

## **Detectability of Halyomorpha halys (Hemiptera: Pentatomidae) by Portable Harmonic Radar in Agricultural Landscapes**

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DETECTABILITY OF *HALYOMORPHA HALYS* (HEMIPTERA: PENTATOMIDAE) BY PORTABLE HARMONIC RADAR IN AGRICULTURAL LANDSCAPESDOO-HYUNG LEE<sup>1\*</sup>, CHANG-GYU PARK<sup>2</sup>, BO YOON SEO<sup>2</sup>, GILLES BOITEAU<sup>3</sup>, CHARLES VINCENT<sup>4</sup>  
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## ABSTRACT

Harmonic radar technology enhances capability to track the movement of individual small insects under field conditions. To maximize the capacity of this technology, it is necessary that radar tags must be securely attached to insects and that the tags remain functional when subjected to mechanical stress. In this study, a series of experiments was carried out to test an improved harmonic radar tag designed to be more resistant to mechanical stresses and to establish that a portable harmonic radar system can effectively detect adult *Halyomorpha halys* Stål (Hemiptera: Pentatomidae) on various structures in different landscapes. The functional resistance of radar tags to ~1-m free falls on a hard surface was improved significantly by reinforcing the adhesive bond between the radar transponder and the radar wire by application of cyanoacrylate glue. This measure did not affect the detectability of radar tags, and it significantly increased the resistance of radar tags against random mechanical impacts inflicted on the insects and tags. The success rates of locating radar-tagged *H. halys* were compared among different landscapes, including a mowed grass-covered plot (250 m<sup>2</sup>), a mature peach tree plot (50 m<sup>2</sup>), and an unmanaged hedgerow (50 m<sup>2</sup>). The success rates were > 90% in all landscapes tested. There was no significant difference in the search time needed to locate tagged adults. In general, it took less than 2 min to detect and recover *H. halys*. The success rates of locating radar-tagged *H. halys* were also compared among different locations within mature fruit trees. There was no significant difference in the success rates between the inner third (87%) and the outer third of the host tree canopy (100%). However, a significantly longer period of time was required to locate *H. halys* in the inner canopy (372 s ± 95 SE) compared with the outer canopy (148 s ± 39 SE). When *H. halys* were concealed in the lower, middle and upper thirds of the outer tree canopy, the success rates of locating tagged adults were consistently 95% or greater at all canopy heights with no significant difference in search times needed to locate tagged adults. The results of this study provide context for researchers to reliably use this radar system in the field to study the dispersal biology of *H. halys*.

Key Words: brown marmorated stink bug, invasive species, tracking, detection

## RESUMEN

La tecnología de radar armónico mejora la capacidad para seguir el movimiento de pequeños insectos individuales bajo condiciones de campo. Para maximizar la capacidad de esta tecnología, es necesario que las etiquetas de radar estén firmemente pegadas a los insectos y que las etiquetas sigan funcionando cuando se someten a estrés mecánico. En este estudio, se realizó una serie de experimentos para probar una etiqueta mejorada de radar armónico diseñada para ser más resistente al estrés mecánico y para establecer un sistema de radar armónico portátil que puede detectar con eficacia los adultos de *Halyomorpha halys* Stål

