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RECOMMENDATIONS

Management Recommendations for Soybean Aphid (Hemiptera: Aphididae) in the United States

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ABSTRACT. Soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), is the primary pest of soybean, *Glycine max* L., in the north central region. After more than a decade of research and extension efforts to manage this pest, several consensus management recommendations have been developed for sustainable and profitable soybean production. A summary of integrated pest management (IPM) tactics for soybean aphid are discussed, including cultural, genetic, economic, and chemical controls. To date, sampling and timely foliar insecticides are routinely recommended to protect yield and delay genetic resistance to insecticides. Host plant resistance is a new tool that can regulate populations and reduce the reliance of insecticides to control soybean aphid. A combination of these management tools also will reduce overall production costs and minimize negative environmental effects such as human exposure, and mortality of beneficial insects and other animals.

Key Words: *Aphis glycines*, economic threshold, IPM, sampling, economic injury level

Soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), is an introduced insect from Asia first confirmed on soybean, *Glycine max* L., in the United States in 2000 (Ragsdale et al. 2004). Widespread soybean aphid outbreaks in the North Central region were observed in 2003 and 2005, with populations exceeding 1,000 per plant (O'Neal 2005). At this infestation level, 40% yield loss was documented and high soybean aphid densities significantly reduced seed size, seed coat quality, pod number, and plant height (Ragsdale et al. 2007, Rhainds et al. 2008). Soybean aphid proved to be economically important and is now the primary soybean pest in the North Central region. There were only occasional pest issues in Midwestern soybean before 2000, which resulted in <1% of soybean fields being treated with insecticides (USDA-NASS). But the damage potential of soybean aphid has resulted in a 130-fold increase of insecticide applications in less than 10 yr (Ragsdale et al. 2011). A decade after the discovery of soybean aphid on soybean, growers have drastically changed management practices to protect yield.

This article will summarize current practices used to monitor and manage soybean aphid. There are several general soybean production factors that must be considered for managing soybean aphid, and the tactics reviewed here are recommendations that can be used as part of an IPM program. A complementary publication, that discusses the history of soybean aphid and reviews the life cycle and population dynamics, was published recently by Tilmon et al. (2011).

Agronomic Practices

Regardless of pest pressure, selecting high-yielding seed always should be a first consideration for successful production (Pedersen 2007). Choosing elite genetic traits and an appropriate maturity group will provide a platform from which healthy plants will grow and resist environmental stressors. In addition to seed selection, there are important cultural control tactics, such as date of planting and row spacing, to consider for developing a sustainable soybean IPM program.

Modifying the date of planting can discourage some insects from being successful such as Hessian fly, *Mayetiola destructor* (Say) (Diptera: Cecidomyiidae). However, selecting a window of time to plant with the hopes of avoiding soybean aphid colonization is difficult. To date, results from variable planting studies are inconsistent and contradictory (van den Berg et al. 1997, Myers et al. 2005a, Rutledge and O'Neil 2006). Planting too early can be attractive to bean leaf beetle, *Cerotoma trifurcata* (Förster) (Coleoptera: Chrysomelidae), and favor other early-season insects. In addition, planting into cold and wet soil can promote soil pathogens that can severely damage or kill seedlings (Pedersen and Robertson 2007). Alternatively, late-planted fields also can be colonized by soybean aphid. Therefore, altering the date of planting solely to depress soybean aphid is not recommended.

There is much research on row spacing and optimal yields in relation to weed control. Spacing will change the plant growth rate and affect the timing of canopy closure in some cropping systems and can be an insect management tool (Pedigo and Rice 2008). In general for soybean, a closed canopy is beneficial for reducing insect problems but can promote foliar diseases. As for soybean aphid, altering row spacing does not appear to affect population growth or alter yield impacts from this pest (Johnson 2010).

Other agronomic factors, including plant nutrition, are relevant for managing soybean aphid. Walter and DiFonzo (2007) evaluated potassium in leaves and showed that a deficiency can lead to higher soybean aphid populations through plant effects. In another study, low potassium treatments had higher peak aphid abundance and rates of population increase compared with medium and high potassium treatments (Myers and Gratton 2006). Agricultural practices also can alter soybean aphid populations by influencing the natural enemies that prey upon them. Costamagna and Landis (2006) studied the impact of agricultural practices and biological control on soybean aphid growth, and showed that natural enemies reduce soybean aphid establishment and overall population growth in all the production systems they tested.

Scouting

Most successful IPM programs involve regular sampling of the target pest. This can be especially important for a multigenerational insect with a complex life cycle like soybean aphid (Fig. 1), which can produce >15 asexual generations in a single growing season (McCornack et al. 2004). In addition, soybean aphid has been a somewhat erratic pest since 2000, and widespread outbreaks do not occur every

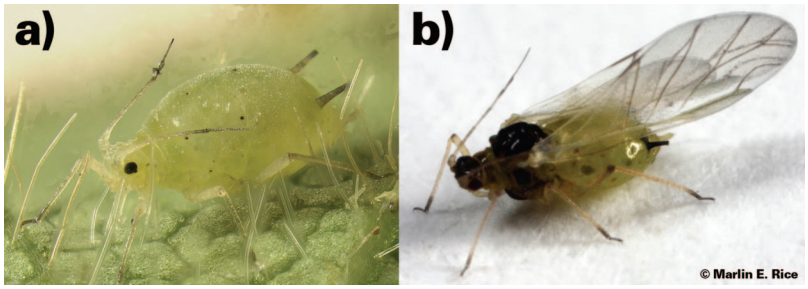

Fig. 1. Soybean aphid: a) typical colony-building wingless (apterous) form. Photo credit to Claudio Gratton; and b) migratory winged (alatae) form. Photo credit to Marlin E. Rice.

year. For those areas with cyclic outbreaks, sampling becomes even more important to help determine cost-effective treatment decisions.

