

Economic Threshold for Soybean Aphid (Hemiptera: Aphididae)

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ABSTRACT Soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), reached damaging levels in 2003 and 2005 in soybean, *Glycine max* (L.) Merrill, in most northern U.S. states and Canadian provinces, and it has become one of the most important pests of soybean throughout the North Central region. A common experimental protocol was adopted by participants in six states who provided data from 19 yield-loss experiments conducted over a 3-yr period. Population doubling times for field populations of soybean aphid averaged $6.8 \text{ d} \pm 0.8 \text{ d}$ (mean \pm SEM). The average economic threshold (ET) over all control costs, market values, and yield was 273 ± 38 (mean \pm 95% confidence interval [CI], range 111–567) aphids per plant. This ET provides a 7-d lead time before aphid populations are expected to exceed the economic injury level (EIL) of 674 ± 95 (mean \pm 95% CI, range 275–1,399) aphids per plant. Peak aphid density in 18 of the 19 location-years occurred during soybean growth stages R3 (beginning pod formation) to R5 (full size pod) with a single data set having aphid populations peaking at R6 (full size green seed). The ET developed here is strongly supported through soybean growth stage R5. Setting an ET at lower aphid densities increases the risk to producers by treating an aphid population that is growing too slowly to exceed the EIL in 7 d, eliminates generalist predators, and exposes a larger portion of the soybean aphid population to selection by insecticides, which could lead to development of insecticide resistance.

KEY WORDS yield loss, population dynamics, invasive species

The soybean aphid, *Aphis glycines* Matsumura (Hemiptera: Aphididae), is native to Asia, and it has caused substantial damage to soybean, *Glycine max* (L.) Merr., in North America since its confirmed occurrence in August 2000 (Ragsdale et al. 2004). At present, the soybean aphid is the most significant insect threat to soybean production in North America. In China and in other parts of Asia, this insect is only an occasional pest of soybean, and when plants are colonized by soybean aphid in early vegetative growth stage, yield loss in excess of 50% can occur (Wang et

al. 1994). In Minnesota, soybean aphid outbreaks are associated with a reduction in plant height, pod number, seed size and quality, and yield (Ostlie 2001). The damage potential at low-to-moderate aphid densities is less clear, but soybean aphid feeding is known to disrupt the photosynthetic processes at relatively low aphid densities (Macedo et al. 2003). Soybean aphid is also a vector of numerous plant viruses (Clark and Perry 2002, Davis et al. 2005), which can further limit soybean yield and seed quality.

Aphid population declines in annual cropping systems are attributed to variable host plant quality (e.g., physiological age and antibiosis), increased activities of natural enemies, and weather extremes (van den Berg et al. 1997, Fox et al. 2004, Karley et al. 2004, Li et al. 2004). In controlled environments, soybean aphid populations can double in 1.5 d (McCornack et al. 2004), but these high intrinsic rates of increase are only obtainable under ideal conditions where population growth is not constrained by host quality, effects of weather, or natural enemies. Soybean aphid biology and the specific conditions that trigger rapid increases in population densities that are associated with yield reductions are not well understood in North America (Ragsdale et al. 2004). However, field estimates of soybean aphid population growth rates are less than

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the theoretical intrinsic rate of increase (Costamagna and Landis 2006). Therefore, basing an economic threshold (ET) on population doubling times derived from laboratory experiments that occurred in the absence of any environmental resistance will result in an artificially low economic threshold. Such an economic threshold based on laboratory derived intrinsic rate of increase has been calculated (Olson and Badibanga 2005a), resulting in a threshold of three aphids per plant, which in their model had the highest economic return. Such a threshold is not realistic, because it assumes that the multiple sources of environmental resistance would not prevent exponential growth of soybean aphid populations.

The objective of this study was to quantify the relationship between aphid densities and yield loss under field conditions in which biotic and abiotic factors were allowed to influence soybean aphid densities. These data were used to estimate the aphid density at which control measures should be applied to prevent yield losses. ETs and economic injury levels (EIL) were developed based on current expected yields, control costs, and market values for U.S. soybean.

Materials and Methods

Field Plot Design. In 2003, 2004, and 2005, a common experimental protocol was used at sites located in six states (Iowa, Michigan, Minnesota, Nebraska, North Dakota, and Wisconsin), so that comparisons could be made across locations and years (19 location-years). At each location, a soybean variety was selected that was adapted for that area, and it was planted from mid- to late May (Table 1). Plots were 3.0 m in width (four rows) by 12.3 m in length with a 76.2-cm (30-in.) row spacing. We used predetermined, targeted aphid population densities based on cumulative aphid-days (CAD) of 0, 2,000, 4,000, 8,000, 12,000, 16,000, and an untreated control (=maximum CAD) as treatments. Cumulative aphid-days is a single value that provides a measure of aphid abundance over time, and it can be calculated weekly as sampling occurs. We calculated CAD by using the procedures outlined in Hanafi et al. (1989).