(Hemiptera: Pentatomidae) sobre varias estructuras en diferentes áreas de campo. La resistencia funcional de las etiquetas de radar a una caída libre de ~ 1 m sobre una superficie dura se ha mejorado de manera significativa al reforzar la unión adhesiva entre el transpondedor de radar y el cable de radar con una aplicación de pegamento cianoacrilato. Esta medida no afectó a la detectabilidad de las etiquetas de radar y aumentó significativamente la resistencia de etiquetas de radar contra los impactos mecánicos infligidos al azar a los insectos y las etiquetas. Las tasas de éxito de localizar las *H. halys* con etiquetas de radar fueron comparadas entre las áreas distintas incluyendo una parcela cubierta de hierba cortada (250 m<sup>2</sup>), una parcela de árboles de durazno maduro (50 m<sup>2</sup>), y una fila de arbustos no manejada (50 m<sup>2</sup>). Las tasas de éxito fueron > 90% en todas las áreas probadas. No hubo diferencia significativa en el tiempo de búsqueda necesario para localizar adultos etiquetados. En general, se tardó menos de 2 minutos para detectar y recuperar las *H. halys*. Se compararon las tasas de éxito de localizar las *H. halys* con etiquetas de radar también entre las diferentes áreas dentro de los árboles frutales maduros. No hubo diferencia significativa en las tasas de éxito entre el tercio interior (87%) y el tercio exterior de la copa de los árboles hospederas (100%). Sin embargo, se requiere un período de tiempo significativamente más largo para localizar *H. halys* en el dosel interior (372 s ± 95 SE) en comparación con la cubierta exterior (148 s ± 39 SE). Cuando *H. halys* se ocultaron en los tercios inferior, medio y superior de la copa del árbol exterior, las tasas de éxito de la localización de los adultos etiquetados fueron consistentemente 95% o más en todas las alturas del dosel con diferencias significativas en los tiempos de búsqueda necesarios para localizar los adultos etiquetados. Los resultados de este estudio proveen un contexto para los investigadores a utilizar de forma fiable este sistema de radar en el campo para el estudio de la biología de la dispersión de *H. halys*.

Palabras Clave: chinche marmorada café, especies invasoras, seguimiento, detección

The brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae), is native to China, Japan, and the Republic of Korea (Lee et al. 2013a), and was accidentally introduced into the United States (Hoebeke & Carter 2003), Canada (Fogain & Graff 2011), and Europe (e.g., Wermelinger et al. 2008). This polyphagous invasive species has caused significant losses to a diverse array of specialty and row crops in the mid-Atlantic states of the USA (Leskey et al. 2012). Anecdotes and empirical data indicate that adult *H. halys* are very mobile and utilize multiple host plants over the growing season (Leskey et al. 2012; Lee et al. 2013a; Wiman et al. 2014). This ability to reach cultivated crops, wild hosts, and overwintering sites suggest a strong dispersal capacity (Zhang et al. 1993; Inkley 2012; Wiman et al. 2014). In the laboratory, Wiman et al. (2014) found that ~20% of *H. halys*, tethered on a flight mill, flew > 5 km per day. However, to the best of our knowledge, there is essentially no information regarding actual dispersal capacity or behavior of *H. halys* in the field.

Over the past 40 years, radar tracking techniques have continuously improved and provided a new tool to study dispersal behavior and ecology of small animals including arthropods (see Chapman et al. 2011). The development of harmonic radar systems for entomological research allows continuous tracking of individual insects under natural field conditions. Harmonic radar tracks insects by illuminating a tag with a high-power microwave signal and recapturing the second harmonic of the transmitted signal radiating from

the tag (Riley & Smith 2002; Boiteau et al. 2009; Chapman et al. 2011). A unique feature of this radar system is that transponders of the tag do not rely on battery power, allowing them to be small, lightweight and capable of being carried by small insects. For example, the harmonic-generating tag used with the bumble bee [*Bombus terrestris* (L.); Hymenoptera: Apidae] by Riley et al. (1996) weighed ~3 mg or 1.5% of the bee's weight. To date, portable harmonic radar systems have been used to study movements of several insect types, for example forest tent caterpillar moth [*Malacosoma disstria* Hubner; Lepidoptera: Lasiocampidae] and its parasitic tachinid fly [*Patelloa pachyppyga* (Aldrich & Webber); Diptera: Tachinidae] (Roland et al. 1996), Asian longhorned beetle [*Anoplophora glabripennis* (Motschulsky); Coleoptera: Cerambycidae] (Williams et al. 2004), plum curculio [*Conotrachelus nenuphar* (Herbst); Coleoptera: Curculionidae] and western corn rootworm [*Diabrotica virgifera virgifera* LeConte; Coleoptera: Chrysomelidae] (Boiteau et al. 2011a,b), Colorado potato beetle [*Leptinotarsa decemlineata* Say; Coleoptera: Chrysomelidae] (Boiteau et al. 2011a,b, Gui et al. 2012) and southern green stink bug, [*Nezara viridula* L.; Hemiptera: Pentatomidae] (Pilkay et al. 2013).