The timing of spring colonization to soybean is highly variable. Some regions in the United States and Canada can be colonized by winged aphids (Fig. 1b) at soybean emergence and can experience continued immigration until seed set (e.g., southeastern Minnesota, southern Ontario). Other areas typically are not colonized until after bloom (e.g., Nebraska, North Dakota, Kentucky). Sampling weekly after bloom (R1) is particularly important because winged aphids are more abundant and likely to migrate within and between fields (Hodgson et al. 2005). Soybean aphid, like many other aphid species, also is capable of moving long distance by jet streams throughout the summer (Favret and Voegtlin 2001). There is a regional suction trapping network that provides real-time data on winged soybean aphids migrating long distances (www.ncipmc.org/traps/).

Regular sampling throughout the growing season will help producers track trends and improve the timing of management decisions. Although colonies can be initially patchy, populations can spread quickly throughout the field under favorable conditions. Soybean fields with >80% of plants infested with aphids should be monitored closely to protect yield. Turn over leaves and look for aphids, cast skins, and honeydew. In some areas within the North Central region, early-season aphids are tended by ants, which is an easy way to locate colonies during early establishment (Fig. 2).

The injury caused by phloem-feeding insects, like soybean aphid, may go undetected without close visual inspection, and feeding damage may become readily apparent only after large, yield-reducing populations have developed (Fig. 3). Taking more samples per visit will improve the accuracy of estimating the actual infestation; however, sampling is usually a compromise of accuracy and time spent looking for insects (Pedigo and Rice 2008). In addition to estimating soybean aphid densities over time, recording plant development is also essential. A description of soybean growth stages is shown in Fig. 4.

The most common type of sampling method is to count every aphid on a plant and calculate an average number of aphids per plant. For soybean aphid, sampling 38 whole plants for every 50 ac (20 ha) will be the most efficient use of time (Hodgson et al. 2004). Samplers usually start at the bottom of the plant and move up to the top. The within-plant distribution fluctuates over the season, especially as the plant produces lateral stems (McCornack et al. 2008) and the weather influences aphid population growth. Soybean aphid is strongly attracted to new growing points on soybean (Fig. 5), including expanding trifoliolate leaves (Costamagna et al. 2010).

While sampling, it is important to distinguish soybean aphid from other insects (Fig. 6). Most commonly mistaken for soybean aphid are the nymphs of potato leafhopper, *Empoasca fabae* (Harris) (Hemiptera: Cicadellidae); and pirate bugs, *Orius* spp. (Hemiptera: Anthocoridae). This aphid species is not easily dislodged from the plant, and sweep netting or beat cloth are not recommended sampling techniques.

Fig. 2. An ant-tended soybean aphid colony developing on a soybean stem. Photo credit to Brian P. McCornack.

Fig. 3. Soybean aphid honeydew can promote black sooty mold on soybean (top leaf). The top leaf is susceptible and bottom is resistant (*Rag1*). Photo credit to Brian P. McCornack.

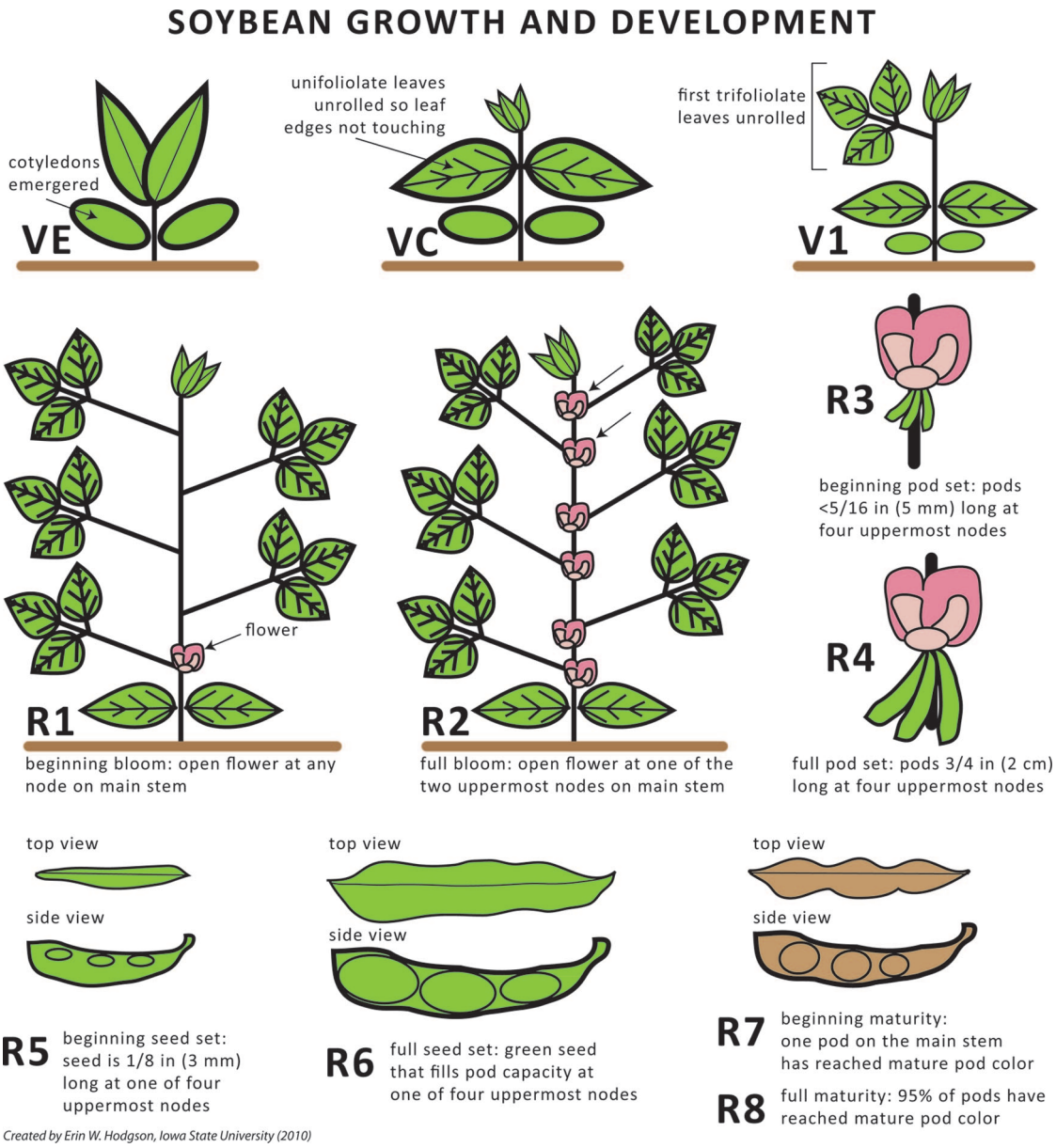

Fig. 4. Soybean growth and development, based on Pedersen (2007).

