Spring 2020

The Soybean Aphid Suction Trap Network: Sampling the Aerobiological "Soup"

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Abstract

The initiation of the soybean aphid suction trap network (STN) in 2001 marked the beginning of a rich and fruitful collaborative effort that has produced a wealth of data about the soybean aphid, other insect species, and other organisms that make up the aerobiological “soup.” Collaboration among researchers, extension specialists, and agriculturalists has provided information about seasonal migration patterns of the soybean aphid and monitoring of other insect species. The physical collections of the “soup” have been stored and used for past research, and will serve as a foundation for future research.

Disciplines

Agriculture | Ecology and Evolutionary Biology | Entomology

Comments

This article is published as Lagos-Kutz, Doris, David J. Voegtlin, David Onstad, David Hogg, David Ragsdale, Kelley Tilmon, Erin Hodgson et al. "The Soybean Aphid Suction Trap Network: Sampling the Aerobiological “Soup”." *American Entomologist* 66, no.1 (2020): 48-55. doi: 10.1093/ae/tmaa009.

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The initiation of the soybean aphid suction trap network (STN) in 2001 marked the beginning of a rich and fruitful collaborative effort that has produced a wealth of data about the soybean aphid, other insect species, and other organisms that make up the aerobiological "soup." Collaboration among researchers, extension specialists, and agriculturalists has provided information about seasonal migration patterns of the soybean aphid and monitoring of other insect species. The physical collections of the "soup" have been stored and used for past research, and will serve as a foundation for future research.

Aerial biota collected by vertical tubes that rise up more than six meters from the ground and suck air and particulates make up the tens of thousands of samples that have been collected through the years. Researchers have used the suction trap data and samples to generate publications on modeling distribution and migration patterns for soybean aphids, providing new reports of aphid species beyond their known distributions and learning more about the distribution of other insect species, such as mosquitoes and thrips. We hope, ultimately, to expand the network nationwide so that monitoring of important aerial biota can continue indefinitely.

So, how did we get here, and where are we? In this article, we describe and proclaim the U.S. soybean aphid STN, from its originally focused objective to our realization that the output has exceeded our expectations; the huge amounts of data generated from the network will benefit both science and society. Long-term, broadly defined geographical projects like this one are highly valuable as changes in aerial biota could well be associated with changing ecological landscapes and environmental conditions. We believe that with continued funding and additional collaborators, this network, if expanded, could serve as a model for long-term aerobiological and ecological studies to answer questions related to insect population dynamics (e.g., whether insects really are

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Fig. 1. Locations of the traps in the soybean aphid suction trap network, 2001–2018.

Fig. 2. David Voegtlin alongside a suction trap located in Hancock, Wisconsin. Photo by D. Lagos-Kutz.

declining in number and species diversity) and other aerobiological questions related to other arthropods and microbes.

The Need for and Genesis of the Soybean Aphid Suction Trap Network

The invasive soybean aphid, *Aphis glycines* (Matsumura), was first reported in the U.S. in 2000 (Hartman et al. 2001). By 2009, the range of the soybean aphid had expanded throughout the midwestern U.S. and Canada (Ragsdale et al. 2011), causing negative economic impact on soybean yields (Ragsdale et al. 2004, Kim et al. 2008). The rapid spread of the soybean aphid in the Midwest was successful because of the extensive production of soybean (Schnitkey 2013) and the wide distribution of buckthorn (*Rhamnus cathartica* L.), its preferred primary winter host (Voegtlin et al. 2005).

The soybean aphid quickly established itself as one of the most devastating invasive insect pests to affect soybeans in the U.S., rousing research and educational efforts to address the unknowns about this invasive species. Because little was known about migratory patterns of the soybean aphid in the U.S., establishment of an STN in the Midwest to monitor soybean aphid movements offered an attractive approach. Suction traps had been used quite successfully for monitoring other invasive aphid species (e.g., Pike et al. 1989), and the rapidly expanding range of the soybean aphid seemed to lend itself well to a similar, albeit more expansive, approach.

The 2000 Soybean Aphid Invasion into the Heartland of the U.S.

