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Source: Journal of Economic Entomology, 106(3):1495-1502. 2013.

Published By: Entomological Society of America

URL: <http://www.bioone.org/doi/full/10.1603/EC12472>

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Use of Black Light Traps to Monitor the Abundance, Spread, and Flight Behavior of *Halyomorpha halys* (Hemiptera: Pentatomidae)

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J. Econ. Entomol. 106(3): 1495–1502 (2013); DOI: <http://dx.doi.org/10.1603/EC12472>

ABSTRACT Monitoring the distribution and abundance of an invasive species is challenging, especially during the initial years of spread when population densities are low and basic biology and monitoring methods are being investigated. Brown marmorated stink bug (*Halyomorpha halys* (Stål)) is an invasive agricultural and urban pest that was first detected in the United States in the late 1990s. At the time of its detection, no method was available to effectively track *H. halys* populations, which are highly mobile and polyphagous. One possible solution was the utilization of black light traps, which are nonspecific traps attractive to night flying insects. To determine if black light traps are a reliable monitoring tool for *H. halys*, a state-wide network of 40–75 traps located on New Jersey farms were monitored from 2004 to 2011 for *H. halys*. This proved to be a highly effective method of monitoring *H. halys* populations and their spread at the landscape level. The total number of brown marmorated stink bug caught in New Jersey increased exponentially during this period at a rate of 75% per year. Logistic regression estimates that 2.84 new farms are invaded each year by *H. halys*. The results indicate that black light traps are attractive to early season populations as well as at low population densities. Weekly trap catch data are being used to generate state-wide population distribution maps made available to farmers in weekly newsletters and online. While no economic threshold currently exists for brown marmorated stink bug, the maps provide farmers with a tool to forecast pest pressure and plan management.

KEY WORDS invasive species ecology, degree-day, distribution, survey

Invasive species are difficult to detect at low population densities, especially during the initial stages of establishment and spread (Mack et al. 2000). Too frequently, a species is widespread before any reliable monitoring method is identified. This is partly because invasive species may not be major pests in their country of origin and little is known about their basic biology, including semiochemistry leading to a lack of species-specific monitoring methods. In this scenario, an unbiased general monitoring and detection program is desirable. In the late 1990s large populations of stink bugs were first reported in Allentown, PA, by Karen Bernhard of Pennsylvania State Cooperative Extension. Richard Hoebeke at Cornell University identified Bernhard's specimens as the Asian species *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), the brown marmorated stink bug, in 2002 (Hoebeke and Carter 2003). By this time, populations were established in eastern Pennsylvania and were becoming noticeable across the river in Phillipsburg, NJ.

H. halys is a highly polyphagous and mobile insect that feeds on a large range of horticultural and agricultural crops (Nielsen and Hamilton 2009, Leskey et

al. 2012). Adults overwinter in natural landscapes (primarily upright dead trees (D. Lee, personal communication) or human-made structures such as houses. It has been hypothesized that the behavior of overwintering in human-made structures provides a fitness benefit, primarily in terms of increased overwintering survival (Kiritani 2006). Overwintered adults, still reproductively immature, begin emerging from these sites in early Spring. Where univoltine, they feed and begin reproducing in late May through mid-July in the mid-Atlantic region (Nielsen and Hamilton 2009). This overwintered generation can cause early season damage to crops, particularly tree fruit (Leskey et al. 2012). Females mate multiple times and continue to lay eggs throughout their lifetime, which may last many months. *H. halys* can have 1–5 generations per year, depending on temperature and photoperiod (Hoffman 1931, Niva and Takeda 2003). In its current distribution in the United States, there are 1–2 generations with a large population peak in late summer (mid-July through mid-September) with the resulting adult generation moving to overwintering sites. The high population density in late summer or early fall coincides with the ripening of many fruiting vegetables, fruit, and field crops and can result in significant

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economic losses (Seetin 2011, Kuhar et al. 2012). In recent years, the number of insecticide applications in tree fruit has increased as much as four times because of *H. halys* (Leskey et al. 2012). The consequences to integrated pest management (IPM) programs have been drastic and better monitoring and management methods are urgently needed to detect new breeding populations as *H. halys* becomes widespread.

