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Management of Insecticide-Resistant Soybean Aphids in the Upper Midwest of the United States

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Abstract

Since the first observation of soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), in North America in 2000, it has become the most economically damaging insect of soybean in the Upper Midwest of the United States. For the last 17 yr, soybean aphid management has relied almost entirely on the use of foliar-applied broad-spectrum insecticides. However, in 2015 in Minnesota, failures of foliar-applied pyrethroid insecticides were reported and pyrethroid resistance was confirmed with laboratory bioassays using lambda-cyhalothrin and bifenthrin. In 2016 and 2017, further reports of failures of pyrethroid insecticides and/or laboratory confirmation of resistance occurred in Iowa, North Dakota, South Dakota, and Manitoba. In response to the challenge posed by insecticide-resistant soybean aphids, we recommend several management strategies for minimizing further development of resistance and subsequent pest-induced crop losses: 1) scout and use the economic threshold to determine when to apply insecticides, 2) apply the insecticides properly, 3) assess efficacy 3–5 d after application, and 4) alternate to a different insecticide group if another application is required. In the long term, soybean aphid management must move beyond insecticide-based management to true integrated pest management by incorporating multiple tactics.

Keywords

insecticide, integrated pest management, resistance management, soybean, Aphis glycines

Disciplines

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Recommendations

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Management of Insecticide-Resistant Soybean Aphids in the Upper Midwest of the United States

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Abstract

Since the first observation of soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), in North America in 2000, it has become the most economically damaging insect of soybean in the Upper Midwest of the United States. For the last 17 yr, soybean aphid management has relied almost entirely on the use of foliar-applied broad-spectrum insecticides. However, in 2015 in Minnesota, failures of foliar-applied pyrethroid insecticides were reported and pyrethroid resistance was confirmed with laboratory bioassays using lambda-cyhalothrin and bifenthrin. In 2016 and 2017, further reports of failures of pyrethroid insecticides and/or laboratory confirmation of resistance occurred in Iowa, North Dakota, South Dakota, and Manitoba. In response to the challenge posed by insecticide-resistant soybean aphids, we recommend several management strategies for minimizing further development of resistance and subsequent pest-induced crop losses: 1) scout and use the economic threshold to determine when to apply insecticides, 2) apply the insecticides properly, 3) assess efficacy 3–5 d after application, and 4) alternate to a different insecticide group if another application is required. In the long term, soybean aphid management must move beyond insecticide-based management to true integrated pest management by incorporating multiple tactics.

Key words: insecticide, integrated pest management, resistance management, soybean, *Aphis glycines*

Soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), continues to be the most significant insect pest of soybean, *Glycine max* (L.) Merr., in the Upper Midwest of the United States (Hurley and Mitchell 2017). The biology, impacts, and management of soybean aphid have been well reviewed (Ragsdale et al. 2004, Wu et al. 2004, Ragsdale et al. 2011, Tilmon et al. 2011, Hodgson et al. 2012). Economically significant infestation of soybean by this phloem-feeding insect can reduce soybean yield by up to 40% (Ragsdale et al. 2007) through decreased number of pods and seeds, and smaller seed size (Beckendorf et al. 2008). Soybean aphid also can affect soybean through transmission of viruses (e.g., *Soybean mosaic virus* and *Alfalfa mosaic virus*) (Hill et al. 2001) and potential facilitation of soybean cyst nematode, *Heterodera glycines* Ichinohe, infestations (McCarville et al. 2012b, Clifton et al. 2017).

Soybean aphid has been actively managed since 2000, because of the potential for severe economic impact. Although multiple pest management tactics are available, such as host-plant resistance and biological control, current management continues to rely almost exclusively on foliar insecticides (Hodgson et al. 2012). Insecticide use on soybean in North America has increased dramatically in response to this pest (Ragsdale et al. 2011, Coupe and Capel 2016). Sampling recommendations were developed and validated to estimate soybean aphid abundance (Hodgson et al. 2004). In addition, an economic threshold of 250 aphids per plant with more than 80% of plants infested and aphid populations increasing was developed to optimize use of foliar insecticides for soybean aphid management (Ragsdale et al. 2007, Koch et al. 2016). Insecticides from three insecticide groups are available in foliar formulations for soybean aphid management (IRAC 2018, Knodel et al. 2018, Varenhorst and Wagner 2018) (Table 1). However, soybean aphid management has relied primarily on organophosphates (Group 1B) and pyrethroids (Group 3A) (Hodgson et al. 2012). Seed treatments containing neonicotinoids (Group 4A) are also commonly used in soybean (Hodgson et al. 2012, Douglas and Tooker 2015, Hurley and Mitchell 2017). However, scouting and threshold-based application of foliar insecticides provides a greater likelihood and magnitude of positive net return than seed-applied insecticides for management of soybean aphid (Krupke et al. 2017).