Insecticide treatments varied among locations and years and depended largely upon the natural level of aphid infestation in any given location-year. Each target aphid density was replicated a minimum of four times within each location-year, and treatments were arranged in a randomized block design. With the exception of one location-year in Minnesota in 2003 where the study was located in a commercial production field, fallow ground of ≈ 3 m surrounded each plot to facilitate application of insecticide to individual plots, minimize spray drift among plots, and encourage uniform aphid colonization throughout the experiment (DiFonzo et al. 1996, Hodgson et al. 2005). Soybean aphids were allowed to naturally colonize the field except in Nebraska in 2004 where soybean aphids were seeded into plots by using field-collected aphids from a nearby field. In the Nebraska plots, an expand-

ing trifoliolate containing three to five aphids was excised and placed on approximately one plant per 30 cm of row within each plot on 23 July 2004. The timing of this artificial infestation matched the general appearance and density of aphids in most Nebraska soybean fields. In all location-years, a foliar insecticide, lambda-cyhalothrin at 16.8–28.0 g (AI)/ha (Warrior with Zeon Technology, Syngenta Crop Protection, Greensboro, NC), was applied to all plots in a given treatment by using ground equipment once a target aphid density in a treatment in terms of CAD was reached (averaged across all blocks). In all cases, insecticides were applied within 2 d after aphid counts were completed. If soybean aphid populations began to increase after the initial insecticide application, additional applications were applied to prevent aphid populations from increasing.

Aphid Sampling and Soybean Yield. Nondestructive whole-plant samples were taken to enumerate the total number of aphids per plant. To detect small populations early in the season, up to 20 plants per plot were inspected. As the season progressed and the frequency of encountering plants with aphids increased to 50%, 10 plants per plot were sampled. When >80% of plants were aphid infested, five plants were counted per plot at each sampling date. For analysis, all data were converted to mean number of aphids per plant per plot. Soybean growth stages (Fehr and Caviness 1977), whether vegetative or reproductive, were noted each week.

Yield was estimated by harvesting the entire middle two rows of each plot with a small-plot combine and adjusting seed moisture to 13%. Linear regression (PROC REG; SAS Institute 2001) was then used to relate percentage yield reduction to CAD; slope and intercept estimates were used in all EIL calculations.

Values Used in Calculation of an Economic Injury Level. Cost estimates for insecticide and application costs, market value, and expected yield were used to calculate an EIL for soybean aphid. A gain threshold (GT) expressed in percentage yield loss was calculated by estimating control costs (C) [\$/ha] divided by estimated market value (V) [\$/ton] by using various yield potentials (Y) [tons/ha] (Pedigo et al. 1986), which is equivalent to

$$GT (\% \text{ yield loss}) = \frac{C}{V \times Y} \times 100 \quad [1]$$

Average retail price of representative insecticides registered for soybean aphid control and their associated application costs were obtained from an informal phone survey of multiple local elevators along with published sources (Dobbins et al. 2004, WASS 2004, Edwards and Smith 2005). Average soybean prices from 2000 to 2005 were obtained from the National Agriculture Statistical Services (NASS 2006). Finally, soybean yield potentials used in the calculation of the GT represent the range of long-term average soybean yield throughout the North Central growing region (NASS 2006).

Table 1. Soybean aphid population growth rates for the untreated controls in each of the 19 location-years

Location (city, state)	Planting date	Brand; variety	Julian start date ^a	Julian end date ^b	Population growth rate ^c (<i>r</i>) ± SEM	Intercept ^d ± SEM	R ²	P value	Discrete daily growth rate (λ)	Doubling time(d) ^e
Rosemount, MN	21 May 2003	NK; S19-V2(RR)	189	209	0.192 ± 0.010	-33.9 ± 2.0	0.995	0.003	1.211	3.6
Rosemount, MN	3 June 2003	NK; S19-V2(RR)	189	209	0.229 ± 0.024	-40.1 ± 4.7	0.979	0.010	1.257	3.0
Lamberton, MN, field 1	10 May 2003	Thompson; 7227CR	200	234	0.198 ± 0.016	-38.1 ± 3.5	0.974	<0.001	1.219	3.5
Lamberton, MN, field 2	16 May 2003	Cropplan; R1976	199	227	0.261 ± 0.031	-50.5 ± 6.8	0.957	0.004	1.298	2.7
New Ulm, MN	5 May 2003	Stine; 1918-4	193	220	0.074 ± 0.022	-9.5 ± 4.6	0.733	0.030	1.077	9.4
Prosper, ND	24 May 2003	Asgrow; AG0801(RR)	202	230	0.144 ± 0.006	-27.9 ± 1.3	0.995	<0.001	1.155	4.8
Rosemount, MN, field 1	28 May 2004	Pioneer; 91B91(RR)	209	223	0.113 ± 0.012	-22.0 ± 2.6	0.988	0.069	1.119	6.2
Rosemount, MN, field 2	28 May 2004	Pioneer; 91B91(RR)	209	223	0.143 ± 0.024	-19.0 ± 11.9	0.781	0.310	1.110	6.7
Rosemount, MN, field 3	28 May 2004	NK; S19-R5(RR)	179	214	0.143 ± 0.024	-25.2 ± 4.7	0.901	0.004	1.153	4.9
Concord, NE	29 May 2004	Asgrow; 2703	207	242	0.139 ± 0.018	-25.5 ± 4.1	0.934	0.002	1.149	5.0
Chariton, IA	10 May 2005	Stine; 3532-4	209	249	0.071 ± 0.022	-11.9 ± 5.0	0.783	0.046	1.073	9.8
Ames, IA	23 May 2005	Stine; 3532-4	209	249	0.067 ± 0.024	-10.8 ± 5.6	0.715	0.071	1.069	10.4
Nashua, Iowa	16 June 2005	Prairie Brand; PB-2183RR	202	241	0.077 ± 0.009	-11.8 ± 2.0	0.944	0.001	1.080	9.0
East Lansing, MI	5 May 2005	Prairie Brand; PB-2183RR	206	243	0.085 ± 0.014	-14.1 ± 3.0	0.906	0.003	1.089	8.2
Rosemount, MN	21 May 2005	Crows; C 2133 R	206	243	0.053 ± 0.011	-6.5 ± 2.5	0.887	0.017	1.055	13.1
Arlington, WI	1 May 2005	Crows; C 2133 R	206	243	0.052 ± 0.014	-6.3 ± 3.3	0.810	0.038	1.053	13.4
Mean			179	229	0.128 ± 0.013	-20.5 ± 2.7	0.942	<0.001	1.137	5.4
SEM			192	214	0.161 ± 0.016	-28.4 ± 3.3	0.980	0.010	1.175	4.3
			164	194	0.129 ± 0.015	-20.4 ± 2.6	0.950	0.001	1.137	5.4
			197	228	0.127				1.138	6.8
			3	4	0.014				0.016	0.8