Pentatomids are generally difficult to monitor because they are considered a nocturnal insect with very good evasive behaviors, including dropping off a plant or switching sides of a leaf or fruit when disturbed (Cullen and Zalom 2000). This may result in a false low prediction of pest abundance. While *H. halys* can be easily found during the day, anecdotal reports suggest that activity increases at dusk and throughout the evening (Leskey and Hamilton 2010). Therefore, a monitoring tool that will exploit these behaviors is needed.

H. halys is attracted to the aggregation pheromone of sympatric species *Plautia stali* Scott (Hemiptera: Pentatomidae). This kairomone, 2,4,6-*E,E,Z* methyl-decatrienoate has been used for monitoring *H. halys* in both its native range and in the United States (Moriya et al. 1987, Khirimiyan et al. 2008, Nielsen et al. 2011, Leskey et al. 2012). While attractive to nymphs and adults, the kairomone is only reliable for monitoring *H. halys* during the large late-season population peaks from mid-July through the first frost (Nielsen et al. 2011). Significant efforts are being made in the identification and development of the true aggregation pheromone for *H. halys* (T. C. Leskey, personal communication). Until then, black light traps may provide a reliable season-long monitoring method for *H. halys* adults.

Black light traps catch a wide range of night flying insects (Harding et al. 1966) by acting to "short circuit" a natural insect behavior during flight. Nocturnal insects navigate by using the moon and mistake the light trap with the moon. Researchers have documented black light trap catch of pentatomids (McPherson 1982, McPherson and Weber 1990), although their utility as a monitoring tool has generally been overlooked. Stink bugs, including *H. halys*, readily move between host plants depending on the most attractive phenological phase of each plant (Panizzi 1997). It is during this interplant movement and search for mates within the landscape that pentatomids are likely intercepted by black lights. Thus, it is a useful tool that permits nonspecific catch of a polyphagous, nocturnal insect. Trap catch may vary with cloud cover, moon phase, and weather, but none the less represent a useful monitoring tool for species detection.

In Japan, *H. halys* was one of the three primary pentatomid species caught in black light traps, along with *P. stali* and *Nezara antennata* Scott (Hemiptera: Pentatomidae), and made up ≈ 1.9 –27.0% of trap catch of pentatomids in Ibaraki Prefecture and Tochigi Prefecture, respectively (Moriya et al. 1987, Katayama et al. 1993). Fifteen years of data demonstrated that attraction by *H. halys* adults occurred primarily from late July through early August with considerably lower