Table 1. Examples of foliar insecticides labeled for soybean aphid management[1]

Group: Site of action[2]	Subgroup[2]	Active ingredient[3]
1. Acetylcholinesterase inhibitors	1A. Carbamates	Methomyl
	1B. Organophosphates	Acephate
		Chlorpyrifos
		Dimethoate
3. Sodium channel modulators	3A. Pyrethroids and Pyrethrins	Alpha-cypermethrin
		Beta-cyfluthrin
		Bifenthrin
		Cyfluthrin
		Deltamethrin
		Esfenvalerate
		Gamma-cyhalothrin
		Lambda-cyhalothrin
		Permethrin
		Zeta-cypermethrin
4. Nicotinic acetylcholine receptor agonists	4A. Neonicotinoids	Acetamiprid
		Clothianidin
		Imidacloprid
		Thiamethoxam
	4D. Butenolides	Flupyradifurone

[1]Based on review of soybean production guides from the Upper Midwest (Knodel et al. 2018, Varenhorst and Wagner 2018).
[2]According to Insecticide Resistance Action Committtee (IRAC 2018).
[3]Insecticides are given as examples only and do not imply endorsement of one insecticide versus another nor discrimination against any insecticide not mentioned by the authors or the universities.

Reliance on insecticide-based management of insect pests often results in development of insecticide resistance (Pedigo and Rice 2009). Resistance can be defined as a 'genetically based decrease in susceptibility to a pesticide' and more than 500 species of arthropods have developed resistance to insecticides (Tabashnik et al. 2014). Numerous aphid species, including those in the genus *Aphis*, have developed resistance to several groups of insecticides (Foster et al. 2007).

Literature from Asia indicates 'light' levels of field-evolved resistance of soybean aphid to organophosphates (Wang et al. 2011, 2012). In the United States, Chandrasena et al. (2011) found no resistance to organophosphates, pyrethroids, or neonicotinoids in field-collected soybean aphid populations from Michigan in 2007 and 2008. However, in an assessment of the susceptibility of soybean aphid populations from the North Central Region to the neonicotinoid, thiamethoxam, Ribeiro et al. (2018) documented resistance ratios greater than 20-fold, which could be considered moderate resistance. We are unaware of reports of neonicotinoids failing to control soybean aphid in the field.

Hanson et al. (2017) provided the first evidence for soybean aphid resistance to insecticides coupled with reports of these insecticides failing to control the pest in North America. From 2015 to 2016, soybean aphid populations from Minnesota and Iowa exhibited resistance ratios up to 40-fold for pyrethroids (i.e., bifenthrin and lambda-cyhalothrin) (Hanson et al. 2017). Furthermore, reports of pyrethroids failing to control soybean aphid in the field were noted from Minnesota and Iowa (Hanson et al. 2017). The geographic scope of field failures of pyrethroids for soybean aphid expanded in 2017, including Minnesota, North Dakota, and South Dakota (Fig. 1) (Koch et al. 2018). In fields where pyrethroids failed to control soybean aphid, surviving (i.e., suspected resistant) aphids have sometimes been observed in patches within the field, which may be due to a mixture of aphid genotypes (e.g., Orantes et al. 2012) with varying levels of insecticide susceptibility colonizing the fields. Laboratory bioassays performed in 2017 confirmed resistance to pyrethroids in soybean aphid from the aforementioned states and Manitoba, Canada (R.L.K., unpublished data).

In China, laboratory experiments exposing soybean aphid to lambda-cyhalothrin for 40 generations resulted in the development of 76-fold resistance to that insecticide and cross resistance to other pyrethroids (i.e., cypermethrin, esfenvalerate, cyfluthrin, and bifenthrin), organophosphates (i.e., chlorpyrifos and acephate), and a carbamate (i.e., carbofuran) (Xi et al. 2015). Aphids, like other insects, employ several different mechanisms (i.e., metabolic resistance mediated by monooxygenases, esterases, and glutathione S-transferases; target site insensitivity such as knock down resistance (kdr) and super-kdr; and reduced cuticular penetration) to overcome pyrethroid insecticides (Liu 2012). Additional research in China has shown that soybean aphid can overcome insecticides through increased esterase and cytochrome P450 expression, which may explain the cross resistance observed by Xi et al. (2015).

Increasingly, widespread detections of pyrethroid resistance in soybean aphid populations in the Upper Midwest of the United States (Hanson et al. 2017, Koch et al. 2018) have created an immediate challenge for effective soybean pest management and profitable soybean production. Due to the mobility of winged soybean aphids (Schmidt et al. 2012), the risk of insecticide-resistant populations of soybean aphid spreading to soybean fields in other soybean producing regions is high. In response to the challenges that insecticide-resistant soybean aphids pose, growers, consultants and applicators are encouraged to evaluate and select their soybean aphid management practices carefully. We provide an overview of factors that may have contributed to development of insecticide resistance in soybean aphid and recommendations for management of potentially resistant soybean aphid populations.