Samples of soybean infested with aphids were collected from a research trial on a private farm near Whitewater, Wisconsin, on 13 July 2000. The unknown aphids were identified as the soybean aphid by Dr. David Voegtlin. On 18 August of the same year, Dr. Voegtlin visited another soybean field near Aurora, Illinois, and found heavy infestations of the soybean aphid, including winged migrants. During the three days after Dr. Voegtlin's visit to Aurora, mild winds from the north spread the aphid infestation to the southern tip of Illinois, about 600 km south of Aurora. His findings revealed how fast the range of invasive aphids could expand and served to warn farmers and the scientific community about the threat that soybean aphids could pose to soybean production in the U.S. By the fall of 2000, the presence of soybean aphids had been confirmed in nine states, with well-established and heavy infestations in northern Illinois, Michigan, and Wisconsin (Steffey 2000, Hartman et al. 2001, Wedberg et al. 2001). Soybean aphids spread rapidly and were detected in 30 states and three Canadian provinces by 2009 (Ragsdale et al. 2011). The exact time and location of the initial introduction of the soybean aphid into North America remain unknown, but it may have occurred through the transport of aphid eggs on ornamental plant material, *Rhamnus* spp. (Ragsdale et al. 2004), or by nymphs and/or adults associated with other live plant material, such as edamame pods.

Fig. 3. Suction-trap sample supplies. (A) Padded mailing envelopes. (B) Jars with liquid collection. (C) Suction-trap sample under dissecting microscope. (D) Suction-trap samples processed and stored into Whirl-paks. Photos by D. Lagos-Kutz.

Building and Delivering the Suction Traps Across the Midwestern U.S.

Suction traps are a convenient method for long-term monitoring of migratory aphids and for conducting aerial insect surveys (Johnson and Taylor 1955, Macaulay et al. 1988, Burt 1998). In the United Kingdom, an STN for detecting aphid migrations and issuing pest management recommendations was established in 1964, with 16 traps operational in 2020 (http://resources.rothamsted.ac.uk/insect-survey/networks). The long-term data generated by the U.K. STN have been used to evaluate aphid response to environmental variation and climate change (Harrington et al. 2007, Bell et al. 2015, Leather 2015, Sheppard et al. 2016). In the northwestern United States (California, Idaho, Oregon, Washington, and Wyoming), an STN was in operation from 1983 to 2003 to monitor crop pest aphids, especially the invasive Russian wheat aphid, *Diuraphis noxia* (Pike et al. 1989, Merickel et al. 2015).

Research efforts to understand the biology and management of the soybean aphid began in earnest across the Midwest in 2001. In Illinois, research support from the Illinois Consortium for Food and Agricultural Research (CFAR) and the Illinois Soybean Association (ISA) provided funds to construct the suction traps and establish the development of an STN to monitor the seasonal movement of the soybean aphid. In the spring of 2001, the STN included sites at the University of Illinois agricultural experiment stations at Brownstown, Dixon Springs, Orr, and Urbana. Suction traps were also established at commercial farms near Freeport, Eureka, and Joliet Junior College, all in Illinois (supplemental Table S1, available at https://doi.org/10.1093/ae/tmaa009).

In 2005, the North Central Integrated Pest Management Center (NCIPMC) supported the construction of new suction traps for distribution to Iowa (four traps); Indiana, Michigan, and Minnesota (five traps each); and Wisconsin (seven traps). In subsequent years, additional traps were established in Kentucky, Missouri, Kansas, South Dakota, and Louisiana. Most of them were placed on agricultural research stations operated by land-grant universities (supplemental Table S1); a few were established on private farms. The NCIPMC developed and maintained a website of the soybean aphid data recorded from 2005 to 2015 (https://www.ncipmc.org/traps/).

The Midwest STN was supported by funding from multiple sources. Sustained support from 2007 to 2019 (except 2015) was provided by the North Central Soybean Research Program (NCSRP). Cooperators in individual states filled in funding gaps by providing in-kind labor, mileage, or postage from other sources. From 2005 to 2009, there were 42 traps operating in 10 states (Fig. 1). Since 2009, attrition associated with reduced funding and technical support resulted in the termination of operation of some suction traps; however, a core of 30 traps remained operational from 2005 to 2018. The locations of the suction traps ranged from Crookston, Minnesota (northernmost) to Chase, Louisiana (southernmost), and from Monroe, Michigan (easternmost) to Brookings, South Dakota (until 2015; westernmost).

Fig. 4. Leaves with heavy infestation of soybean aphids (*Aphis glycines*). (A) Winged adults on soybean, *Glycine max*. (B) Mostly apterous viviparae adults on soybeans. (C) Dense soybean aphid congregation on the winter host, buckthorn (*Rhamnus cathartica*). Photos by C. DiFonzo, Michigan State University (A), and D. Voegtlin, University of Illinois at Urbana-Champaign (B and C).