Recently, Lee et al. (2013b) showed that a portable harmonic radar can be used to track adult *H. halys* without affecting its survival, walking mobility or flight capacity. Pilkay et al. (2013) also demonstrated that a 6-cm-long monopole radar tag did not significantly reduce walking or flying mobility of another stink bug species *N. viridula* in

the laboratory. To reliably operate the radar system, it is critical for the radar tag to be securely attached on the insect and remain functional when subjected to mechanical stress in the field, notably during severe weather conditions (Williams et al. 2004; Boiteau et al. 2009; Hall & Hadfield 2009). Lee et al. (2013b) demonstrated that the radar tag can be securely attached to the pronotum of *H. halys* adult by gently sanding the pronotum and applying cyanoacrylate glue. However, there has been no attempt to enhance the adhesive bond between radar transponder and wire. Solder paste has been used as an adhesive to form and maintain a resonant structure consisting of the transponder and wire loop. However, the strength of this solder paste bond varied substantially and often failed to securely hold the transponder on the wire when the radar tag was subjected to mechanical impacts in the field (Hall & Hadfield 2009). Such occurrences caused tagged individuals to be undetectable by the radar. In the field, obscuration of radar waves by vegetation and occurrence of false positive detection (i.e., harmonic generation by elements of the environment) would also affect the efficacy of the radar with respect to tag detection. Based on the findings of previous research, this study was conducted to (1) improve the resistance of radar tags to mechanical stresses, and (2) confirm and establish the efficacy of the harmonic radar in detecting adult *H. halys* in various agricultural landscapes. These data were required to enhance the proficiency of radar operations in the field to elucidate the dispersal behavior and ecology of *H. halys*.

## MATERIALS AND METHODS

### Insects and Harmonic Radar

*Halyomorpha halys* adults used in this study were collected in the vicinity of Kearneysville, West Virginia (N 39° 31' W 77° 53'). Adults were maintained in screen cages (30 cm<sup>3</sup>) with food including potted soybean plants, peanuts, sunflower seeds and water at 25 ± 1 °C, 70 ± 10% RH and 16:8 h L:D. A portable harmonic radar system was custom-made by B. Colpitts and his laboratory at the University of New Brunswick, Fredericton, New Brunswick, Canada. The harmonic radar transceiver is portable (~10 kg) and battery-powered. The main radar components consist of the transmitter, the receiver, the signal processor, and the power supply. A 4 kW, 9.41 GHz radar transmitter is used to generate 100 ns long pulses at a rate of 1 kHz. The dipole radar tags (~3 mg) are passive (no battery) and consist of a small copper wire (9 mm long; 0.16 mm diam) (Belden Inc., Richmond, Indiana) and a transponder (Schottky diode - Agilent HSC5340, Agilent Technologies Inc., Santa Clara, California) (Fig. 1). The radar tags were assembled on site by attaching the diode to the wire loop (~1 mm diam) using solder paste (R276, Kester, Itasca, Illinois), so that the diode and loop formed a resonant structure that effectively converted energy from the fundamental frequency to the harmonic frequency. When a tag is illuminated by the 9.41 GHz radar signal, the diode causes harmonic currents to flow, which in turn cause the radar tag to radiate harmonic