^a Date when soybean plants in untreated control plots reached 80% infestation.

^b Date when soybean aphid populations peaked in untreated control plots.

^c The underlying model for population growth is $N_t = N_0 e^{rt}$, which is equivalent to $\ln(N_t) = \ln(N_0) + rt$, where N_0 is the initial density, r is the population growth rate (i.e., slope from the linear regression), and t is expressed in Julian days.

^d The intercept equals the $\ln(N_0)$, where N_0 is the initial density.

^e Doubling time equals $\ln(2)$ divided by r .

An EIL expressed in CAD was calculated using an adjusted percentage yield potential by subtracting the GT calculated in equation 1 from the maximum potential yield set at 100% and incorporating the y -intercept (β_0) and slope (β_1) parameters estimated from the linear regression of CAD against percentage yield loss and can be written as follows:

$$\text{EIL (CAD)} = \frac{\beta_0 - (\% \text{ yield potential})}{\beta_1} \quad [2]$$

To convert the EIL expressed as CAD to an EIL based on aphid density (aphids per plant) at a particular point in time, we used the general formula for the summation of a geometric progression:

$$s = \frac{l\lambda - a}{\lambda - 1} \quad [3]$$

where in our application, s is the CAD on a per plant basis; λ is the discrete time population growth rate ($\lambda = e^r$ with e being the base of the natural logarithm and r being the population growth rate); a is aphid density at the start of accumulation of aphid-days; and l is aphid density on the last day of the series. In this case, l is also the EIL but expressed as aphids per plant. For convenience we conservatively set $a = 1$ under the assumption that the accumulation of aphid-days is insignificant until densities reach an average of one aphid per plant. We rearrange this equation to solve for l , which yields the following:

$$l = \frac{s(\lambda - 1) + 1}{\lambda} \quad [4]$$

In this equation, s is equivalent to the EIL calculated from equation 2. Finally, to convert this EIL to an economic threshold, expressed in aphids per plant that crop managers will use, we calculated aphid densities t days before reaching the EIL based on the equation λ^t . For our purposes we set t , or lead time, to 1, 3, 5, and 7 d. This ET also assumes that the aphid population is increasing and that crop managers will need anywhere from 1 to 7 d to make arrangements to have a foliar insecticide applied to a field. To solve for the number of d (t) it takes for a given aphid density to reach a specific EIL (l) we can rearrange the equation used to calculate lead time,

$$t = \frac{\ln(l/a)}{\ln(\lambda)} \quad [5]$$

where a is the initial aphid density and λ is derived from the estimated population growth rates.

To estimate λ used in equations 4 and 5, we averaged the population growth rate (r) from all 19 location-years by using aphid population growth data from the untreated control plots where maximum CAD occurred. Aphid densities were natural log transformed and simple linear regression was used to estimate r for each individual location-year. The population growth rate was calculated using aphid densities between the periods when aphid populations first reached 80% plant infestation and the point in time when peak aphid densities were observed. For this application,

the underlying model for population growth is $N_t = N_0 e^{rt}$, which is equivalent to $\ln(N_t) = \ln(N_0) + rt$, where N_0 is the initial aphid density, r is the population growth rate (i.e., slope from the linear regression), and t is expressed in d (Julian days). Discrete daily growth rate (λ) was calculated as e^r , averaged across all location-years, and used in the calculation of all ETs.