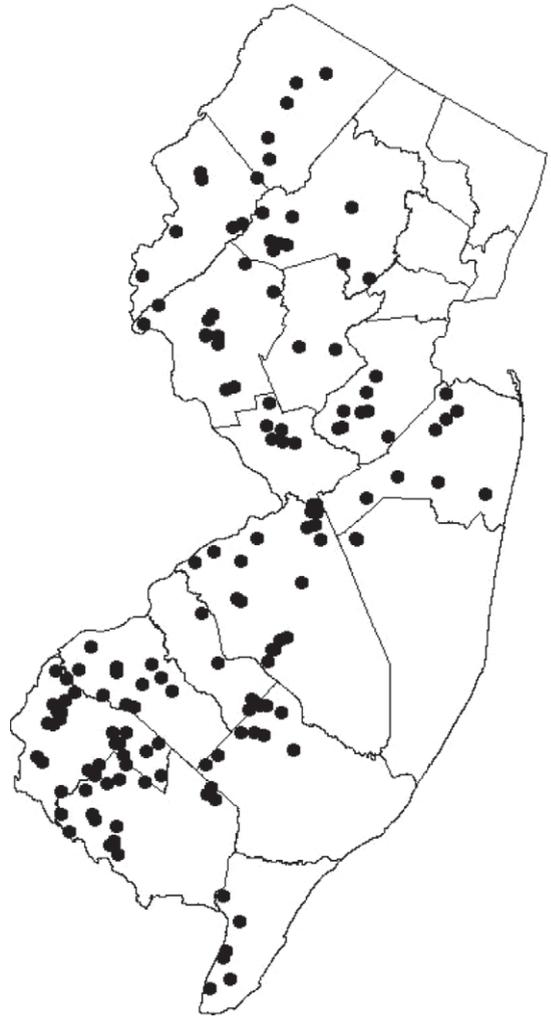


Fig. 1. Map of Rutgers University (New Jersey) black light trapping network. The geographic location of each farm with a black light trap is indicated by a black circle.

numbers from May through June (Katayama et al. 1993). This prompted us to inspect trap catch and specimens for *H. halys*. Rutgers Cooperative Extension has a network of 70+ black light traps located throughout the state on vegetable and fruit farms participating in the IPM scouting program (Fig. 1) (Holmstrom et al. 2001). Their primary use is for the detection of European corn borer [*Ostrinia nubilalis* Hübner (Lepidoptera: Pyralidae)] and corn earworm [*Helicoverpa zea* Boddie (Lepidoptera: Noctuidae)] and occasionally endemic stink bugs. Here, we used this data set to: 1) determine if black light traps can serve as a reliable season-long monitoring tool for *H. halys*, 2) document the spread and population increases of *H. halys* in time and space, and 3) apply degree-day (DD) requirements for *H. halys* to investigate relationship between flight activity and DD accumulation.