For those samplers strictly looking for a management decision (i.e., to treat or not to treat), *Speed Scouting for Soybean Aphid* is an efficient binomial sequential sampling plan (Hodgson et al. 2007) (Fig. 7). Speed Scouting uses a tally threshold of 40 aphids per plant; 40 or more aphids is considered infested whereas a plant with 39 or fewer aphids is not considered infested. This plan is conservative because most of the plants have to be infested to reach a "treat" decision. Visit (ISU) to print additional Speed Scouting forms. A web-based paperless option, called SoyPod DSS, is also available (http://my.soypod.info/). This free management tool allows users to make treatment decisions, keep historical field notes, and prioritize fields to be sampled next.

Economics

Establishing treatment guidelines for a widespead pest, like soybean aphid, is essential in an IPM program. The first step was to understand the EIL for soybean aphid and then derive an economic threshold (ET) to protect yield. Ragsdale et al. (2007) published the most significant work on threshold recommendations and is the primary reference throughout the North Central region for managing soybean aphid. This study was a multistate effort that served as the basis for the consensus threshold recommendation for soybean aphid management. A projected economic net benefit of $1.3 billion from 2003 to 2018 will be saved because of the development and adoption of the ET for soybean aphid (Song and Swinton 2009).

Before treatment recommendations are made, it is imperative to understand the relationship between yield loss and pest density. In many cases this is a linear response; as density increases there is an equal decrease in total yield. For soybean aphid, Ragsdale et al. (2007) showed a yield decrease of 6% for every 10,000 cumulative aphid-days (CAD) during the early vegetative to pod set (R4). The CAD calculation gives a season-long estimate or the total aphid pressure (i.e., number of aphids per plant per day) that a soybean plant endured within a given timeframe.

To calculate the EIL and ET of soybean aphid, the growth and damage potential must be known. In other words, how fast can soybean aphid colonies build up under ideal conditions and how much yield loss can they cause? A valid ET also takes into consideration the value of the crop and application costs to prevent the EIL. A decision

Fig. 5. Winged soybean aphid depositing nymphs on soybean. Photo credit to Brian P. McCornack.

to treat populations below the EIL, or more specifically at the ET, assumes that the treatment is justified and aphid populations will reach or exceed the EIL. Therefore, the ET is a management tool that is designed to prevent populations from reaching a damaging level and allows producers to schedule timely treatments. The ET concept is different from a gain threshold, which is the amount of yield (bu/ac) one needs to recover when a pesticide treatment is made (i.e., treatment cost divided by the market value) (Pedigo and Rice 2008). When the market value is high and the treatment cost are low, then the gain threshold is low (e.g., a gain threshold of 0.35 bu/ac is reached when the market value = $14/bu and treatment cost = $5/ac).

Treating solely based on the gain threshold is not a sustainable solution to managing soybean aphid. Aphids in general have a high propensity for developing resistance to insecticides (Devonshire et al. 1998, ffrench-Constant et al. 2004) because of their reproductive capacities and high level of dispersal. Although there are no documented cases of soybean aphid resistance in the United States yet, volatile market prices and low treatment costs should not take precedence over pest biology. Instead, management practices need to consider the long-term stewardship of insecticide use on the ecosystem and human health as well as maintaining the viability of various management tools (e.g., host plant resistance, insecticides, biological control).

Establishing a Threshold. A multistate, multiyear evaluation for the soybean aphid EIL and ET for soybean aphid was based on 19 yield-loss experiments conducted over a 3-yr period in six states (Iowa, Michigan, Minnesota, Nebraska, North Dakota, Wisconsin) (Ragsdale et al. 2007). These studies were conducted under field conditions that incorporated various naturally occurring factors such as weather and the impact of natural enemies. During bloom (R1) through beginning seed set (R5), the ET is defined as when populations exceed 250 aphids per plant with 80% of the plants infested and populations are increasing. This ET was calculated to give lead time to arrange a foliar insecticidal treatment before the EIL (≈674 aphids per plant) is reached (Ragsdale et al. 2007). Application of a foliar insecticide is recommended within 3–7 d after populations reach the ET depending on the population growth rate; faster aphid growth means less time before a treatment needs to be made.

Once soybean reaches full seed set (R6), research has not shown a reliable yield gain from an insecticide treatment (Ragsdale et al. 2007). Awareness and use of these recommendations is common for 70% of growers throughout the North Central region (Olson et al. 2008), and this approach has been shown to be more cost effective than a preventative approach of applying insecticide based on the growth stage of the plant (Johnson et al. 2009).

Recall that treating at the ET assumes the population will reach the EIL. However, this is not always the case. Many biotic and abiotic factors affect soybean aphid population growth or doubling times (number of days before the aphid population doubles). Declines in aphid populations are attributed to changes in host plant quality, natural enemies, weather extremes (van den Berg et al. 1997, Fox et al. 2004, Karley et al. 2004, Li et al. 2004) or, more realistically, a combination of all these factors. Soybean aphid populations in the laboratory can double in 1.5 d (McCornack et al. 2004). To date, such doubling rates are only obtainable under ideal environmental conditions where regulatory factors, like plant stage, natural enemies, and temperature, are not affecting aphid population growth.

