while in maize (*Zea mays* L.), weed suppression and crop tolerance to weeds are associated with leaf area index and light interception differences (Lindquist and Mortensen, 1998). Selection of soybean competitive genotypes might also be based on such similar characteristics. An early season growth rate, plant height, canopy volume, plant width, and visual estimates of ground cover could be potentially useful measurements for selection of soybean competitive genotypes (Rose et al., 1984; Norsworthy and Shipe, 2006). Ground cover of soybean is particularly important to competitiveness because the rate of canopy formation increases with decreasing row width and increasing population, leading to a reduction in weed emergence (Norsworthy and Shipe, 2006).

Most research evaluating the competitive ability of soybean has screened genotypes against a narrow range of weed species or multiple species with a single level of competition. There has been a lack of information on the competitive interaction of multiple weed species or levels of weed pressure on competitive ability of different soybean genotypes. For a single type of weed species growing in the field, a producer can make efficient decision, but such decisions are very difficult when multiple weed species are dominant in the field due to their variable densities, emergence time, and site-specific environmental conditions (Knezevic et al., 1997, 2002, 2003a,b; Evans et al., 2003). However, now a number of computer-based decision support systems (DSS) have been developed for making efficient weed management decisions (Martin et al., 1997; Neeser et al., 2004; Hock et al., 2006a).

Hock et al. (2006b) evaluated the performance of several WeedSOFT versions to predict yield loss of soybean from competition using CI values in WeedSOFT version 9.0 compared with new CI values obtained from dry matter and volume of weeds and soybean yield loss from soybean grown under two row spacings of 19 and 76 cm along with two weed emergence times (at soybean emergence and first trifoliate leaf stage). New CI values generated from this experiment improved predictions of yield loss of soybean by nearly 63% (Hock et al., 2006b). New CI values were found more robust in soybean yield loss prediction compared with those based on dry matter or volume of weed. Prediction of soybean yield loss by WeedSOFT as affected by weed emergence time was investigated by Jeschke et al. (2011) to assess the accuracy of this program. Weed communities of mixed species established during four soybean growth stages of emergence (VE), cotyledon (VC), first node (V1), and third node (V3) were analyzed and responses in the form of yield loss were recorded. Weed species were mostly of two types that included annual grasses and moderately competitive annual broadleaf species. Most of the yield loss of soybean was observed at emergence (VE) followed by cotyledon (VC) with no yield loss occurred at third node (V3) weed establishment stage. The predicted yield loss was found less than the actual yield loss due to overestimation of the competitive ability of high densities of *Setaria pumila* (Poir.) Roem. & Schult. and *S. faberi* with soybean. The authors concluded that adjustment of CI values or parameters of the yield loss function for these species might be helpful in improving the accuracy of yield loss prediction and in increasing the usefulness of WeedSOFT.

6. Cover crops

Alternative methods of weed control are required to reduce herbicide use. One of such alternatives is the use of interseeding of cover crops. Interseeding refers to seeding into an established vegetation of main crops (Uchino et al., 2009). Companion crops, e.g., rye (*Secale cereale* L.), and narrow row spacing have been used for weed control in soybean since 1950s (Robinson and Dunham, 1954). Many studies have evaluated the effect of cover crops interseeded within main crops. A summary of the effect of interseeded cover crops on weed suppression for different crops is presented in Table 4. Cover crop (winter rye) significantly suppressed weeds without affecting crop yield when the cover crop was sown three weeks after sowing the main crop in organic farming system (Uchino et al., 2009). Liebl et al. (1992) reported excellent control of weeds except *C. album* with *S. cereale* used as mulch in soybean. Winter *S. cereale* and hairy vetch (*Vicia villosa* Roth.) were found the best cover crops for weed suppression (Uchino et al., 2005). However, Reddy (2003) observed not much effect of *S. cereale* on weed control in three soybean systems. Similarly, Koger et al. (2002) observed that *S. cereale* was effective as cover only in the presence of herbicide. Cover crop reduced weed density by 59% in soybean and 29% in maize (Uchino et al., 2009). Abdin et al. (2000) also reported that cover crop interseeded in maize 10–20 days after its emergence significantly suppressed the weeds and had a little effect on maize yield.