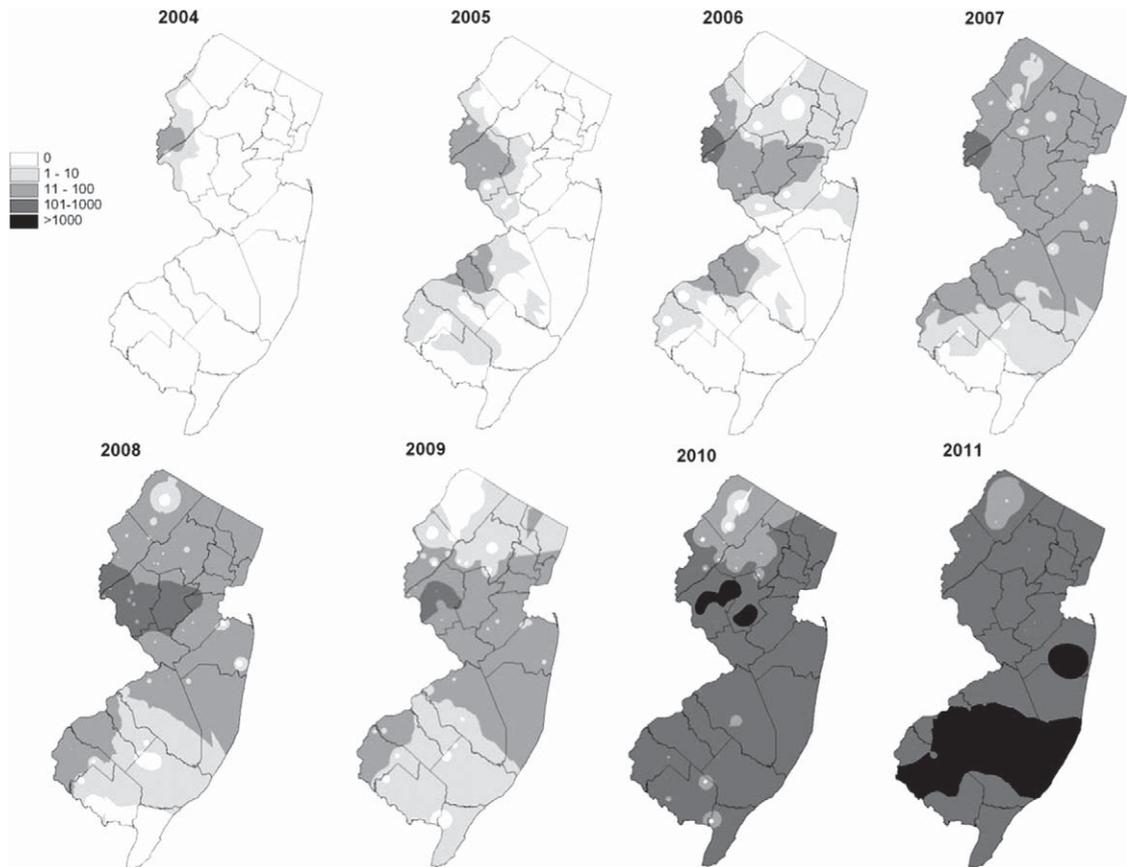


Fig. 2. Maps depicting the spread and density of *Halyomorpha halys* in New Jersey as indicated by black light trap catch from 2004 to 2011.

Methods and Materials

New Jersey farming regions can be generally divided into three regions: North, Central, and South. This is based on climate conditions, soil type and production type. Farms within the northern and central regions of the state are typically ≈ 100 acre mixed farming production with vegetables, field crops, small fruit, and/or tree fruit. Farms in the southern regions of the state have larger acreage of monocultures, typically of tree fruit, small fruit, or field crops. There is also large-scale vegetable production in this part of the state. None of the farms participating in the vegetable IPM program in the Southern region have tree fruit.

Black light Trap Monitoring. AC traps (110 V, 1.3 meter height, Old Boys Enterprises Inc., Oregon, WI) equipped with GE T8 black light bulbs (15 watt, 0.45 m length) were placed ≈ 1 meter away from a building structure at farms participating in the Rutgers University vegetable IPM program. Each trap was georeferenced using a handheld Trimble GeoExplorer II (Trimble Navigation Ltd., Sunnyvale, CA). Traps were checked twice weekly by IPM scouts from 1 May through 1 October for pests of interest, primarily European corn borer and corn earworm, and occasionally wireworms and pentatomids. IPM agents or their trained

scouts, collected the entire trap catch twice weekly into collection containers labeled with farm location and date. Trap catches were kept in a -20°C freezer until sorting and identification later that year. Beginning in 2004 the authors individually sorted through each trap catch and removed all pentatomid specimens.

Relative Abundance of *H. halys* and Population Growth. Active black light traps throughout the state were sorted for possible *H. halys* specimens beginning in 2004. Data were collected in 2002 by K.H. Data collection for this study was conducted in 2004–2011 for North Jersey farms and 2005–2011 for Central and South Jersey. Therefore, at minimum, the data presented here represents a conservative record of *H. halys* throughout New Jersey. All pentatomid specimens were sorted from the black light trap catches (above). Specimens were identified to genus or species (dependent on the quality of specimen) and gender and recorded for the start date of each trapping period. Voucher specimens are in the Rutgers Entomology Insect Museum in New Brunswick, NJ. Data analysis on the spread of *H. halys* was restricted to traps that were active beginning in 2004 to eliminate independence of data points by the addition of new trap sites.