The Nuts and Bolts of the Soybean Aphid Suction Trap Network

The design of the traps used in the Midwest STN was based on the traps developed at Washington State University (Allison and Pike 1988). The traps consist of a PVC pipe with a motor at the bottom end to suck in air (see footnote in supplemental Table S1 for more details). The intake at the top of the PVC pipe is 5.8 m above the ground; the bottom of the trap is about 0.46 m above the ground (Fig. 2). The electric fan draws 60 m^3 of air per minute. The traps were built at the Illinois Natural History Survey (INHS) and were then transported to each location. Winged insects drawn in by the suction are captured in a 250 ml polypropylene jar filled with 85 ml of a mixture of 50% water and 50% antifreeze (propylene glycol), which preserves the insects and is not considered a hazardous liquid for shipping purposes (Thomas 2008). It is also a proven preservative for microbial DNA from insect hosts and has been used in pitfall traps to collect insects to characterize insect-associated microbiota (Moreau et al. 2013).

Operators and Collaborators Who Run the Network

The operation of each suction trap relies on the kindness of each collaborator year after year. The STN would not have continued for 14 years without the collaborators who maintained and replaced samples throughout the collection period. The collaborators receive supplies before each growing season, including pre-paid, padded envelope mailers and jars with collection liquid as previously described (Fig. 3A, 3B). The traps are controlled by an electronic timer, operating from 7:00 a.m. to 8:00 p.m. from the third week of May through the third week of October. The jars are collected and replaced weekly at each location, and all samples are mailed to the USDA Soybean Diseases and Pests Laboratory at the University of Illinois.

Incoming samples are initially screened under a stereomicroscope, and aphids are removed and temporarily stored in 75% ethanol for later taxonomic identification. Identified and unidentified aphids are stored long-term in 95% ethanol at -20°C (2012 through 2019, except 2015). Samples of other arthropods (Araneae, Coleoptera, Diptera, Hemiptera, Hymenoptera, Neuroptera, and Thysanoptera; Fig. 3C) collected from 2015 to 2019 were also stored in 95% ethanol at -20°C for further analysis. Aphids are stored in 1.5 ml safe-lock tubes, and other taxa are stored in 100 ml capacity sample bags (185 mm × 75 mm, 0.057 mm thick; Fig. 3D).

Keeping Records of Soybean Aphid Populations

Annual soybean aphid counts (summer and fall migrants; Fig. 4A–C) varied in their abundance geographically from 2005 to 2018. Mean soybean aphid captures per week were highest in Indiana and Michigan in 2005; in Minnesota and South Dakota in 2008; and in Illinois, Indiana, Iowa, Minnesota, and South Dakota in 2009. Lower numbers of soybean aphids were counted from traps located in Missouri, Kansas, and Kentucky (Fig. 5). No soybean aphids were captured in Chase, Louisiana. In 2009, the population of fall migrants was extremely high, becoming a nuisance to people outdoors, who thought the aphids were gnats (dailyillini.com/news/2009/09/22/, dailyiowan.lib.uiowa.edu/DI/2009/di2009-09-30, purdue.edu/newsroom/outreach/2009/090924KrupkeAphids). That fall, high numbers of fall migrants (gynoparae [females that produce oviparae on winter host] and males) and eggs were also found on the overwintering host, buckthorn, in some states. Trap captures after 2009 have been low, never reaching the levels of captures or counts recorded during or before 2009. Although the exact reason for the lower population densities is not known, a combination of factors that include increased densities of predators and/or parasitoids, increased use of insecticides, and unfavorable weather patterns may all have played a role.

Inverse-distance-weighted maps for weekly mean soybean aphid counts in July and October from 2005 to 2018 show the spatial and temporal variability of population density across the Midwest (Fig. 6). In 2009, aphid counts were highest among all years. The sites with a weekly mean soybean aphid count greater than 1,000 that year included Dekalb, Metamora, and Urbana-Champaign in Illinois; Nashua and Sutherland in Iowa; and Morris in Minnesota. All other sites had lower aphid counts.