Basing an ET on population doubling times derived from laboratory or even caged experiments will result in an extremely low ET (Ragsdale et al. 2007, O'Neal and Johnson 2010). For example, Catangui et al. (2009) calculated an EIL based on caged plants that resulted in an artificially low ET for soybean aphid, which would lead to overtreating aphid populations and possibly accelerating insecticide resistance. It is imperative that ETs and EILs account for multiple sources of environmental resistance (Ragsdale et al. 2007) and are applicable to a broad, geographic range for making well-informed, low-risk decisions.

Aphids can occur in "hot spots" but treatment decisions should be based on a broad sample of randomly selected plants. Producers with a field approaching the ET should consider checking aphid densities again before treatment (3–4 d after the initial treatment decision is made). If aphid numbers have decreased, or are still just below the ET, or if natural enemies such as lady beetles are present, producers may wish to delay treatment, as populations sometimes can decline naturally before exceeding the ET.

Chemical Control

Insecticides have been the primary pest management strategy used for soybean aphid control in the United States during the first decade, and there are many effective insecticides available (DiFonzo 2009, Hodgson et al. 2010). There are currently three different active ingredients for seed-applied insecticides and over 20 different active ingredients for foliar-applied insecticides that are registered for soybean aphid control (www.cdms.net/LabelsMsds/LMDefault.aspx?t).

Insecticide applications and the numbers of acres treated in soybean has increased dramatically in the Midwest since 2000. Insecticide inputs in soybean surged from <1% before 2000 to 20% in 2005 in six states (Iowa, Illinois, Indiana, Michigan, Minnesota, and Ohio) (Ragsdale et al. 2007, Song and Swinton 2009). Insecticide use for soybean aphid control has increased soybean production costs by $10–20/ac (Song et al. 2006), as well as increased risks of human pesticide poisoning and environmental impacts (Yu 2008, Bahlai et al. 2010).

As mentioned in the Economics and Establishing a Threshold sections, aphids can develop genetic resistance to insecticides and growers can help delay these events by minimizing exposure to aphid populations and only treating when populations exceed the ET. Also, rotating modes of action (e.g., pyrethroids, organophosphates, neonicotinoids) will prolong the effectiveness of available products. We strongly encourage alternating modes of action if more than one application, including seed treatments, is made during a single growing season.

Because of the high reproductive capacity and migratory movements of soybean aphid, field populations often can rebound quickly in spite of an insecticide application (Myers et al. 2005b). As a result, frequent application of insecticides may be accelerating the development of aphid resistance to certain classes of insecticides. In China, soybean aphid resistance has been reported to organophosphate insecticides (Huang et al. 1998). Strategies for reducing insecticide

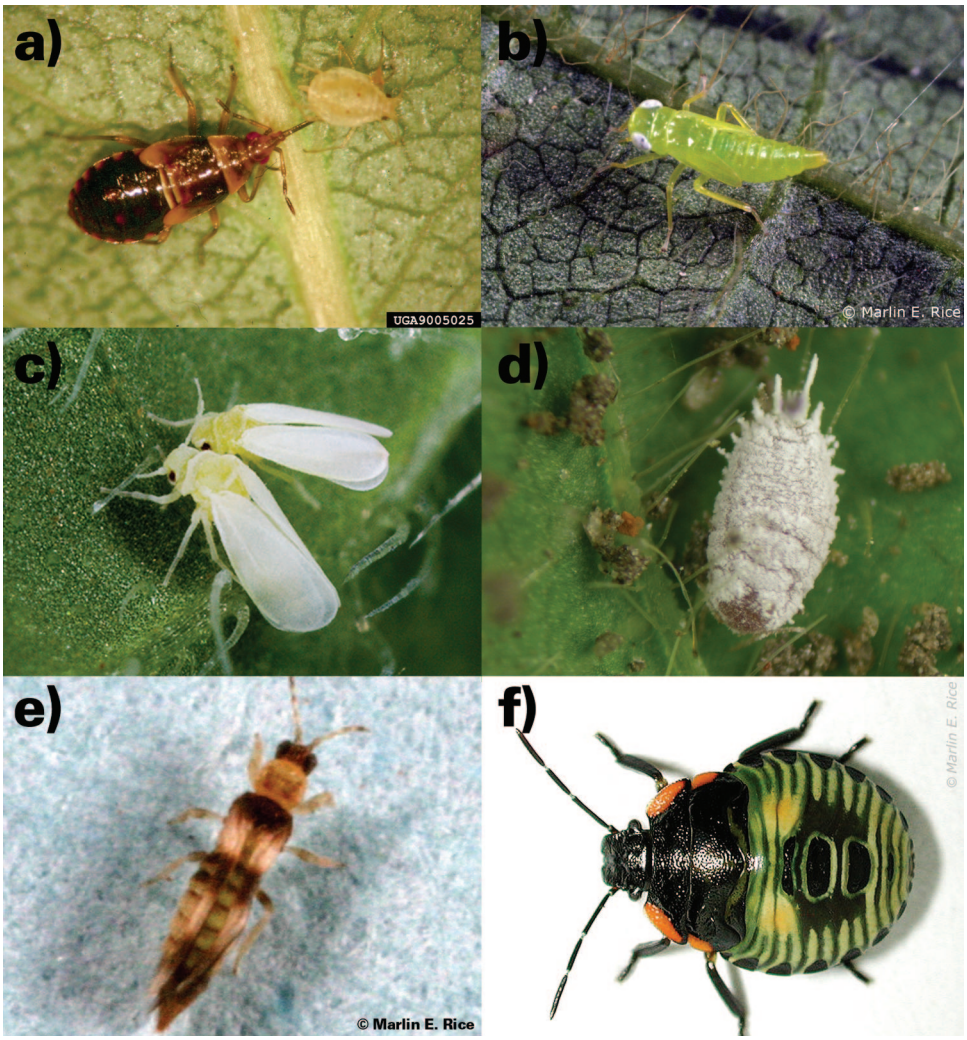

Fig. 6. Common soybean aphid look-alikes, including a) minute pirate bug, *Orius tristicolor*, nymph. Photo credit to Bradley Higbee; b) potato leafhopper, *Empoasca fabae*, nymph. Photo credit to Marlin E. Rice.; c) silverleaf whitefly, *Bemisia tabaci*. Photo credit to Stephen Ausmus; d) trochanter mealybug, *Pseudococcus sorghiellus*. Photo credit to Ronald Hammond; e) soybean thrips, *Sericothrips variabilis*. Photo credit to Marlin E. Rice; and f) green stink bug, *Acrosternum hilare*, nymph. Photo credit to Marlin E. Rice.