Risk Factors for Resistance Development in Soybean Aphid

Several factors related to soybean aphid infestations and management likely contributed to the development of pyrethroid resistance in this pest in the Upper Midwest of the United States. First, economically threatening infestations of soybean aphid continue to occur in

Minnesota and portions of Iowa, North Dakota, and South Dakota (R.L.K., B.D.P., E.W.H., J.J.K., and A.J.V., personal observations), while such infestations have diminished in other parts of the United States (Bahlai et al. 2015). This pattern of greater pest pressure in Minnesota and neighboring states is further evidenced by data from NASS (2018). Over recent years, the percentage of soybean acres that have been treated with insecticides, not including seed treatments, has been highest in Minnesota, followed by Iowa and North Dakota compared to other states in the Midwest Region (Fig. 2). Similarly, a higher percentage of soybean acres has been scouted for arthropod pests in Minnesota, Iowa, and North Dakota than in other states in the region (Fig. 2). These continued infestations by soybean aphid in parts of the Upper Midwest have resulted in a long history (i.e., about 17 yr) of selection pressure for development of insecticide resistance. In particular, the area of southwest Minnesota (i.e., Blue Earth, Brown, Cottonwood, Faribault, Martin, Redwood, Renville, and Watonwan counties) from which pyrethroid performance issues were first reported (Hanson et al. 2017) has had chronically high soybean aphid populations (i.e., exceeding the economic threshold) every year, except 2003. This area of Minnesota also receives significant numbers of pyrethroid insecticide applications to canning crops, which are often adjacent to soybean.

Second, as indicated earlier, there are a limited number of insecticide groups available for soybean aphid management (Table 1). Among these, management has relied primarily on foliar applications of pyrethroids (Group 3A) and organophosphates (Group 1B) since detection of this pest (Hodgson et al. 2012), which has increased selection pressure for these particular groups.

Third, failure to use proper scouting methods and established thresholds for the determination of when to apply insecticides can result in aphids being exposed to insecticides more frequently than necessary. Use of reduced rates of insecticide or improper use resulting

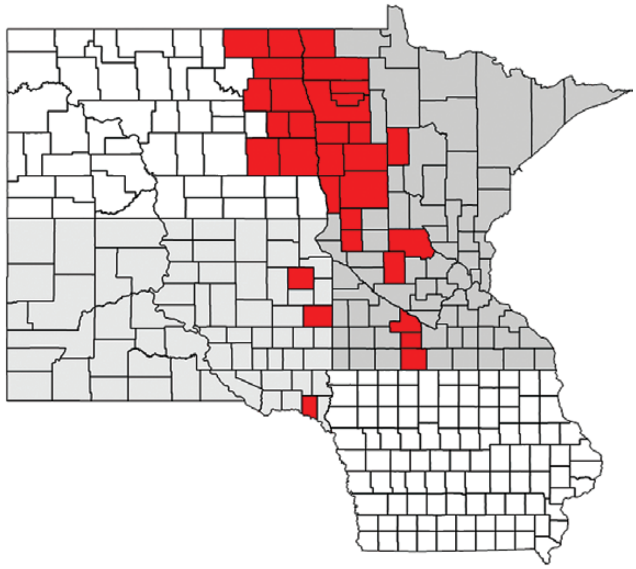

Fig. 1. Counties with reports of pyrethroids failing to control soybean aphid in the field in 2017. Red-shaded counties indicate those from which reports of pyrethroid failures were received. Image from Koch et al. (2018).