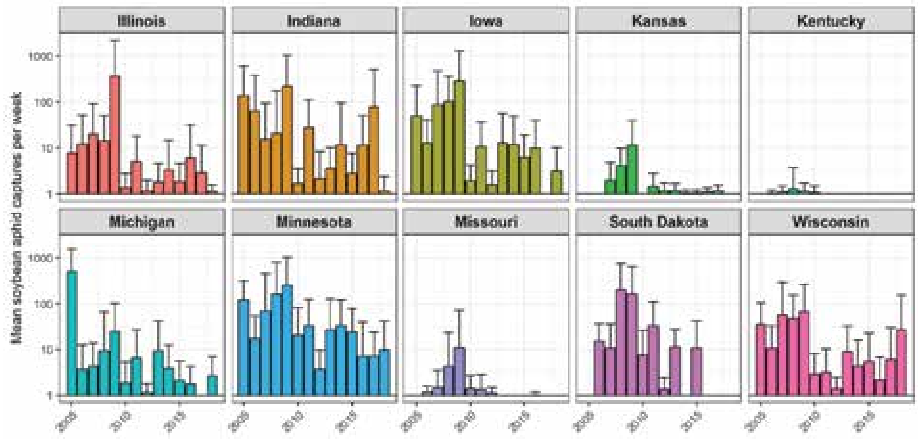

Fig. 5. Mean soybean aphid captures per trap per year from the Midwest Suction Trap Network.

Accounts of Aphids Captured in the Midwest Suction Trap Network

Winged aphids captured in the STN samples were identified to genus and species based on morphological characters. Winged aphids collected in the suction traps do not have host data, and taxonomic keys such as Blackman and Eastop (2006) that rely on wingless adults collected from known hosts to identify the aphid species could not be used. The available taxonomic literature associated with morphological keys for winged morphs (Hottes and Frison 1931; Palmer 1952; Meddler and Ghosh 1969; Brown 1989; Pike et al. 1991, 2003; Voegtlin et al. 2003) was complemented with the reference collection borrowed from the INHS. Archival aphid slides made for identification purposes were deposited at the INHS Insect Collection (http://inhsinsectcollection.speciesfile.org/InsectCollection.aspx). Photographs of the mounted specimens were taken using a Leica DM 2000 digital camera and SPOT Software 5.0 (Diagnostic Instruments, Inc., Sterling Heights, MI). A collection of photographs of mounted winged aphids was created to facilitate accurate identification of the aphid species.

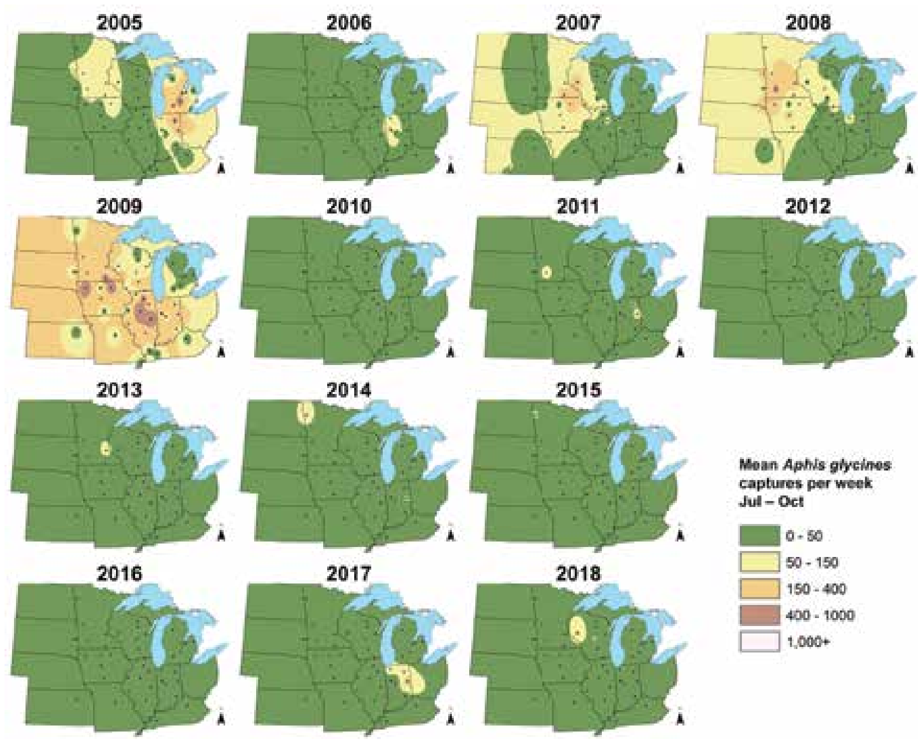

Fig. 6. Mean soybean aphid captures per trap from July through October each year, generated by the inverse-distance weighted algorithm, representing interpolated population densities across the upper Midwest.