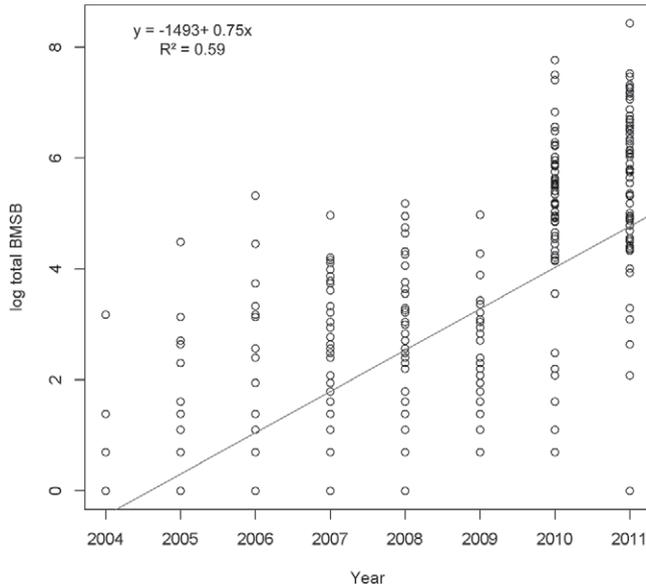


Fig. 3. The linear relationship between *Halyomorpha halys* population density and year (2004–2011) based on black light trap captures. This indicates a 75% population increase each year.

Spread. Black light trap locations throughout the state were mapped with ArcView GIS (Environmental Systems Research Institute, Inc., Redland, CA). Trap data were then interpolated to a grid using an inverse distance weighted algorithm where grid cell values are influenced by the 12 nearest data points (collection sites). Average nightly brown marmorated stink bug catches by week per trap were calculated and imported into the ArcView program and linked to their corresponding trap locations. This technique produces surfaces with clearly delineated zones representing uniform pest populations while maintaining points of higher or lower intensity where they occurred (Holmstrom et al. 2001). Beginning in 2010 these weekly distribution maps were distributed to growers via the IPM program (Holmstrom and Ingerson–Mahar, 2012).

DD Model. Accumulated DD values were calculated from 1 January to 31 December according to Nielsen et al. (2008) using average heat units less the minimum developmental threshold for *H. halys*. Daily maximum and minimum temperature data were downloaded from NJ Weather and Climate Network (<http://climate.rutgers.edu/njwxnet/>). Daily values below 0°C were recorded as 0°C. Because of the differences in weather between regions of the state, a northern (Pittstown, NJ) and southern (Upper Deerfield, NJ) station were selected and farms within a 15 mile radius were analyzed for brown marmorated stink bug flight activity. Two farms within range of Pittstown, NJ, provided trap capture data from 2006 to 2011 while five farms near Upper Deerfield, NJ, provided data from 2008 to 2011. Average weekly *H. halys*

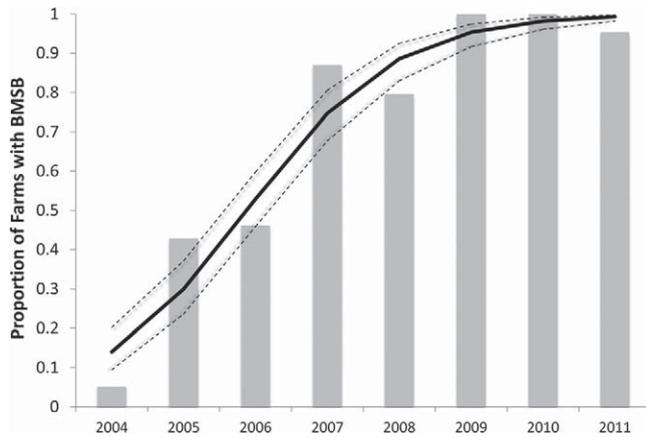


Fig. 4. Logistic regression prediction for the number of farms with *Halyomorpha halys* (black line with 95% CI) populations. The histogram indicates the proportion of farms/black light traps that were positive for *H. halys* each year.

Table 1. Annual total no. of pentatomids caught in New Jersey black light traps

Genus	2005 (59)	2006 (67)	2007 (64)	2008 (72)	2009 (52)	2010 (59)
<i>Aelia</i>	0	1	0	0	0	0
<i>Banasa</i>	287	336	428	643	94	1,400
<i>Brochymena</i>	1	0	0	0	0	0
<i>Chinavia</i>	166	640	592	646	4	719
<i>Edessa</i>	0	0	0	0	1	48
<i>Euschistus</i>	529	132	79	319	4	96
<i>Halyomorpha</i>	190	473	819	1,305	712	17,814
<i>Holcostethus</i>	0	0	0	1	0	0
<i>Hymenarcys</i>	2	0	0	0	0	0
<i>Meneclis</i>	1	4	2	8	0	1
<i>Murgantia</i>	0	0	0	1	0	0
<i>Oebalus</i>	9	2	0	6	0	2
<i>Piezodorus</i>	0	0	0	1	0	19
<i>Podisus</i>	172	92	35	135	3	50
<i>Rhytidolomia</i>	0	0	0	12	0	2
<i>Thyanta</i>	30	146	167	172	0	49