resistance should be implemented in North America to delay genetic resistance. Some of the most important strategies include rotating different classes of insecticides, treatments only when pest populations reach ETs, and using nonchemical strategies, such as host plant resistance and protecting natural enemies (NAS 1986, O'Neal and Johnson 2010).

Insecticidal Seed Treatments. Currently, neonicotinoids are the only class of insecticides registered for seed treatments in soybean, including three active ingredients: clothianidin, imidacloprid, and thiamethoxam. Their mode of action is nicotinic acetylcholine receptor agonists. Neonicotinoids are systemic and are absorbed through the roots and translocated through the xylem (apoplastic movement), which make them highly effective against piercing-sucking insects (Tomizawa and Casida 2005, O'Neal and Johnson 2010). Insecticide seed treatments need to be ordered well in advance to planting because seed treatments are most often applied commercially. Most available insecticide seed treatments are also packaged with a fungicide application for control of soil-borne diseases. Costs of seed treatments depend on local agronomy suppliers, and prices can range from $9 to 12/50-lb bag (or about $10–14/ac).

McCornack and Ragsdale (2006) found that thiamethoxam-treated soybean had lower CAD or aphid pressure, increased aphid mortality, and delayed colonization. Thiamethoxam-treated soybean was most effective against soybean aphid during the vegetative stages up to 49 d after planting (McCornack and Ragsdale 2006). The residual activity of systemic neonicotinoid seed treatments breaks down after 35–42 d after planting (typically V2-V4 growth stage) as the plant biomass increases and then the effectiveness of the toxin decreases (Tomizawa and Casida 2003, Johnson et al. 2008, O'Neal and Johnson 2010). When soybean aphid populations are high, populations may continue to increase after insecticide seed treatment activity has diminished and reach the ET later in the season. Such fields would need to be treated with a foliar insecticide application to prevent yield loss. Research indicates that applying a foliar spray in addition to seed treatment may result in increased yield during early aphid infestations with high aphid densities (Knodel et al. 2009, ISU, MSU). However, in years with low soybean aphid populations or when aphid infestation occurred later in the season, there was no yield gain from using insecticidal seed treatments (McCornack and Ragsdale 2006, Johnson et al. 2008, Knodel et al. 2009, Magalhaes et al. 2009).

Use of seed treatments is more of an insurance policy than an IPM strategy to protect against early season soybean aphid infestations. It is difficult to predict if soybean aphid will reach economic levels early in the season when seed treatments are most effective. A predictive forecasting system for soybean aphid would be helpful for growers to make decisions on whether to use a seed treatment the next year. Research has demon-

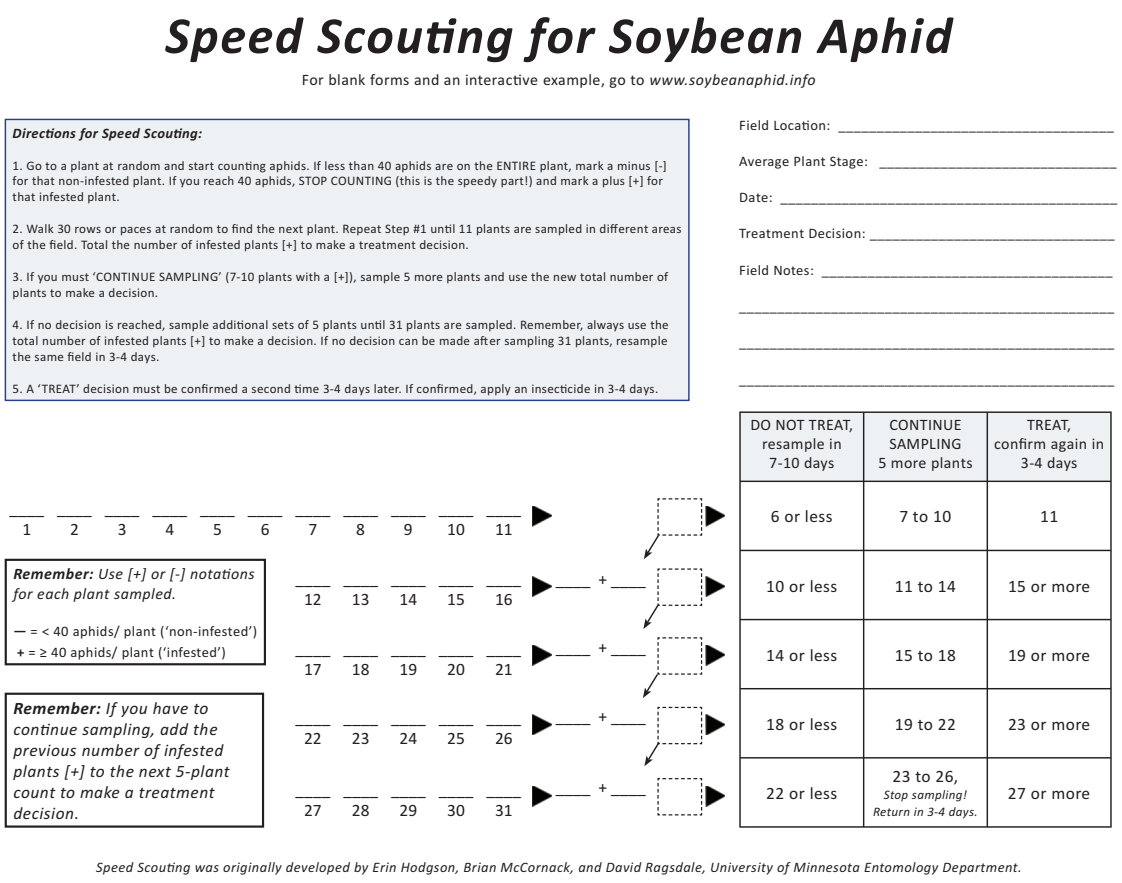

Fig. 7. *Speed Scouting for Soybean Aphid* form used to make treatment decisions, based on Hodgson et al. (2007).