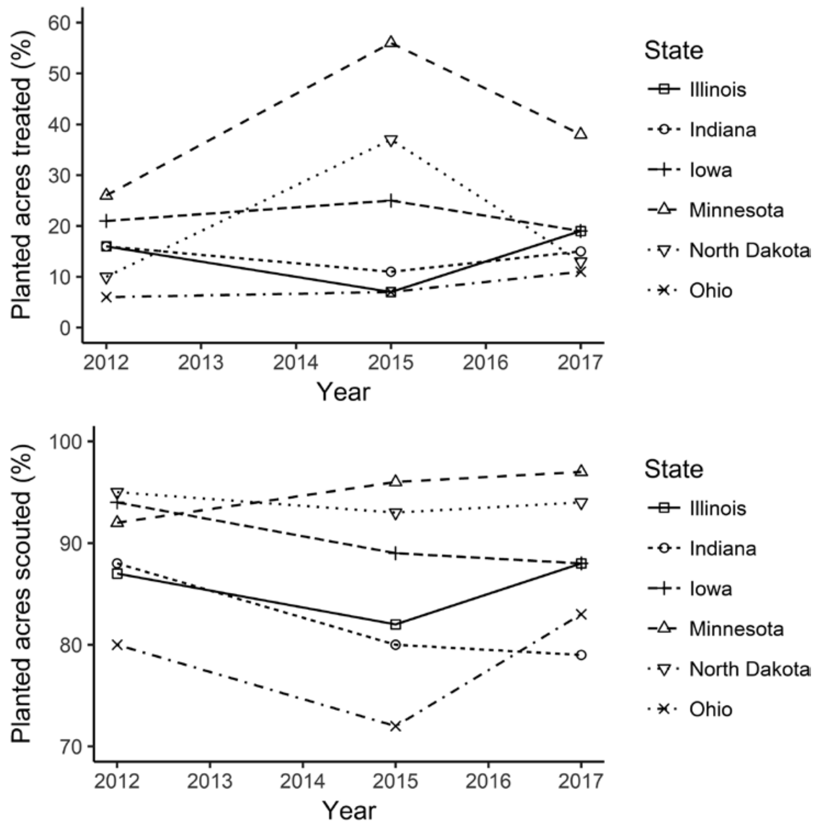

Fig. 2. Insecticide use (i.e., percent of planted acres treated with insecticide) (top figure) and crop scouting for insects and mites (i.e., percent of planted acres scouted) (bottom figure) in soybean in the Midwestern Region of the United States. Data from NASS (2018); data do not include seed-applied insecticides (Douglas and Tooker 2015). States included had data available for the three survey years.

in drift can result in aphids being exposed to low doses of insecticide, which can further increase selection pressure. Unnecessary exposure of soybean aphid to insecticides can result from tank mixing insecticide with other pesticide applications regardless of soybean aphid populations. The continued validity of the 250-aphid-per-plant threshold is explained by Koch et al. (2016).

Strategies for Management of Insecticide-Resistant Soybean Aphid

In response to the challenge posed by insecticide-resistant soybean aphid, we recommend several management strategies for minimizing further development of resistance and subsequent pest-induced crop losses. To reduce the selection pressure for development of resistance to insecticides, treat fields only when necessary (Fig. 3). From vegetative growth through the R5 soybean growth stage, soybean fields should be scouted for soybean aphids on a regular schedule (every 7–10 d) (Hodgson et al. 2004, Hodgson et al. 2007). Use the economic threshold (i.e., 250 aphids per plant with more than 80% of plants infested and aphid populations increasing) to determine if insecticides should be applied (Ragsdale et al. 2007, Koch et al. 2016). Application of insecticides for soybean aphid below the economic threshold is unlikely to provide economic benefit and will subject the pest to unnecessary insecticide exposure and allow further selection pressure for resistance (Koch et al. 2016). Upon reaching threshold, treat the field within 5–7 d to protect yield (Ragsdale et al. 2007). Alternatively, 'Speed Scouting' can be used as a more efficient approach to scouting and making treatment decisions (Hodgson et al. 2007).

If a soybean field exceeds the economic threshold, use an effective insecticide at a labeled rate (IRAC 2009) (Fig. 3). If insecticide resistance is not suspected in the aphid population, then the choice of insecticide could include the various labeled products (Table 1, Fig. 3). If pyrethroid-resistance is suspected in an aphid population, products containing insecticides other than pyrethroids should be considered. Pyrethroid-containing mixtures may provide adequate control of some pyrethroid-resistant populations of soybean aphid (IRAC 2012, R.L.K. and B.D.P., unpublished data). However, pyrethroid-containing mixtures should generally be avoided for use against pyrethroid-resistant populations (IRAC 2012) (Fig. 3). In such situations, the pyrethroid component of such products may be compromised by the resistance. In addition, the amount of each active ingredient in some mixtures is less than that of products with single active ingredients. Furthermore, depending on factors such as relative efficacy, durations of residual activity, and levels of cross resistance, use of some mixtures could provide additional selection pressure for further development of insecticide resistance (IRAC 2012). When selecting insecticides, keep in mind that the 'the primary intention for the use of an insecticide mixture (tank-mix or pre-formulated mixture) is, in most cases, not resistance management but pest management' (IRAC 2012). It should also be noted that soybean fields planted with neonicotinoid-treated seeds have already received an application of a Group 4 insecticide (i.e., neonicotinoids). Populations of clonally reproducing aphids in such fields may have already been exposed to this systemic, seed-applied insecticide. Therefore, we caution against the use of neonicotinoid-containing insecticides for a first foliar application to such fields (Fig. 3). Finally, if soybean is in bloom, consider insecticide options with reduced risk to pollinators (Zhu et al. 2015).

When making insecticide applications, use appropriate nozzles, water volumes, and pressures to ensure thorough spray coverage deep into the soybean canopy (IRAC 2009, Hodgson et al. 2012). To minimize drift, which could result in an effectively reduced rate of insecticide in the field, only spray under favorable environmental