The no. of active traps in the state each year is indicated in parentheses.

trap catch were graphed against weekly accumulated DD to generate seasonality as a function of DD.

Data Analysis. Annual totals for *H. halys* were calculated from 2004 to 2011. Because of year-to-year variation in the location of some traps, we restricted analysis to farms that participated in the program in 2004 and successive years (2004 = 70, 2005 = 56, 2006 = 60, 2007 = 56, 2008 = 60, 2009 = 45, 2010 = 50, and 2011 = 55) so that new traps were not added to avoid violating assumptions of independence. The state-wide population was analyzed using linear regression with year as the explanatory variable. The total number of *H. halys* did not conform to assumptions of normality and was log transformed ($\log(X+1)$) for all data analyses. To calculate the rate of spread, the probability of farms infested with *H. halys* (Prob_+) was calculated with logistic regression according to the formula: $y = \text{Prob}_+ / (1 - \text{Prob}_+)$. Differences in total trap catches between males and females were compared as the total yearly number of each gender among farms using an analysis of variance (ANOVA). All data analysis was performed using R (R Development Team 2012) or SAS (SAS Institute, Cary, NC).

Results

We examined an existing network of 45–70 traps (Fig. 1) located at farms over an 8 yr period and successfully monitored *H. halys* and endemic pentatomids throughout the state.

Spread and Population Growth. Results indicate that the total number of *H. halys* caught throughout the state increased exponentially since the first specimen was found in 1999 to >35,000 in 2011 (Fig. 2). This increase not only documents high population densities throughout the state but also the utility of black light traps as a nonspecific monitoring tool for *H. halys*. There was a significant ($R^2 = 0.59$; $F = 511.5$; $df = 1, 371$; $P < 0.0001$) positive relationship between the state-wide population of *H. halys* and year suggesting a rate of population increase of 75% each year (Fig. 3). Spatial maps on the spread of *H. halys* were

generated to visually identify state-wide spread. From 2004–2011 there were a total of 294 farms with black light trap catch of *H. halys*. The proportion of positive farms ranged from 5 to 100% during this time period (Fig. 2) and logistic regression predicted a significant ($\chi^2 = 11.91$; $P < 0.0001$) increase in the number of positive farms by year ($y = \log(\text{Prob}_+ / 1 - \text{Prob}_+) = -2094.4 + 1.04x$). The logistic regression similarly estimated that the number of *H. halys* positive farms increased by 2.84 new farms each year (Fig. 4).

Relative Abundance of *H. halys*. While we have no knowledge regarding species-specific attraction to black light, many common pentatomid (Hemiptera: Pentatomidae) species, such as *Chinavia hilaris* (Say) (previously *Acrosternum hilare*), *Euschistus servus* (Say), *E. variolarius* (Palisot de Beauvois), *E. tristigma* (Say), *Banasa* spp., and *Thyanta* spp., and the predatory species *Podisus maculiventris* (Say) were collected state-wide (Table 1). *H. halys* was the most abundant species collected in New Jersey over this time period. There was also no difference between annual total catch of male and female *H. halys* ($F = 0.44$; $df = 1, 87$; $P = 0.51$) and no interaction between gender and farm ($F = 0.26$; $df = 87, 300$; $P = 1.00$).