Results and Discussion

Market Value and Control Costs Used in Calculation of the EIL. Application cost of using a personally owned, nonpropelled, boom sprayer was estimated at \$5.09/ha by Lazarus and Selley (2005). Their costs included fuel, lubricants, repairs, maintenance, labor, and power and implement depreciation, interest, insurance, and housing of equipment. Custom application costs for ground application in 2005 averaged \$12.23/ha (range, \$8.65 to \$21.00/ha) (Dobbins et al. 2004, WASS 2004, Edwards and Smith 2005). Custom aerial application costs in 2004 and 2005 averaged \$14.85/ha (ranged from \$12.36 to \$16.68/ha) (Dobbins et al. 2004; Edwards and Smith 2005). We obtained retail cost of commonly used insecticides for soybean aphid control that included pyrethroids (lambda-cyhalothrin; zeta-cypermethrin, or Mustang, FMC Corporation, Philadelphia, PA; and esfenvalerate or Asana XL, DuPont, Wilmington, DE) and an organophosphate (chlorpyrifos or Lorsban-4E, Dow AgroSciences LLC, Indianapolis, IN). Total control costs included the insecticide and its application, and we derived three estimates of soybean aphid control costs: 1) lowest application rate of \$16.41/ha (\$6.64/acre) by using the lowest cost insecticide applied with grower-owned equipment, 2) a mid-range control cost of \$24.51/ha (\$9.92/acre) that is representative of custom ground application of a moderately priced insecticide, and 3) a high control cost option at \$32.94/ha (\$13.33/acre), which represents a maximum labeled rate of an expensive insecticide custom applied by air (Table 2).

Market values used in the calculation of the EIL represented three probable soybean prices for the North Central Region: 1) \$202.09/ton soybean (\$5.50/bu) as a conservative or lowest expected market price, 2) a mid-range market price of \$220.46/ton (\$6.00/bu), and 3) an optimistic soybean price of \$238.83/ton (\$6.50/bu). Our soybean price estimates are not a fine-tuned forecast for soybean prices, but rather we used these different values to assess the sensitivity of the soybean aphid EIL to fluctuating soybean prices and application costs (Barrigossi et al. 2003). Yield expectations used in calculating the EIL ranged from 2.02 ton/ha (30 bu/acre) to 4.04 ton/ha (60 bu/acre). These yield expectations represent a range of average yields reported for various states or regions within the United States (NASS 2006). Other economic factors that may affect some production systems also should be considered when estimating an ET, but they are too numerous to estimate here. For example, in narrow row soybean production systems, yield losses from 1 to 2.5% are caused by driving ground equipment through

Table 2. Economic thresholds (ET) and economic injury levels (EIL) for soybean aphid with various control costs, market prices, and soybean yield potentials

Cost of control (\$/ha) ^a	Market price (\$/ton) ^b	Yield potential (ton/ha) ^c	EIL: cumulative aphid-days	EIL: aphids per plant	ET with different lead times (d):			
					1	3	5	7
16.41	202.09	2.02	5,649	684	601	465	359	278
		2.69	4,188	507	446	345	266	206
		3.36	3,309	401	353	272	211	163
		4.04	2,715	329	289	224	173	134
	220.46	2.02	5,160	625	549	425	328	254
		2.69	3,821	463	407	314	243	188
		3.36	3,015	366	321	248	192	148
		4.04	2,471	300	263	204	157	122
	238.83	2.02	4,747	575	505	391	302	233
		2.69	3,510	425	374	289	223	173
		3.36	2,766	335	295	228	176	136
		4.04	2,264	275	241	187	144	111
24.51	202.09	2.02	8,546	1,035	909	703	543	420
		2.69	6,363	771	677	523	404	313
		3.36	5,051	612	538	416	321	248
		4.04	4,164	504	443	343	265	205
	220.46	2.02	7,816	946	832	643	497	384
		2.69	5,815	704	619	478	370	286
		3.36	4,611	559	491	379	293	227
		4.04	3,798	460	405	313	242	187
	238.83	2.02	7,198	871	766	592	457	353
		2.69	5,350	648	570	440	340	263
		3.36	4,240	514	452	349	270	208
		4.04	3,489	423	372	287	222	172
32.94	202.09	2.02	11,561	1,399	1,230	950	734	567
		2.69	8,627	1,044	918	709	548	424
		3.36	6,863	831	730	564	436	337
		4.04	5,671	687	604	467	360	279
	220.46	2.02	9,696	1,174	1,032	797	616	476
		2.69	7,890	955	840	649	501	387
		3.36	6,273	760	668	516	399	308
		4.04	5,180	627	552	426	329	254
	238.83	2.02	8,933	1,081	951	735	568	439
		2.69	7,266	880	773	598	462	357
		3.36	5,773	699	615	475	367	284
		4.04	4,765	577	507	392	303	234
		Mean	5,563	674	592	458	354	273

^a Cost of control in \$/ac equivalents are \$6.64, 9.92, and 13.33, respectively.
^b Market value estimates in \$/bu equivalents are \$5.50, 6.00, and 6.50, respectively.
^c Yield expectations in bu/ac equivalents are 30, 40, 50 and 60, respectively.

mature soybean fields without a nonplanted tram line to apply insecticides (Beuerlein et al. 2005). Such mechanical losses caused by ground application are not included in our calculated ET. Conversely, availability of generic insecticides could reduce control costs and seed treatment does seem to slow the early season population growth rate of soybean aphid. However, to obtain maximum economic yield during aphid outbreak years, a foliar application may still be warranted in fields where seed treatments were used (McCornack and Ragsdale 2006). Here, we focused on the major economic variables when calculating a range of ETs and EILs.