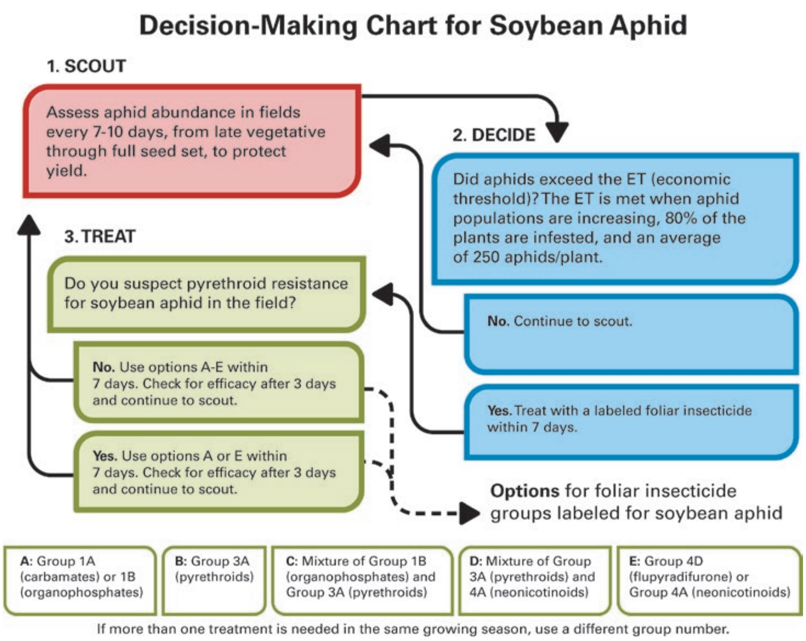

Fig. 3. Decision aide for management of soybean aphid with or without insecticide resistance. If pyrethroid resistance is suspected in the aphid population, application of pyrethroid-containing mixtures (e.g., options C and D) may provide pest control, but the pyrethroid component of the product is compromised by resistance and use may provide additional selection pressure for further development of insecticide resistance. If more than one treatment is needed in the same growing season, alternate to a different insecticide group number. If fields were planted with neonicotinoid-treated seed, avoid application of neonicotinoid-containing products (e.g., options D and E) for the first foliar application to the field. Insecticide options are given as examples only and do not imply endorsement of one insecticide versus another nor discrimination against any insecticide not mentioned by the authors or the universities. This graphic was modified from Hodgson and Koch (2018).

conditions (e.g., wind speeds less than 10 miles per hour, no air temperature inversions). After soybean aphid populations reach the economic threshold, a single application of a foliar insecticide is usually sufficient for soybean aphid management (Hodgson et al. 2012, Krupke et al. 2017). However, the emergence of insecticide-resistant soybean aphids means the scouting of soybean fields 3–5 d after application has now become even more important to determine if the insecticide has provided the expected level of pest control (Fig. 3).

Not all failures of insecticides are due to insecticide resistance. If the insecticide application fails to control the pest population, try to rule out other potential causes for an insecticide failure, such as incorrect insecticide rate or application method, unfavorable environmental conditions, or recolonization of a treated field by winged soybean aphids. If a field needs to be retreated, alternate to a different insecticide group for the follow-up application (NRC 1986, IRAC 2009) (Fig. 3). Alternation of individual insecticide groups is generally preferred for insecticide resistance management (IRM) (IRAC 2012). In contrast, recommendations for the use of mixtures are prominent in programs for herbicide resistance management (NRC 2012). Table 1 lists insecticide groups and active ingredients available for soybean aphid management. For example, if a field was treated with a pyrethroid (Group 3A) and a follow-up insecticide application is needed, then an insecticide from different insecticide group, such as an organophosphate (Group 1B), should be selected. Report suspected cases of insecticide-resistant soybean aphids to a local/regional extension educator or extension entomologist.

Conclusions

Insecticide resistance in soybean aphid has emerged as a new challenge to soybean production. As more is learned about the genetics and mechanisms underlying soybean aphid resistance to insecticides, recommendations for resistance management are likely to change. In the short term, however, cost-effective management of soybean aphid will continue to rely on scouting and threshold-based insecticide applications of the few labeled insecticide groups (Table 1, Fig. 3). Due to the paucity of insecticide groups available for soybean aphid management, IRM will be essential in prolonging the effectiveness of these chemical tools. Improvements in the efficiency of soybean aphid scouting, such as the potential for remote sensing (Alves et al. 2015), could further increase the use of scouting-based decision making for soybean aphid management. Implementation of user-friendly scouting tools and other management tactics may decrease unnecessary exposure of the pest to insecticides and, in turn, reduce further development of insecticide resistance.

In the long term, soybean aphid management must move beyond insecticide-based management toward true integrated pest management incorporating multiple, proactive tactics. For example, host-plant resistance is the cornerstone for many pest management programs (Smith 2005), but is largely lacking in soybean aphid management. Aphid-resistant soybean varieties have proven effective for soybean aphid management, particularly when multiple resistance (*Rag*) genes are pyramided in individual lines (Hesler et al. 2013, McCarville et al. 2014). However, availability of well-adapted, aphid-resistant soybean varieties remains low (McCarville et al. 2012a, Hanson et al. 2016) and biotypes of soybean aphid able to survive on some aphid-resistant soybean have been identified (Hesler et al. 2013).