DD Model. *H. halys* requires 538 DD (base 14.17°C) for total development plus 148 DD for female maturation (Nielsen et al. 2008). Here, in 2010 and 2011, the application of the DD accumulations from 1 January occurs just before a peak in flight activity in both North and South Jersey and can be used to predict F1 generation eclosion (Fig. 5A). When this same data are looked at by Julian week, the mean DD accumulations for south New Jersey (Upper Deerfield, NJ) occurred on the 29th week (19 July 2010 and 23 July 2011) and in north New Jersey (Pittstown, NJ) during the 31st week (31 July 2010 and 5 August 2011) (Fig. 5B; Table 2).

Discussion

The invasive *H. halys* has proven to be a serious pest of a wide range of horticultural, agronomic and ornamental crops (Nielsen et al. 2011, Seetin 2011, Kuhar

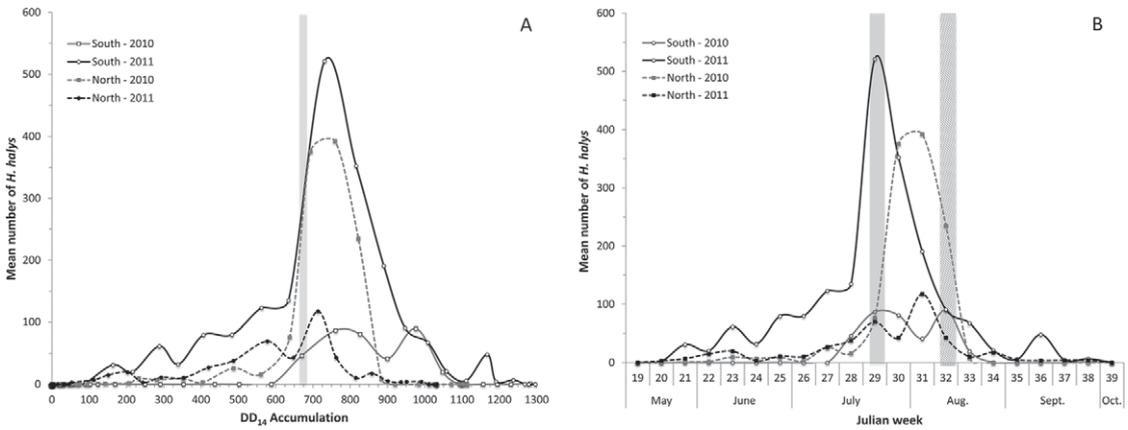


Fig. 5. Seasonal flight activity of *H. halys* at farms in north (Pittstown = dashed line) and south (Upper Deerfield = solid line) New Jersey in 2010 (gray line) and 2011 (black line). (A) Mean weekly flight activity by accumulated degree-day requirements. Gray bar indicates 685 DD₁₄ required for female maturation and total development. (B) Mean weekly flight activity by Julian week. Solid gray bar indicates the week where 685 DD₁₄ was satisfied in south New Jersey and the hashed gray bar for north New Jersey.

et al. 2012, Leskey et al. 2012) in the mid-Atlantic United States. Initial efforts to identify a monitoring program proved difficult because the chemical ecology of *H. halys* was unknown. Much progress has been made in optimizing the available lure and trap design (Khrimian et al. 2008, Leskey et al. 2012); still, they do not provide reliable information on season-long adult activity or for landscape-level analysis. Our primary objective was to determine if black light traps could provide a reliable monitoring method for *H. halys* adults in the New Jersey agroecosystem. This collection provides a unique data set representing the entire history of an invasive species in a geographic area.

The rapid increase in population density (75%) and rate of geographic spread (2.84 farms/year) provides evidence that *H. halys* is a highly invasive species that is thriving in the mid-Atlantic states, where natural enemies are currently having minimal impact on population growth (K. Hoelmer, personal communication). Both measurements of population spread and density successfully document that black light traps are effective monitoring tools especially at low population densities; before *H. halys* reaches economically damaging thresholds. An informal survey in New Jersey detected *H. halys* in black light traps ≈1.5 yr before homeowner reports (G. C. Hamilton, unpublished data) and 2 yr before catch in traps baited with the *P. stali* kairomone (A. L. Nielsen, unpublished data). As *H. halys* continues to spread and increase in

density through the United States, black light traps could provide an indication of population increase before economic injury so that farmers would not be caught unaware. Because of the absence of species-specific cues, this monitoring method could be applied to other invasive species of interest, if the labor is available for species identification.