Aphid Population Densities and Associated Yields. An example of the graphical relationship between aphids per plant and CAD from one location-year is presented in Fig. 1A and B, respectively. It is difficult to discern the population trends among various target aphid densities (Fig. 1A) when plotting aphid density on a per plant basis. Differences are apparent when converting from aphids per plant to a CAD scale (Fig. 1B). When an individual CAD line remains parallel

with the x-axis (Fig. 1B), this represents few or no aphids per plant were found during subsequent sampling periods.

Initial soybean aphid colonization across all location-years occurred between 1 June and 23 July, corresponding with plant growth stages V1 (first trifoliolate) to reproductive stage R2 (multiple flowers). Mean peak aphid density and standard error (\pm SEM) in untreated control plots for all location-years was $1,262 \pm 351$ aphids per plant with peak densities ranging from 17 to 4,275 aphids per plant. Peak aphid densities typically occurred between late July and late August (Fig. 2) when soybeans were in reproductive growth stages R3 (pod formation) through R5 (full size pod). Mean CAD across all location-years was $10,573 \pm 1,338$ and ranged from 1 to 70,771 across all target aphid densities (Fig. 2). Mean population growth rate, r , across all location-years was $0.127/d \pm 0.014$ or $\lambda = e^r = 1.138/d \pm 0.016$ with R^2 values for all location-years ranging from 0.715 to 0.995 (Table 1). Recall, r was calculated using transformed weekly aphid counts beginning when sampling data showed

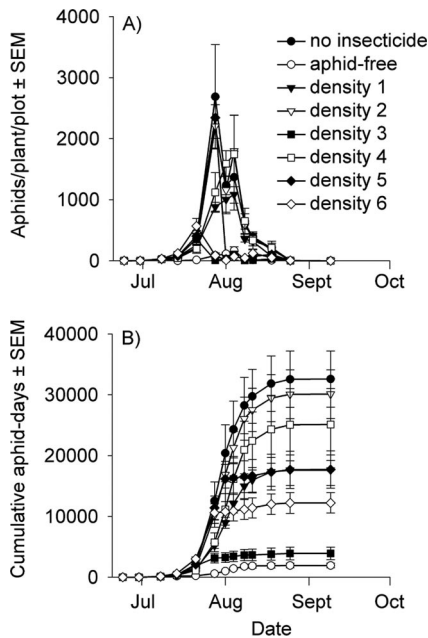


Fig. 1. Soybean aphid population curves expressed as aphids per plant (A) and CAD (i.e., one aphid per plant per day equals one aphid-day) (B) over multiple sampling times in one location-year (Rosemount, MN, in 2003).

>80% of plants were infested and ended when peak aphid density was attained. Average aphid density at 80% infestation was 21 ± 7 aphids per plant in the untreated controls. From the estimates of r we calculated the average doubling time in days using the equation $\ln(2)/r$ (Table 1) and for all 19 location-years the average doubling time for field populations was 6.8 ± 0.8 d with observed doubling times ranging from 2.7 to 13.4 d. McCornack et al. (2004) estimated intrinsic rate of increase under controlled conditions at various constant temperatures and values ranged from 0.383–0.474 at constant 35 and 20°C, respectively. Their estimate of population doubling time at the optimal temperature of 27.8°C was calculated as 1.3 d. These population growth estimates by McCornack et al. (2004) represent the biotic potential for soybean aphid in absence of environmental resistance. Here, we estimated growth rates (r) of field populations which accounted for impact of natural enemies, weather, increase or loss of aphids from winged aphids (immigration and emigration), and other factors (van den Berg et al. 1997, Li et al. 2004, Costamagna and Landis 2006).

Others have calculated an ET for soybean aphid by using laboratory-derived intrinsic rate of increase (Olson and Badibanga 2005a) or from population growth rates of caged field populations (Catangui 2006), which excluded natural enemies and other events such as rainfall that can significantly reduce population growth rates (Dixon 1976). Setting an ET too low by using population doubling times based on laboratory-derived reproductive rates or those that occur in

the absence of natural enemies will result in too many fields requiring treatment without realizing an economic benefit. In other work (McCornack and Ragsdale 2006), treating soybean aphid populations that did not exceed the ET calculated here resulted in accrued control costs without a measurable yield benefit, thus a net loss to producers. For other aphid pests, frequent application of insecticide has resulted in high levels of insecticide resistance (Radcliffe and Ragsdale 2002, Wang et al. 2002). Care must always be exercised when dealing with aphids that reproduce parthenogenically during the growing season to avoid repeated insecticide applications that could lead to resistance.