Furthermore, research has shown that natural enemies (i.e., predators, parasitic wasps, and entomopathogenic fungi) can play an important role in prevention and suppression of soybean aphid outbreaks (Koch et al. 2010, Ragsdale et al. 2011, Koch and Costamagna 2017). However, many of these natural enemies are also adversely affected by broad-spectrum insecticides (e.g., organophosphates and pyrethroids) currently used to manage soybean aphid. Selective insecticides (i.e., toxic to pest, but less toxic to natural enemies), such as flonicamid (Group 29) (Bahlai et al. 2010, Frewin et al. 2012, Pezzini and Koch 2015), pymetrozine (Group 9B) (Ohnesorg et al. 2009), spirotetramat (Group 23) (Bahlai et al. 2010, Frewin et al. 2012, Varenhorst and O'Neal 2012), and sulfoxaflor (Group 4C) (Tran et al. 2016), have been evaluated for soybean aphid management, and could potentially provide for better integration of chemical and biological controls for this pest. Integration of multiple preventative and therapeutic tactics (Pedigo and Rice 2009) for soybean aphid management will increase the sustainability of soybean production in the Upper Midwest.

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References Cited

Alves, T. M., I. V. MacRae, and R. L. Koch. 2015. Soybean aphid (Hemiptera: Aphididae) affects soybean spectral reflectance. J. Econ. Entomol. 108: 2655–2664.

Bahlai, C. A., Y. Xue, C. M. McCreary, A. W. Schaafsma, and R. H. Hallett. 2010. Choosing organic pesticides over synthetic pesticides may not effectively mitigate environmental risk in soybeans. PLoS One. 5: e11250.

Bahlai, C. A., W. van der Werf, M. O'Neal, L. Hemerik, and D. A. Landis. 2015. Shifts in dynamic regime of an invasive lady beetle are linked to the invasion and insecticidal management of its prey. Ecol. Appl. 25: 1807–1818.

Beckendorf, E. A., M. A. Catangui, and W. E. Riedell. 2008. Soybean aphid feeding injury and soybean yield, yield components, and seed composition. Agron. J. 100: 237–246.

Chandrasena, D., C. DiFonzo, A. Byrne. 2011. An aphid-dip bioassay to evaluate susceptibility of soybean aphid (Hemiptera: Aphididae) to pyrethroid, organophosphate, and neonicotinoid insecticides. J. Econ. Entomol. 104: 1357–1363.

Clifton, E. H., G. L. Tylka, and A. J. Gassmann, and E. W. Hodgson. 2017. Interactions of effects of host plant resistance and seed treatments on soybean aphid (*Aphis glycines* Matsumura) and soybean cyst nematode (*Heterodera glycines* Ichinohe). Pest Manag. Sci. 74: 992–1000.

Coupe, R. H., and P. D. Capel. 2016. Trends in pesticide use on soybean, corn and cotton since the introduction of major genetically modified crops in the United States. Pest Manag. Sci. 72: 1013–1022.

Douglas, M. R., and J. F. Tooker. 2015. Large-scale deployment of seed treatments has driven rapid increase in use of neonicotinoid insecticides and preemptive pest management in US field crops. Environ. Sci. Technol. 49: 5088–5097.

Foster, S. P., G. Devine, and A. L. Devonshire. 2007. Insecticide resistance, pp. 261–285. *In* H. van Emden and R. Harrington (eds.), Aphids as crop pests. CAB International, Oxfordshire, UK.

Frewin, A. J., A. W. Schaafsma, and R. H. Hallett. 2012. Susceptibility of *Aphelinus certus* to foliar-applied insecticides currently or potentially registered for soybean aphid control. Pest Manag. Sci. 68: 202–208.

Hanson, A. A., S. J. Bhusal, A. Lorenz, and R. L. Koch. 2016. Aphid-resistant soybean varieties for Minnesota. University of Minnesota Extension.

(http://apps.extension.umn.edu/agriculture/soybean/pest/soybean-aphid/aphid-resistant-soybean/) (accessed 5 August 2018).

Hanson, A. A., J. Menger-Anderson, C. Silverstein, B. D. Potter, I. V. MacRae, E. W. Hodgson, and R. L. Koch. 2017. Evidence for soybean aphid (Hemiptera: Aphididae) resistance to pyrethroid insecticides in the upper midwestern United States. J. Econ. Entomol. 110: 2235–2246.

Hesler, L. S., M. V. Chiozza, M. E. O'Neal, G. C. MacIntosh, K. J. Tilmon, D. I. Chandrasena, N. A. Tinsley, S. R. Cianzio, A. C. Costamagna, E. M. Cullen, et al. 2013. Performance and prospects of *Rag* genes for management of soybean aphid. Entomol. Exp. Appl. 147: 201–216.

Hill, J. H., R. Alleman, D. B. Hogg, and C. R. Grau. 2001. First report of transmission of *Soybean mosaic virus* and *Alfalfa mosaic virus* by *Aphis glycines* in the New World. Plant Dis. 85: 561.

Hodgson, E. W., and R. L. Koch. 2018. Soybean aphid field guide for the north-central region (2nd edition). Publication IPM 0060. North Central Soybean Research Program, Ankeny, IA. 62 pp.

Hodgson, E. W., E. C. Burkness, W. D. Hutchison, and D. W. Ragsdale. 2004. Enumerative and binomial sequential sampling plans for soybean aphid (Homoptera: Aphididae) in soybean. J. Econ. Entomol. 97: 2127–2136.