Management programs specific for *H. halys* are being developed in a wide range of crops. However, this pest has already negatively impacted IPM programs with farmers applying approximately four times more insecticide sprays than pre-*H. halys* (Leskey et al. 2012). Beginning in 2010, maps depicting the mean nightly *H. halys* density per farm based on black light trap catch (Fig. 6) were distributed to growers through the Rutgers' Plant and Pest Advisory publication as well as on the vegetable IPM website (Holmstrom and Ingerson-Mahar, 2012). No economic threshold exists for *H. halys*, but management in most crops has returned to calendar based sprays. The ability to forecast activity and relative density provides farmers a tool to improve management timings.

We have demonstrated here that black light traps are effective tools for monitoring the spread and population increase of an invasive species. However, can we exploit the same behaviors that make *H. halys* difficult to sample, including nocturnal activity and mobility, and incorporate population densities into

Table 2. Degree-day accumulations and occurrence of first generation eclosion for *Halyomorpha halys* in two distinct climatic regions of New Jersey

Region	Total degree-day accumulation for <i>H. halys</i>						Average occurrence of first generation week
	2006	2007	2008	2009	2010	2011	
North	902.82	1,023.89	923.10	801.72	1,113.62	1,032.26	31
South	1,233.58	1,378.29	1,216.09	1,152.22	1,355.00	1,309.96	29

Degree day requirements for first generations are 686 DD₁₄°C (preoviposition period plus development).



Fig. 6. Example of distribution maps of *H. halys* distributed by Rutgers Cooperative Extension showing the average nightly population densities by week (A) Week ending 20 July 2011 (B) Week ending 27 July 2011 (C) Week ending 3 August 2011.

predictive models as in Kamminga et al. (2009) for pest management? Current work on 1) a model correlating black light trap catch to in-field samples and damage 2) a model to predict late-season populations from early season black light trap catch is in development. Unlike other monitoring tools, such as sex pheromones, that are sex biased, *H. halys* males and females were equally attracted to black light traps. Given the sex ratio in the field is $\approx 1:1$ (Nielsen and Hamilton 2009) this provides further support for incorporation as a monitoring tool into IPM programs.

Currently, the flight activity of *H. halys* can be incorporated into phenological models. *H. halys* emergence from overwintering sites is protracted and termination of diapause is hypothesized to be a combination of cues with increasing photoperiod as the primary driver, making a biofix for DD accumulation difficult. Before overwintering, the induction of diapause is driven primarily by photoperiod although temperatures above 25°C may override decreasing photoperiod (Niva and Takeda 2003). Initiation of flight activity, as indicated by black light catch, has been previously used as a DD biofix (Nielsen and Hamilton 2009). Because DD accumulations predict the completion of the first generation (F1) adult eclosion just before the peak in flight activity, this suggests that DD accumulation is a better fit than using calendar dates.

From this large data set we can conclude that black light traps: 1) provide an efficient sampling method for pentatomids, 2) were able to detect *H. halys* at low population densities, 3) were able to detect early-season populations, 4) successfully monitored the spread of an invasive species throughout a large geographic region, and 5) can be a useful tool to predict seasonal flight activity of *H. halys*.

Acknowledgments

The authors would like to thank the numerous vegetable IPM scouts who collected black light data. We would especially like to thank Amy Willmott, Andrea Wagner, Thomas Pike, and Thomas Konar for assisting in the sorting, identification, and recording of the numerous pentatomid specimens used for this data set. This project was supported in part by New Jersey Agricultural Experiment Station Hatch funds 08191 and is publication D-08-08191-02-13.

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Received 19 November 2012; accepted 11 March 2013.