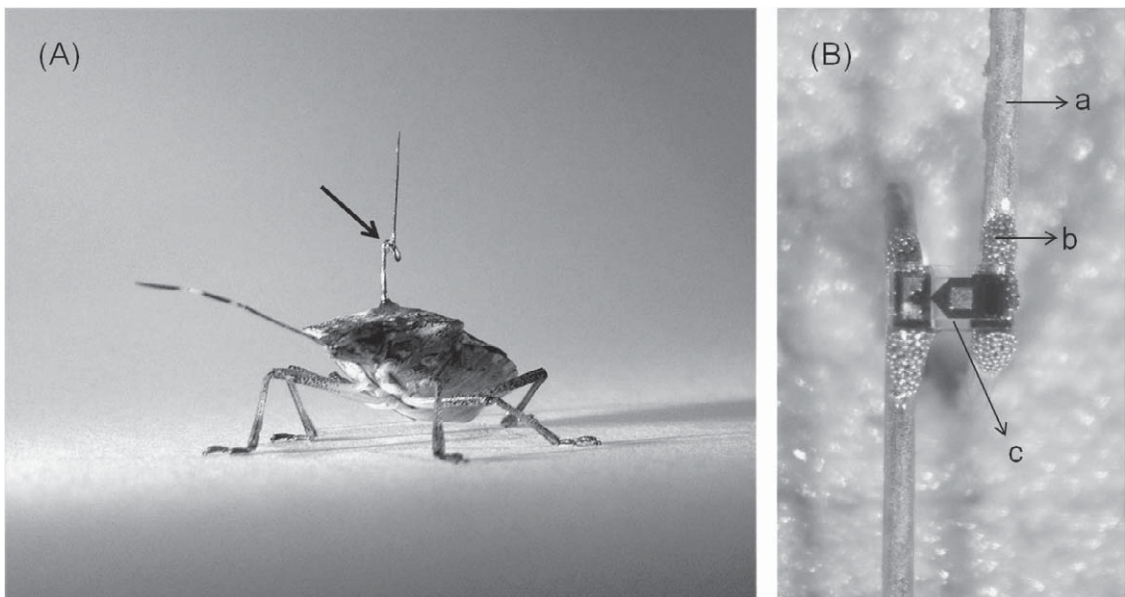


Fig. 1. (A) Adult *Halyomorpha halys* with a 9-mm dipole harmonic radar tag. (B) Magnified image of the area indicated by the arrow in Fig. 1A: a) copper wire; b) solder paste; c) transponder.



signals; the radar receiver is tuned to detect the first of these harmonics at double the signal frequency, 18.82 GHz. Each tag was then attached to the pronotum of an adult *H. halys* using a cyanoacrylate glue (FSA; Barnes Distribution, Cleveland, Ohio) as described in Lee et al. (2013b).

#### Reinforcement of Radar Tag Mechanical Resistance

This experiment was conducted to determine if the strength of the Kester® solder paste bond between radar transponder and radar wire (Fig. 1) could be increased to reduce the probability of tag failure due to mechanical impacts. Preliminary tests suggested that coating the tag loop with a cyanoacrylate glue (FSA; Barnes Distribution, Cleveland, Ohio) might protect the bond. The glue was applied in 2 ways: 1) as a strip across the solder paste bonding area between radar transponder and radar wire, and 2) by dipping the entire bonding area into the glue. The treated tags were left to dry at room temperature. These experimental tag treatments (glue strip or dipped) were compared with standard radar tags (no cyanoacrylate glue present on the bonding area between the transponder and the wire). All radar tags were attached to the pronotum of adult *H. halys* as described in Lee et al. (2013b) (Fig. 1A). Detectability of each tagged individual was verified by pinning the individual on the top of a yellow pyramid trap base (~50 cm tall) in a mowed grass-covered plot and operating the radar unit at a distance of 5 m away and from all 4 cardinal directions. Then, each *H. halys* tagged with one of the 3 treatments was subject to a drop test. Each radar-tagged insect was placed individually inside a plastic container (163 mL) and dropped (92 cm) 3 times from a laboratory counter to the laboratory floor (Lee et al. 2013b). After 3 drops, each *H. halys* test subject was checked to determine if the tag remained attached to the pronotum. If the tag remained attached to the insect, the detectability of the radar tag was evaluated again as described above. Twenty individuals were tested for each treatment. The data were analyzed using likelihood ratio tests based on nominal logistic models to compare the radar tag detectability among the 3 treatments (JMP Genomics 5.0, SAS Institute).