Hodgson, E. W., B. P. McCornack, K. A. Koch, D. W. Ragsdale, K. D. Johnson, M. E. O'Neal, E. M. Cullen, H. J. Kraiss, C. D. DiFonzo, M. Jewett, et al. 2007. Field validation of speed scouting for soybean aphid. Crop Manage. 6. doi:10.1094/CM-2007-0511-01-RS.

Hodgson, E. W., B. P. McCornack, K. J. Tilmon, and J. Knodel. 2012. Management recommendations for soybean aphid (Hemiptera: Aphididae) in the United States. J. Integr. Pest Manag. 3: E1–E10.

Hurley, T., and P. Mitchell. 2017. Value of neonicotinoid seed treatments to US soybean farmers. Pest Manag. Sci. 73: 102–112.

Insecticide Resistance Action Committee (IRAC). 2009. General Principles of Insecticide Resistance Management from IRAC. 2 pp. (http://www.irac-online.org/documents/principles-of-irm/?ext=pdf) (accessed 5 August 2018).

Insecticide Resistance Action Committee (IRAC). 2012. IRAC International Insecticide Mixture Statement. 2 pp. (http://www.irac-online.org/content/uploads/irac_mixture_statement_v1.0_10sept12.pdf) (accessed 5 August 2018).

Insecticide Resistance Action Committee (IRAC). 2018. IRAC Mode of Action Classification Scheme. 26 pp. (http://www.irac-online.org/documents/moa-classification/) (accessed 5 August 2018).

Knodel, J. J., P. Beauzay, M. Boetel, and T. Prochaska. 2018. 2018 field crop insect management guide. publication E-1143. North Dakota State University Extension Service. 115 pp. (www.ag.ndsu.edu/pubs/plantsci/pests/e1143.pdf) (accessed 5 August 2018).

Koch, R. L., and A. C. Costamagna. 2017. Reaping benefits from an invasive species: role of *Harmonia axyridis* in natural biological control of *Aphis glycines* in North America. BioControl. 62: 331–340.

Koch, K., B. D. Potter and D. W. Ragsdale. 2010. Non-target impacts of soybean rust fungicides on the fungal entomopathogens of soybean aphid. J. Invertebr. Pathol. 103: 156–164.

Koch, R. L., B. D. Potter, P. A. Glogoza, E. W. Hodgson, C. H. Krupke, J. F. Tooker, C. D. DiFonzo, A. P. Michel, K. J. Tilmon, T. J. Prochaska, et al. 2016. Biology and economics of recommendations for insecticide-based management of soybean aphid. Plant Health Prog. 17: 265–269.

Koch, R., E. Hodgson, J. Knodel, and A. Varenhorst. 2018. Management of insecticide-resistant soybean aphids. Publication E1878. North Dakota State University Extension Service, Fargo, ND, 4 pp.

Krupke, C. H., A. M. Alford, E. M. Cullen, E. W. Hodgson, J. J. Knodel, B. McCornack, B. D. Potter, M. I. Spigler, K. Tilmon, and K. Welch. 2017. Assessing the value and pest management window provided by neonicotinoid seed treatments for management of soybean aphid (*Aphis glycines* Matsumura) in the Upper Midwestern United States. Pest Manag. Sci. 73: 2184–2193.

Liu, N. 2012. Pyrethroid resistance in insects: genes, mechanisms, and regulation, pp. 457–468. *In* F. Perveen (ed.), Insecticides: advances in integrated pest management, InTech, Rijeka, Croatia.

McCarville, M. T., M. E. O'Neal, and E. W. Hodgson. 2012a. Soybean aphid-resistant soybean varieties for Iowa. Agric. and Environment Extension Publications. http://works.bepress.com/matthew_oneal/37 (accessed 5 August 2018).

McCarville, M. T., M. O'Neal, G. L. Tylka, C. Kanobe, and G. C. MacIntosh. 2012b. A nematode, fungus, and aphid interact via a shared host plant: implications for soybean management. Entomol. Exp. Appl. 143: 55–66.

McCarville, M. T., M. E. O'Neil, B. D. Potter, K. J. Tilmon, E. M. Cullen, B. P. McCornack, J. F. Tooker, and D. A. Prischmann-Voldseth. 2014. One gene versus two: a regional study on the efficacy of single gene versus pyramided resistance for soybean aphid management. J. Econ. Entomol. 107: 1680–1687.

National Agricultural Statistics Service (NASS). 2018. Agricultural chemical use survey. United States Department of Agriculture. (https://www.nass.usda.gov/Surveys/Guide_to_NASS_Surveys/Chemical_Use/) (accessed 5 August 2018).

National Research Council (NRC). 1986. Pesticide resistance: strategies and tactics for management. The National Academies Press, Washington, DC.

National Research Council (NRC). 2012. National Summit on strategies to manage herbicide-resistant weeds: proceedings of a workshop. The National Academies Press, Washington, DC.

Ohnesorg, W. J., K. D. Johnson, and M. E. O'Neal. 2009. Impact of reduced-risk insecticides on soybean aphid and associated natural enemies. J. Econ. Entomol. 102: 1816–1826.