A total of 9,167 samples were processed from 10 states between 2001 and 2018 (Table 1). The states with the highest total counts of aphids included Illinois, Indiana, Iowa, Michigan, Minnesota, and Wisconsin, with counts ranging between 146,114 (Minnesota) and 167,893 (Illinois). Among these states, Wisconsin had the greatest number of species (134), and Minnesota had the lowest (106).

A total of 152 aphid species have been identified from the Midwest STN thus far (supplemental Table S2), a number expected to grow; there are many unknown aphid species stored in ethanol for future identification. The most diverse genera in terms of species identified in suction-trap samples were *Aphis* and *Uroleucon*. The most abundant aphid species, besides the soybean aphid, were *Rhopalosiphum padi*, *R. maidis*, *Pemphigus* spp., *Tetraneura* spp., *Therioaphis trifolii*, *Capitophorus elaeagni*, *R. rufiabdominale*, and *Sitobion avenae*. The total captures of all aphids were more than 1 million individuals through 2019. The relationship between aphid diversity and population density at individual sites is likely related to local landscape and weather differences.

Records of aphids collected in the suction traps from 2005 to 2019 are available at the Suction Trap Network website (https://suctiontrapnetwork.org/), which is supported by the University of Georgia Center for Invasive Species and Ecosystem Health ("Bugwood Center"), as part of the Southern IPM Center's IPM Information Supplement funded by USDA-NIFA (National Institute of Food and Agriculture). It provides a data-entry interface to collect information and disseminate the information as the data are entered. This connects the STN with other pest-monitoring efforts, such as the Integrated Pest Information Platform for Extension and Education (iPiPE, http://www.ipipe.org/) and myFields (https://www.myfields.info/). By connecting with EDDMapS (http://www.eddmaps.org/), the data on the STN is visualized on a site, county, and/or species basis and shows trends in population size over time and location.

Research Successes Using the Suction Trap Network

Multiple studies have used the suction trap data and samples through the years, generating publications related to soybean aphid distribution, aphid taxonomy, new reports of aphid species beyond their known distributions, and studies of other insects captured, such as mosquitoes and thrips.

Rhainds et al. (2010) correlated the counts of soybean aphids captured in the suction traps to the local abundance of soybean aphids in soybean fields between 2006 and 2008 in four counties in Illinois and Indiana. They found that the migratory patterns of soybean aphids caught in the suction traps were distinct each year, but the cumulative number of aphids captured in suction traps was positively correlated to the aphid densities on soybean plants. In 2006, dispersal was predominantly from soybean to buckthorn. In 2007, dispersal was between soybean fields. In 2008, the flight period of aphids extended from August to late September, suggesting that migration to soybean fields or buckthorn were both common events. These results indicated that two types of variation were associated with the migration pattern of soybean aphids: the temporal patterns observed between suction traps and soybean plants each year, and the spatial variation in soybean aphids' abundance among soybean fields within counties.

A spatial distribution study of *A. glycines* based on suction trap data from 2005 to 2008 showed that parthenogenic winged aphids (alates) were usually not collected until June (Schmidt et al. 2012). Collections of alates peaked during a three-week period from late July to mid-August (soybean to soybean movement), with another peak capture during the last two weeks of September (fall migrants to overwintering hosts). In addition, the study showed that frequency of alates captured was positively correlated with latitude, following a pattern consistent with the distribution of *R. cathartica* (common buckthorn) in the United States. This result suggested that in-season outbreaks in the southern U.S. resulted from immigrants from the northern states where buckthorn (the primary host of soybean aphid) is distributed. In another study, summer flight activity measured in suction traps was positively correlated with the level of aphid infestation in local fields near the trapping site during growing seasons from 2005 to 2009 (Bahlai et al. 2014). In the fall, gynoparae and male flight activity tended to increase with declining photoperiod.

Mitochondrial DNA sequences from uncommon specimens of *Aphis* caught in suction traps (e.g., *A. cephalanthi*, *A. maculatae*, *A. polygonata*, *A. rubicol*a, *A. sambuci*, and *Protaphis* (=*Aphis*) *middletonii*) were used to elucidate the phylogenetic relationships among the genera *Aphis*, *Iowana*, *Protaphis,* and *Toxoptera* in the midwestern U.S. (Lagos et al. 2014). The main *Aphis* species groups in the Midwest were *Aphis asclepiadis, A. fabae,* and *A. gossypii.* The group of particular interest was the *A. gossypii* group, with both exotic (*A. glycines*, *A. gossypii*, *A. nasturtii*, and *A. sedii*) and native (*A. elena, A. forbesi, A. monardae,* and *A. oeatlundi*) members. The importance of learning about and monitoring for *Aphis* species in the Midwest is based, in part, on being able to estimate the ecological impact of the potential introduction and release of soybean aphid parasitoids (e.g., *Binodoxus communis* Gahan) on native *Aphis* species (Wyckhuys et al. 2007).