Across all 19 location-years in plots where the target aphid density was 0 CAD, the observed CAD averaged $1,567 \pm 446$. Most of the CAD in these plots occurred during vegetative growth stages V1 to V8, and subsequent insecticide application kept aphid density low during the reproductive stages. Myers et al. (2005) showed that application of insecticides to vegetative growth stages for soybean aphid control had no measurable impact on yield, so any plant injury caused by aphids feeding during vegetative growth stage in this study was likely immeasurable. At the time of the first insecticide application to the plots with a target aphid density of 0 CAD, mean aphid density on a per plant basis was 17 ± 3 aphids per plant. Mean aphid density on a per plant basis after application of lambda-cyhalothrin was 3 ± 1 and ranged from 0 to 20. Only in four of the 19 location-years (two locations in Minnesota in 2003 and two locations in Iowa in 2005) was a second insecticide application made to plots with a target aphid density of 0 CAD, and in two location-years (one each in Iowa and Michigan in 2005), a third insecticide application was needed. In these six location-years where additional insecticide application were deemed necessary, mean aphid density at the time of the second application was 77 ± 13 and for the third application mean aphid density was 12 ± 9 aphids per plant. We intentionally avoided more frequent application of insecticides, e.g., weekly, to plots where the target aphid density was 0 CAD. By applying insecticides too frequently, especially pyrethroids, twospotted spider mite, *Tetranychus urticae* Koch, outbreaks can occur (Yang et al. 2002, Steffey et al. 2006), which would confound the yield loss relationship. No spider mite outbreaks were noted from any of the 19 location-years. In all remaining location-years (13 of 19) only a single application was needed to control aphids and population growth did not increase after an insecticide application.

Because the experiment was conducted in six states where the soybean maturity group typically planted in each state ranged from group 00 to group 3, we were unable to directly compare yield losses among locations. Average yield in plots that had the fewest CAD was 3.38 ± 0.23 ton/ha (50.2 ± 3.4 bu/acre) and ranged from 1.96 to 4.8 ton/ha (29.2–71.4 bu/acre). Because weather conditions, soil type, maturity group, and other agronomic factors were highly variable among location-years, we measured the change in

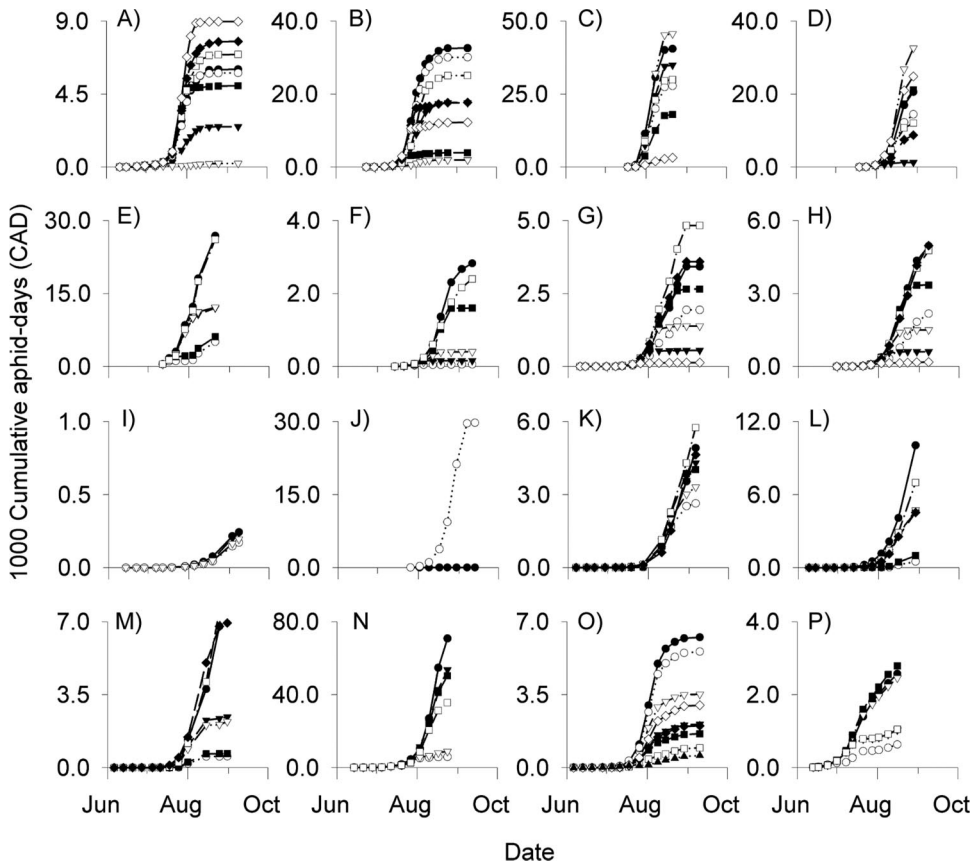


Fig. 2. Cumulative aphid-day curves for all 19 location-years during the 2003, 2004, and 2005 seasons. (A–E) Minnesota 2003. (G–I) Minnesota 2004. (O) Minnesota 2005. (F) North Dakota 2004. (J) Nebraska 2004. (K–M) Iowa 2005 (each panel for Iowa represents two planting dates at each of three unique locations for a total of six location-years). (N) Michigan 2005. (P) Wisconsin 2005. Symbols represent different target CAD densities within each location-year.