Orantes, L. C., W. Zhang, M. A. R. Mian, and A. P. Michel. 2012. Maintaining genetic diversity and population panmixia through dispersal and not gene flow in a holocyclic heteroecious aphid species. Heredity (Edinb). 109: 127–134.

Pedigo, L. P., and M. E. Rice. 2009. Entomology and pest management, 6th ed. Prentice Hall, Upper Saddle River, NJ.

Pezzini, D. T., and R. L. Koch. 2015. Compatibility of flonicamid and a formulated mixture of pyrethrins and azadirachtin with predators for soybean aphid (Hemiptera: Aphididae) management. Biocontrol Sci. Technol. 25: 1024–1035.

Ragsdale, D. W., D. J. Voegtlin, and R. J. O'Neil. 2004. Soybean aphid biology in North America. Ann. Entomol. Soc. Am. 97: 204–208.

Ragsdale, D. W., B. P. McCornack, R. C. Venette, B. D. Potter, I. V. MacRae, E. W. Hodgson, M. E. O'Neal, K. D. Johnson, R. J. O'Neil, C. D. DiFonzo, et al. 2007. Economic threshold for soybean aphid (Hemiptera: Aphididae). J. Econ. Entomol. 100: 1258–1267.

Ragsdale, D. W., D. A. Landis, J. Brodeur, G. E. Heimpel, and N. Desneux. 2011. Ecology and management of the soybean aphid in North America. Ann. Rev. Entomol. 56: 375–399.

Ribeiro, M. G. P. M., T. E. Hunt, and B. D. Siegfried. 2018. Acute-contact and chronic-systemic in vivo bioassays: regional monitoring of susceptibility to thiamethoxam in soybean aphid (Hemiptera: Aphididae) populations from the North Central United States. J. Econ. Entomol. 111: 337–347.

Schmidt, N. P., M. E. O'Neal, P. F. Anderson, D. Lagos, D. Voegtlin, W. Bailey, P. Caragea, E. Cullen, C. DiFonzo, K. Elliot, et al. 2012. Spatial distribution of *Aphis glycines* (Hemiptera: Aphididae): a summary of the suction trap network. J. Econ. Entomol. 105: 259–271.

Smith, C. M. 2005. Plant resistance to arthropods: molecular and conventional approaches. Springer, Dordrecht.

Tabashnik, B. E., D. Mota-Sanchez, M. E. Whalon, R. M. Hollingworth, and Y. Carriere. 2014. Defining terms for proactive management of resistance to Bt crops and pesticides. J. Econ. Entomol. 107: 496–507.

Tilmon, K. J., E. W. Hodgson, M. E. O'Neal, and D. W. Ragsdale. 2011. Biology of the soybean aphid, *Aphis glycines* (Hemiptera: Aphididae) in the United States. J. Integr. Pest Manag. 2: A1–A7.

Tran, A. K., T. M. Alves, and R. L. Koch. 2016. Potential for sulfoxaflor to improve conservation biological control of *Aphis glycines* (Hemiptera: Aphididae) in soybean. J. Econ. Entomol. 109: 2105–2114.

Varenhorst, A. J., and M. E. O'Neal. 2012. The response of natural enemies to selective insecticides applied to soybean. Environ. Entomol. 41: 1565–1574.

Varenhorst, A. J., and P. M. Wagner. 2018. Foliar Insecticides in Soybean. *In:* A. Bachmann (ed.). 2018 South Dakota pest management guide: soybeans. South Dakota State University Extension. 78 pp. (http://igrow.org/up/resources/03-3042-2017.pdf) (accessed 5 August 2018).

Wang, Q., W. Xu, and S. C. Yan. 2011. Research on insecticide resistance of *Aphis glycines* in Heilongjiang Province. Dongbei Nongye Daxue Xuebao. 42: 137–140.

Wang, Q., S. Yan, W. Xu, and C. Wang. 2012. Research on resistance of soybean aphid (*Aphis glycines*) in Heilongjiang Province. Chin. Agr. Sci. Bull. 28: 218–221.

Wu, Z., D. Schenk-Hamlin, W. Zhan, D. W. Ragsdale, and G. E. Heimpel. 2004. The soybean aphid in China: a historical review. Ann. Entomol. Soc. Am. 97: 209–218.

Xi, J., Y. Pan, R. Bi, X. Gao, X. Chen, T. Peng, M. Zhang, H. Zhang, X. Hu, and Q. Shang. 2015. Elevated expression of esterase and cytochrome P450 are related with lambda-cyhalothrin resistance and lead to cross resistance in *Aphis glycines* Matsumura. Pest. Biochem. Physiol. 118: 77–81.

Zhu, Y.C., J. Adamczyk, T. Rinderer, J. Yao, R. Danka, R. Luttrell, and J. Gore. 2015. Spray toxicity and risk potential of 42 commonly used formulations of row crop pesticides to adult honey bees (Hymenoptera: Apidae). J. Econ. Entomol. 108: 2640–2647.