Knowledge on the growth dynamics of the main crop, type of cover crop, and weeds, as well as environmental and field variables is important to develop more effective weed suppression by cover crops (Uchino et al., 2009). Knowledge on spatial distribution of weeds is also important for efficient weed management. Uchino et al. (2015) evaluated the effects of soybean and maize (main

Table 4
Interseeded cover crops and their effect on weed suppression.

Main crop	Cover crop	Major findings	References
Soybean	*Secale cereale* L.	Soybean row spacing had minimal effects on specific weeds and total biomass or density of weeds	Nelson et al., 2011
Maize, potato, soybean	Comparison of 10 different species	Winter *S. cereale* and hairy vetch (*Vicia villosa*) were found the best cover crops for weed suppression	Uchino et al., 2005
Soybean	*Secale cereale*	No difference was found in weed control response for three soybean systems and weed density and biomass was reduced up to 27 and 38%, respectively	Reddy, 2003
Soybean	*Secale cereale*	*S. cereale* cover crop-based soybean production system was found non-significant for weed control, and *S. cereale* was found effective only in the presence of herbicide	Koger et al., 2002
Soybean	*Lolium multiflorum* Lam., *Avena sativa* L., *Secale cereale*, *Triticum aestivum* L., *Vicia villosa* Roth., *Trifolium incarnatum* L., *T. subterraneum* L.	*Echinochloa crus-galli* (L.) P. Beauv., *Sida spinosa* L., and *Cyperus esculentus* L. were not effectively controlled while density of *Urochloa ramosa* (L.) Nguyen was altered	Reddy, 2001
Soybean	*Secale cereale*	*S. cereale* mulch excellently controlled weeds except *Chenopodium album* L.	Liebl et al., 1992

crops) ground cover and cover crops on the spatial distribution of weeds in two rows section, within the row and between the rows. When the cover crop was interseeded 3–4 weeks after sowing the main crop in between the row system, a significant difference was recorded on the spatial distribution of weeds between the two main crops. A higher weed density was found in maize compared with soybean grown within the row system and a higher weed density was recorded in soybean grown in between the row system.

Weed suppression through cover crops is a good alternative to herbicides, especially in organic farming systems (Uchino et al., 2009). However, cover crops could also compete with the main crop. Sowing date of the cover crop is important. Uchino et al. (2009) showed that cover crop (rye) sown before the main crop (soybean) or on the same date with the main crop significantly reduced biomass of the main crop. The chlorophyll content of the main crop was also adversely affected when cover crops were sown earlier although the height of the cover crop was considerably shorter than the main crop (Uchino et al., 2009). Sowing of cover crop in later time than the main crop had a negligible effect on biomass and chlorophyll content of the main crop.

7. Conclusions

Herbicides have often been cited as one of the main factors responsible for impoverishment of the flora and fauna in the agricultural landscape. Repeated use and heavy reliance on herbicides has resulted in an increasing number of herbicide-resistant weeds, shifts in weed species population, higher cost of chemical control measures, leaching of herbicide into ground and surface water as well as herbicide residues in drinking water and food, which have sparked public awareness and restrictions on herbicide use. To address these challenges, many countries have developed policies that mandate the reduction of herbicide use and provide incentives to producers for reducing overall chemical use. Using the principles of IWM can aid in reducing the dependence on herbicides. There is presently a renewed interest in exploiting crop competitiveness to suppress weeds in both conventional and organic crops.

The efficacy of weed control can be improved through developing crop management practices that promote crop competitiveness. Weeds resurgence in narrow rows is less likely to occur than wide rows, because narrow rows close canopy earlier and shade weeds, and delay the CTWC. Weed suppression can also be achieved by increasing seeding rate of the crop. This results in higher plant populations, rapid canopy closure, and suppression of weeds. Increasing seeding density may increase seed cost, but more profitable in the long-term as it may reduce the chance of development of resistance and losing effective herbicides or the need for higher dose or number of applications of herbicides. The use of cover crops can help suppress weeds in the main crop. Therefore, developing a cropping system that improves soybean competitiveness is a key component of IWM and must be an imperative for long-term and sustainable management of weeds.

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