strated that a single well-timed foliar insecticide application at the ET usually results in higher yield gains than the use of insecticide seed treatment alone (Myers et al. 2005a, Johnson et al. 2009, Ohnesorg et al. 2009). With the widespread and increasing use of neonicotinoids as seed treatments and foliar insecticides, there is concern among researchers about the increased potential for the development of insecticide resistance for soybean aphid (Magalhaes et al. 2008).

Foliar Insecticides. Two major classes of insecticides, organophosphates and pyrethroids, are primarily used for foliar insecticide control of soybean aphid (Johnson et al. 2009). Recent releases of new insecticides include foliar-applied neonicotinoids. Insecticide selection should take into account efficacy (kill), residual activity, resistance management, worker safety, least environmental impact (mortality of beneficial insects), price, availability, and preharvest interval (Hodgson and O'Neal 2011). Research has demonstrated significant yield differences between insecticide treated plots and untreated plots, although differences between products are not inconsistent (Rice et al. 2007). Insecticide efficacy reports of common products and formulations for soybean aphid control are available at several university entomology websites (ISU, MSU). An aphid-dip bioassay recently was developed to evaluate susceptibility of soybean aphid to foliar insecticides (Chandrasena et al. 2011); this tool will become especially valuable if soybean aphid starts to develop genetic resistance to insecticides.

Spray Timing. Proper insecticide timing is critical for effective soybean aphid management, and can result in higher and more consistent yields (Johnson et al. 2009). One of the problems in controlling soybean aphid with only insecticides is the rapid reproductive rate (Myers et al. 2005b) and their ability to rebound from insecticide applications in the absence of natural enemies and other competitive feeders. Insecticides applied early in the growing season may cause resurgence in aphid populations and secondary insect problems, which could negatively impact yield (Song et al. 2006). For example, the twospotted spider mite, *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) is rarely a major pest of soybean except when hot dry conditions favor its development (O'Neal and Johnson 2010). However, the application of pyrethroids to control soybean aphid has caused spider mite populations to flare because of the loss of mite predators (Rice et al. 2007, O'Neal and Johnson 2010). Conversely, if insecticides are applied late after aphid populations have reached the EIL, yield loss already has occurred and the cost of the insecticide often is not recouped (Song et al. 2006, Johnson et al. 2008).

On-farm strip trial data from Iowa, Minnesota, and Michigan show that fields sprayed later in August tend to have lower yields than fields sprayed in late July or early August (Song et al. 2006). Although heavy aphid infestations at full seed set (R6) in late August into September are uncommon, occasionally R6 insecticide applications are made based on field history. The preharvest interval of labeled products ranges from 7 to 60 d, and should be taken into consideration for applications made later in the summer. Warranted multiple applications of insecticides typically are not needed for management of soybean aphid, unless the field had early colonization and ideal summer growth conditions. Repeated insecticide applications can lead to increased selection pressures for pests to develop genetic resistance to insecticides and may cause higher production costs of pest management in the future (Song and Swinton 2009).

Bloom (R1-R2) and pod development (R3-R4) are the most critical growth stages to protect for obtaining optimal yields (Pederson 2007, Rice et al. 2007). Heavy soybean aphid feeding injury during R1-R4 causes flowers and small pods to abort, which significantly reduces the number and size of beans per pod and per plant (Wang et al. 1994). Myers et al. (2005b) found that when aphid populations are above the ET, insecticide applications made at the R2 and R3 crop stages had a significant yield gain over the untreated check. When soybean aphid was above the ET, Rice et al. (2007) also found that insecticides

applied during R1-R4 have higher and more consistent yields. Research indicates that a well-timed, foliar-applied insecticide at the ET is the best pest management strategy to control soybean aphid and results in the highest yield increase over untreated soybean (Ragsdale et al. 2007, Rice et al. 2007, Knodel et al. 2009, ISU). This is accomplished through regular visits to the field and estimating aphid populations through diligent scouting efforts.

Application Methods. Proper insecticide spraying methods often are more important than the selection of a particular insecticide for control of soybean aphid because most labeled products are very effective (MSU). Entomologists recommend using the full rate of an insecticide, in contrast to tank-mixing several insecticide products with reduced rates. Reduced rates of insecticides do not always provide adequate soybean aphid control or improve yield (MSU), and can lead to increased risk of insecticide resistance. To optimize foliar coverage, growers should increase pressure (40 psi), increase carrier (20 gpa of water), and use small droplet-size nozzles. Complete coverage is important for optimum aphid control because soybean aphid feeds on the undersides of leaves (Hodgson and O'Neal 2011). Soybean aphid research indicated that aerial and ground applications of foliar-applied insecticides provided comparable efficacy of soybean aphid control (NCSRP).

Because of the rapid adoption of herbicide-tolerant soybean in the Midwest, herbicides typically are applied from late May to early July depending on crop development and weed pressures (Coulter and Nafziger 2007). Many growers have adopted a preventative approach to soybean aphid management by tank-mixing insecticides with herbicides to save cost and time. There are few phytotoxicity issues with combining insecticides and herbicides; however, the optimal spray timing and method of application are different. For example, herbicide applications are conducted early in the growing season (June) when weeds are <4-inches tall, typically with low-pressure and large droplet-size nozzles to reduce spray drift (Kandel 2010). In contrast, insecticides for soybean aphid normally are sprayed between R1 and R5 (late July to late August), typically using high pressure and small droplet-size nozzles. Rice et al. (2007) have shown that tank-mixing insecticides with herbicides results in decreased insecticide efficacy. For these reasons, growers should avoid tank-mixing insecticides with herbicides.