yield (percentage of maximum yield) as aphid-days accumulated. This allowed us to directly compare data from all 19 location-years. Within a single location-year we measured yield where the target aphid density was 0 CAD and designated this yield as the maximum yield (100%) obtainable. We then measured the percentage yield loss relative to this maximum yield in treatments where the target aphid density was >0 CAD. It is not possible to totally eliminate aphids even with repeated insecticide application, but the goal was to keep aphids as low as possible in the treatment where the target aphid density was 0 CAD without flaring secondary pests. For these 19 location-years, there was no evidence of bean leaf beetle, *Cerotoma trifurcata* (Forster), feeding or injury caused from other defoliating insects reported, so yield losses measured here are from plant damage solely attributed to soybean aphid feeding injury.

We used linear regression to relate relative yield obtained in the plots where the target aphid density was 0 CAD to relative yield in plots where aphids were allowed to accrue higher CAD. We observed that CAD was negatively correlated with yield ($F = 212.09$; $df = 1, 103$; $P < 0.0001$; $R^2 = 0.665$) (Fig. 3). In

addition, the y-intercept [$y = 0.9985 - 0.0688(\text{CAD})$] from the linear regression passed through 100% of the proportion maximum yield (Fig. 2), indicating that the yield loss relationship was best explained by the linear regression and that when CAD were near zero yield

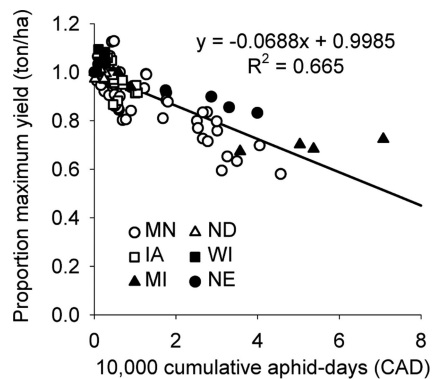


Fig. 3. Percentage of maximum yield comparing plots with the target aphid density of 0 CAD to plots with target aphid densities >0 CAD for all 19 location-years ($n = 116$).

observed was not different from the yield potential. The 95% confidence interval (CI) for the y-intercept was 0.984–1.016, and, therefore not significantly different from 1.0 at $\alpha = 0.05$. Yield (tons per hectare) was reduced by 6.88% (95% CI was 5.94–7.82%) for every 10,000 aphid-days accumulated (Fig. 3).

As an example of how long it takes to accumulate $\approx 5,563$ aphid-days, the mean EIL listed in Table 2, for a 7-d lead time, we provide the following hypothetical calculation. If the starting aphid population was one aphid per plant (a) and we used the lowest and highest EILs from Table 2 of 275 and 1,399 for the values of (l) in equation 5 and the mean value for λ of 1.138 (Table 1), we can solve for the number of d (t) it will take this aphid population to reach either EIL. For the EIL of 275, it will take 43 d and for the EIL of 1,399, it will take 56 d or ≈ 6 –8 wk for aphids to go from one aphid per plant until they reach the EIL.

A more relevant question might be how long will a starting population of 100 aphids per plant take to reach the EIL? First, we must use equation 3 to estimate how many CAD occurred between 1 and 100 aphids per plant. Solving for s in equation 3, there were 817 CAD, and this value is subtracted from the average EIL in CAD (Table 2) of 5,563, leaving 4,746 CAD remaining. Using this remaining value in equation 4, we can solve for l , which is 576 aphids per plant. The number of days it will take to go from 100 aphids per plant to 576 aphids per plant can be estimated using equation 5 by using the value of λ as 1.138 (Table 1), which when solved for (t) in equation 5, the EIL will be reached in 14 d.

In general, as aphid populations increase, the more accurate the prediction of when the EIL will be reached. To predict when the aphid density will reach the EIL starting with a density of one aphid per plant is nearly impossible. There is too much time (6–8 wk) where weather, natural enemies, disease, host plant quality, and other factors could influence the aphid population growth rate. In the examples above, only 15% of the CAD needed to reach the EIL were realized when aphid populations were between 1 and 100 aphids per plant. It would take ≈ 4 –6 wk for aphid densities to reach 100 aphids per plant. Conversely, 85% of the CAD needed to achieve the EIL occurred after the aphid density reached 100 per plant and an estimated additional 14 d at the average aphid population growth rates to reach the EIL once aphid densities reached 100 per plant.