Table 1. Summary for each state in the suction trap network and the taxonomic diversity of aphids captured between 2005 and 2018 and the total number of individual aphids counted and summed over all the sites and years.

State	Sites	Years	Samples	Species	Total number of aphids counted
Illinois	10	14	1,835	112	167,893
Indiana	7	14	1,469	114	150,198
Iowa	5	13	1,043	108	132,940
Kansas	1	12	202	76	13,509
Kentucky	2	5	315	86	14,329
Michigan	7	13	1,012	115	87,822
Minnesota	5	14	987	106	146,144
Missouri	2	11	375	82	20,111
South Dakota	2	9	176	71	20,709
Wisconsin	8	14	1,753	134	150,826
Summation	49	14	9,167	176	904,481

STN records were also used to document the increased distribution and numbers of sugarcane aphid, *Melanaphis sacchari* (Zehtner) (Hemiptera:Aphididae), in Kansas (Manhattan), Missouri (Columbia and Portageville), Louisiana (Chase), and northern Wisconsin during 2015 and 2017 (Lagos-Kutz et al. 2018a). Two aphid species occurring near industrial hemp fields, *Rhopalosiphum rufiabdominale* and *Phorodon cannabis*, were also collected in the network in 2016 and 2017 in the Midwest (Lagos-Kutz et al. 2018b).

Other insects have been collected routinely in the traps. Suction traps in Indiana in 2013 and 2014 were used to determine the effects of temperature and precipitation on the spatio-temporal patterns of three species of thrips (Thysanoptera: Thripidae) known to be vectors of soybean vein necrosis virus (SVNV): soybean thrips, *Neohydatothrips variabilis* (Beach); eastern flower thrips, *Frankliniella tritici* (Fitch); and tobacco thrips, *Frankliniella fusca* (Hinds) (Keough et al. 2018). SVNV detections in mid-to-late August coincided with the peak catch of *N. variabilis*.

In another study, DNA sequencing of microbial communities from nine mosquito species collected in suction traps in six states showed that microbes within the mosquito body may influence survival, reproduction, and susceptibility to pathogens (Muturi et al. 2018).

Aerial Suction Traps Describe Life in the Skies

The Midwest Suction Trap Network covers a broad area and has been in continuous operation for 14 years, due to the devoted collaboration of farmers and extension and research personnel. The samples and data generated by this network have already led to a number of interesting research projects, but many more possibilities remain. Much of the effort of the STN has highlighted the soybean aphid, including spatial and temporal patterns of migration through the years. By following these spatial and temporal patterns, long-term climate simulations will be able to project the distribution of these insects under various climate-change scenarios. Other studies based on molecular probes of collected specimens may be able to tell more about these aphids, including if they had developed resistance to insecticides or to aphid-resistant soybean cultivars.

In the future, we hope to expand the suction trap network both in geography and scope of the data being gathered and distributed from the samples. Potential collaborators are encouraged to contact the authors for more information about specimens or data, or about establishing new trap sites to help expand the geographic scope and scientific value of this network.

THE SAMPLES AND DATA GENERATED BY THIS NETWORK HAVE ALREADY LED TO A NUMBER OF INTERESTING RESEARCH PROJECTS, BUT MANY MORE POSSIBILITIES REMAIN.

Acknowledgments

We thank the many institutions that have supported the development and operation of the Suction Trap Network, including CFAR, ISA, NCIPMC, NCSRP, and USDA-ARS. We especially appreciate the work of Larry Gross and James MacNamara, Illinois Natural History Survey, who built the traps. We are very grateful to our collaborators for their consistent collection and shipment of the suction-trap samples. We gratefully acknowledge the collaboration of Dr. Christie Bahlai, applied quantitative ecologist and population ecologist at Kent State University. Our thanks also go to Dr. Susan Halbert, taxonomic entomologist of the Florida Department of Agriculture & Consumer Services, Florida, for sharing her expertise about morphology of winged aphids; and to Dr. Roger Bowen, USDA, for his help with moving and maintaining the traps.

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DOI: 10.1093/ae/tmaa009