With the introduction of invasive soybean rust, *Phakopsora pachyrhizi* Sydow, in 2004 to the southeastern United States (Schneider et al. 2005), the use of fungicides on soybean has continued to increase to reduce the risk of soybean rust outbreaks and significant yield loss (Yorinori et al. 2005, Koch et al. 2010). The adoption of preventative applications of fungicide or tank-mixing fungicides and insecticides based on calendar date or crop stage has the potential to negatively impact beneficial fungal entomopathogens that suppress soybean aphid populations when environmental conditions are conducive for fungal infection.

Several species of fungi have been found to infect soybean aphid in North America, with *Pandora neoaphidis* (Remaduiere and Hennbert) being the most commonly encountered (Nielson and Hajek 2005, Noma and Brewer 2007) (Fig. 8). The use of broad-spectrum fungicides from the strobilurin or triazole groups has been shown to reduce entomopathogens that attack soybean aphid (Koch et al. 2010). Growers, crop consultants, and agronomists need to be aware of the potential pest resurgence caused by prophylactic use of fungicides and of the interactions with soybean aphid populations and fungal entomopathogens. Market promotions advertising tank-mixing pesticides or prophylactic applications of pesticides are inconsistent with IPM strategies for soybean aphid management of soybean aphid. Knodel and Bradley (2007) and Johnson et al. (2009) found that a single insecticide application based on weekly scouting and adherence to the soybean aphid ET resulted in the highest probability of cost effectiveness and enhanced soybean production profitability compared with the prophylactic tank-mix of fungicide and insecticide. Growers who apply fungicides for soybean rust or other diseases need to monitor fields closely for aphid populations (Rice et al. 2007).

Fig. 8. Soybean aphid infected with *Pandora neoaphidis*. Photo credits to Karrie Koch.

Impacts of Insecticides on Natural Enemies. There is a suite of beneficial insects in the North Central region that attack soybean aphid. Lady beetles, *Orius* bugs, lacewing larvae, and syrphid fly larvae frequently are seen attacking aphid colonies (Fig. 9a–e). Parasitoid wasps (Fig. 9f) attack aphids and create "mummies" in soybean. Early season colonization of predators and parasitoids is important in reducing pest outbreaks (Daane and Yokota 1997). Most foliar-applied insecticides are disruptive to biological control by decreasing natural enemy populations (Johnson and Tabashnik 1999, Johnson et al. 2008, O'Neal and Johnson 2010). Ohnesorg et al. (2009) observed that neonicotinoid seed treatments had a lower impact on natural enemies than foliar-applied insecticides. However, Moser and Obrycki (2009) found neonicotinoid seed treatments caused mortality to multicolored Asian lady beetle, *Harmonia axyridis* (Pallas) (Coleoptera: Coccinellidae), larvae that fed directly on seedlings as a plant-feeding predator. Kraiss and Cullen (2008a) found that three biorational pesticides (pyrethrins, mineral oil, and insecticidal soap) provided effective management of soybean aphid, while minimizing negative impacts on the multicolored Asian lady beetle in laboratory studies.

Although biorational insecticides generally are less disruptive to natural enemy communities that suppress soybean aphid, education is needed on the role of biorational insecticides in an IPM program (Ohnesorg et al. 2009). Heimpel et al. (2004) emphasized that insecticide use may negatively impact classical biological control and the release of exotic natural enemies targeting soybean aphid.

Though natural enemies can have a significant impact on soybean aphid population growth (Costamagna and Landis 2006, Noma and Brewer 2008), insecticides currently are the most-used control method for soybean aphid. Insecticides are most profitably used in an IPM program based on scouting and the use of ETs to guide application