Economic Threshold. Although we estimated the yield response of soybean injury to soybean aphid feeding using CAD as a measure of season-long exposure of plants to soybean aphid, we suggest that this method will not be as useful to most producers or their advisors as an ET based on aphid density per plant. To calculate CAD requires regular and multiple visits to the field. If sampling occurs less frequently or at irregular intervals that greatly exceed 7 d, such estimates of CAD are less reliable. Therefore, we converted the EIL based on CAD to the average aphid density per plant using the average, field-based, finite population doubling time of 6.8 d (Table 1) to calcu-

late the aphid density on a per plant basis that would occur at selected intervals before reaching the EIL. We arbitrarily selected 1, 3, 5, and 7 d before reaching the EIL, and we estimated the ET in terms of aphids per plant (Table 2). The mean ET across all yield expectations, market values, and control costs presented in Table 2 with a lead time of 7 d was 273 ± 38 (95% CI) aphids per plant. The corresponding EIL was 674 ± 95 (95% CI) aphids per plant.

In 18 of the 19 location-years, peak aphid abundance was reached between growth stages R3 to R5; at the time of 80% infestation, when measurement of aphid population growth rates were initiated, plots were in plant growth stages R1 (first flower) to R4 (intermediate pod formation). Only one location-year (Nebraska 2004) had peak aphid abundance that occurred during soybean growth stage R6 (full size green seed). Although a significant yield loss was measured at the Nebraska 2004 location, Ostlie (2001) showed with on-farm strip trials that producers were less likely to achieve an economic benefit by treating aphid populations when plants were in reproductive stage R6 or later. With the majority of the location-years having peak aphid abundance that exceeded 80% infestation as early as R1 and the ET exceeded at the latest during R5, the ET developed here using a 7d lead time is valid between R1 to R5. More research is needed to estimate a valid threshold for growth stages after R5. Our data suggest that an ET for R6 and later growth stages will exceed 273 aphids per plant, but we have too few data sets to accurately estimate the ET during R6 and no data for aphid populations that might peak during R7.

These data collected from 19 location-years over a 3-yr period and in six states represent a wide range of soybean production systems and aphid infestations with respect to the period between initial colonization and peak population density (Fig. 2). EILs and the calculated ET for any pest needs to be dynamic and respond to changing conditions in market value, expected yield, and variable control costs (Barrigossi et al. 2003). Table 2 covers a wide variation in the associated costs and market values using the yield-loss regression equation (Fig. 3) to calculate an ET. The aphid population data we used to derive the EIL and corresponding ET were from field populations that increased in the presence of natural enemies (predators, parasites, and pathogens), adverse weather conditions (heavy rainfall, drought stress, and low and high temperatures that are beyond optimal ranges), and plant growth stages. We made the assumption that all varieties used in the study were susceptible to soybean aphid, because no aphid-resistant soybean variety is currently available to growers in the North Central region (Li et al. 2004). In the future, soybean varieties will be developed and released that are resistant or tolerant to soybean aphid. Equally likely is the release and establishment of classical biological control agents along with a greater understanding of the value of native natural enemies. This ET will therefore need to be modified to account for such changes to the soybean production system. For example, re-

sistant soybean varieties may delay aphid doubling times and EILs for tolerant varieties would be higher than our reported values. Also, new yield loss relationships will need to be estimated for resistant or tolerant soybean varieties.

If the maximum soybean yield and highest soybean price is expected and the lowest possible treatment cost is assumed, the ET with a 7-d lead time is 111 aphids per plant with a corresponding EIL of 275 (Table 2). However, caution must be used in interpreting these calculated thresholds that fall well below the average ET of 273 and EIL of 674 aphids per plant. The GT for the lowest treatment cost is approximately the value of 0.07 ton/ha (≈ 1 bu/acre), and significant yield differences this small were not measurable from any of our 19 location-years. Essentially, ET and EIL values can be calculated using the yield-loss equation from this study (Fig. 3), but we consider these low ET values impractical, and the yield loss associated with the corresponding EILs is immeasurable. The value of Table 2 is to demonstrate the relative sensitivity of the variables used in the EIL and ET calculations.

The ET calculated from this study of 273 ± 38 (95% CI) overlaps a consensus action threshold that was promoted after a widespread soybean aphid outbreak that occurred in 2003 of 250 aphids per plant with >80% of plants being aphid-infested (NCSRP 2006). This action threshold was derived from a subset of location-years included in this study (six of the 19 location-years). In a recent survey, 66% of respondents correctly identified, this action threshold and 84% indicated that scouting for aphids was critical for effective aphid management (Olson and Badibanga 2005b). The long-term benefits of delaying treatment for as long as practical are far reaching. Some natural enemies in soybean are known to follow soybean aphid to its principal overwintering host, common buckthorn, *Rhamnus cathartica* L., (Yoo et al. 2005), and these predators and pathogens (Nielsen and Hajeck 2005) continue to reduce aphid populations on the overwintering host well past soybean harvest. Conserving soybean aphid natural enemies is of utmost importance and this ET, if widely adopted, will help preserve natural enemies on a landscape level and provide producers the means to make decisions that avoid treating subeconomic aphid populations.

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