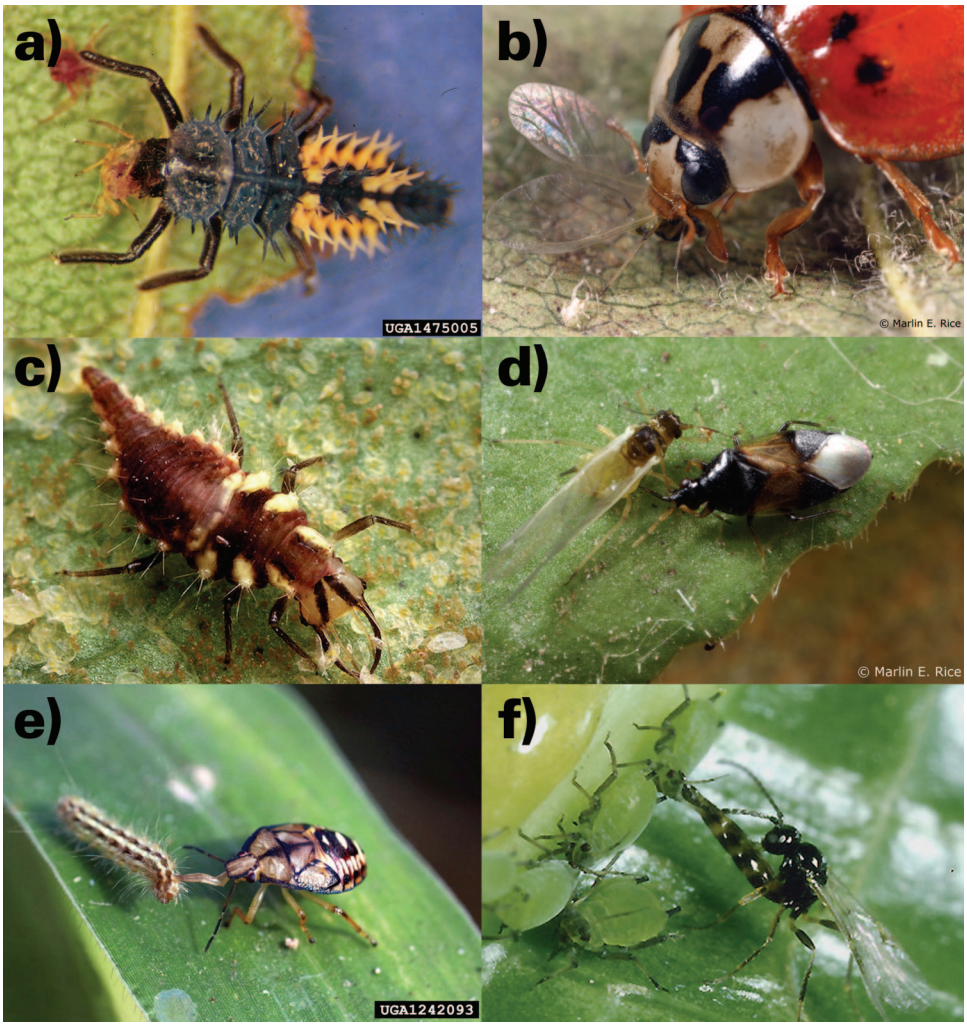

Fig. 9. Common soybean aphid natural enemies, including a) multicolor Asian lady beetle, *Harmonia axyridis*, larva. Photo credit to Whitney Cranshaw; b) multicolored Asian lady beetle adult. Photo credit to Marlin E. Rice; c) green lacewing, *Chrysoperla* spp., larva. Photo credit to Jack Dykinga; d) insidious flower bug, *Orius insidiosus*, nymph. Photo credit to Marlin E. Rice; d) spined soldier bug, *Podisus maculiventris*, nymph. Photo credit to Russ Ottens; and e) parasitoid wasp, *Lysiphlebus testaceipes*. Photo credit to Peter J. Bryant.

decisions (Johnson et al. 2009). Additional research on the impacts of insecticides on natural enemies that attack soybean aphid is needed to further understand their interactions (Stern et al. 1959, Bozsik 2006).

Host Plant Resistance

Host plant resistance is another management tool for soybean aphid. This IPM tactic has been successful for other pests (Smith 2005), such as potato leafhopper; European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae); and corn rootworm, *Diabrotica* spp. (Coleoptera: Chrysomelidae). Aphid-resistant varieties have the potential to simultaneously reduce insecticide usage and associated production costs, and preserve natural enemies in soybean.

Through intense screenings of naturally-occurring germplasm, host plant resistance in the forms of antibiosis and antixenosis to soybean aphid has been found (Hill et al. 2004, Mensah et al. 2005, Mian et al. 2008a, Zhang et al. 2009). Antibiosis is a type of resistance where exposed insects do not live as long or produce as many offspring as they could on susceptible plants. Antixenosis often is referred to as repellency where insects avoid colonizing resistant plants. To date, host plant resistant genes for soybean aphid are prefixed with "*Rag*," which is an abbreviation for *R*esistant *A*phis *g*lycines. Molecular mapping for host plant resistance is ongoing (Li et al. 2007, Mian et al. 2008b, Zhang et al. 2009), and at least four *Rag* genes for soybean aphid have been identified: *Rag*1 (Hill et al. 2004), *Rag*2 (Mian et al. 2008b), and *Rag3/rag3* and *rag4* (Zhang et al. 2009).

The *Rag1* gene is a single-gene source of antibiosis identified at the University of Illinois. In field trials, the *Rag1* gene significantly reduced aphid populations compared with susceptible controls (Hill et al. 2004; 2006a,b) (Fig. 3). However, it should be noted that *Rag1*-containing soybean are not aphid-free, and large aphid colonies can develop under favorable growing conditions. In 2009, *Rag1* soybean lines became commercially available in the United States on a limited maturity group availability basis (e.g., Syngenta, Blue River Hybrids). We expect *Rag1* soybean to be widely used throughout the United States for herbicide tolerant and organic production systems, and additional resistance genes are likely to follow. Work to calculate an EIL and ET for *Rag1* soybean currently is underway.

Host plant resistance is a management strategy that is complicated by the appearance of populations that overcome resistant genes. Insects that survive on resistant plants often are termed biotypes. Soybean aphid biotypes that can overcome *Rag1* and *Rag2* resistance have been identified in the United States (Kim et al. 2008, Hill et al. 2010), and work in this area continues. As additional *Rag* genes are developed for the commercial market, a sustainable resistance management strategy should be considered to prolong the effectiveness of this IPM tool.

Summary

Within a relatively short time, soybean aphid has become a dominant pest in soybean. As a result of the potential for yield loss, many research and extension programs have been developed for this pest. Rather than relying solely on chemical control, incorporating multiple tactics will improve longterm soybean aphid management and also reduce production costs. A management plan with an IPM focus is now available with the following recommendations:

- Select high-yielding seed that is most appropriate for the growing region, and incorporate host plant resistant genes if available.
- Insecticidal seed treatments are not recommended for soybean aphid management.
- Plant when seeds can germinate quickly and will grow vigorously.
- Scout for soybean aphid every 7–10 d after plant emergence, with the most attention focused on R1-R5. Estimate aphids based on whole plant counts and track population growth over the season, or use Speed Scouting to make treatment decisions.
- Take notice of fluctuating aphid populations. Beneficial insects and fungi can help regulate low aphid densities. Weather, plant quality, and crowding also can cause natural declines throughout the season.
- If aphids exceed the ET (250 aphids per plant during R1-R5), make a foliar insecticide application within 7 d to protect yield. Continue to check treated fields for possible reinfestations.
- Consider alternating modes of action to delay genetic resistance to soybean aphid. Avoid tank-mixing with herbicides for optimal soybean aphid coverage.

We anticipate that soybean aphid management will continue to evolve as more tools become available and as our ability to integrate them becomes more sophisticated. Important areas for future research include aphid population modeling and forecasting, importation of biological control agents, stronger host plant resistance genes, and the development of targeted insecticides.

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