#### Radar Efficacy in Various Landscapes

Experiments were conducted in 4 different landscapes with increasing plant obscurative structure. The ability of the harmonic radar to detect radar-tagged *H. halys* in these landscapes was assessed by having one person pin the tagged insects and another person (unaware of the location of tagged insects) attempt to locate the insects using the portable harmonic radar unit.

Three individuals were trained for this radar operation; all three were involved as radar operators in the study. Thirty trials were conducted for each landscape type. The search was recorded for time duration and success rate of locating insects with functional radar tags in each trial. The success rate was compared among the landscapes using likelihood ratio test based on nominal logistic models. The time duration was log-transformed for normality and analyzed using ANOVA (JMP Genomics 5.0, SAS Institute).

The first experiment (open landscape) was conducted in the absence of obscurative plant structures. A 30-m radius circular plot was laid out, and 8 yellow pyramid trap bases (~50 cm tall) were deployed every 45° on the 188-m long circumference. Among those 8 trap bases, one was randomly chosen and a *H. halys* adult was pinned on the top of the trap base (~50 cm from the ground), whereas the other 7 trap bases had insects with non-functional radar tags pinned on the top. A blind search was conducted to locate *H. halys* having a functional radar tag. The search began from the center of the plot and continued until either the radar detected a signal or a maximum of 10 min per trial had lapsed.

The second experiment (mowed grass landscape) was conducted to locate *H. halys* adults concealed on a mowed grassy field (50 × 5 m). Radar-tagged adults were concealed individually by pinning each one on grass or other vegetation in the experimental plot. The radar operator, unaware of the location of the tagged insects, searched the experimental plot by sweeping and walking through the arena with the radar. Once a positive signal from the radar system indicated the general location of the target insect, the operator started using both radar and visual methods to recover the tagged *H. halys*. The search continued until either a radar operator recovered the insect, or a maximum of 10 min per trial had lapsed.

The third experiment (exterior tree-canopy landscape I) was conducted within the border row of ~2.5 m tall cv. 'Loring' peach [*Prunus persica* (L.) Stokes; Rosales: Rosaceae] trees planted in 1999 with 1.5-m within row spacing and tree row length of ~50 m. Radar-tagged *H. halys* were pinned at exterior locations of the canopy at 1.0-1.5 m from the orchard floor on or near limbs, leaves and 1-2 cm diam fruit. When a radar operator received a positive signal from the radar system indicating the location of the tree with the radar-tagged insect, the operator started using both radar and visual methods to pinpoint and recover the tagged *H. halys* from the tree. The search continued until either the radar operator recovered the insect, or a maximum of 20 min per trial had lapsed.

The fourth experiment (exterior tree-canopy landscape II) was conducted in a similar manner in a ~15 m tall tree hedgerow of wild trees and

shrubs including walnut [*Juglans* spp.; Fagales: Juglandaceae], tree of heaven [*Ailanthus altissima* (Mill.) Swingle; Sapindales: Simaroubaceae] and black locust [*Robinia pseudoacacia* L.: Fabales: Fabaceae]. A 50-m long section of hedgerow was used as an experimental plot in this study. Radar-tagged adults were deployed and recovered using methods described in experiment 3 (exterior tree-canopy landscape I).

#### Radar Efficacy in Various Within-Tree Locations

The first experiment was conducted using mature 'Paula Red' apple [*Malus domestica* Borkh.; Rosales: Rosaceae] trees (~4 m tall; ~15 m canopy circumference) planted in 1997 at 6.8-m within row spacing that had fruit and foliage present. This orchard plot was located at the University of West Virginia's Kearneysville Tree Fruit Research and Education Center. Within the apple tree canopy, the efficacy of radar at detecting *H. halys* was evaluated at 2 different locations. Radar-tagged *H. halys* were pinned at a height of ~1.5 m either 1) within the inner third of the tree canopy near the main tree trunk in locations covered by foliage that could potentially block and interfere with radar signals, or 2) within the outer third of the tree canopy that lacked objects that could potentially block radar signals. In each trial, a radar-tagged adult was randomly placed and pinned among 10 trees within the orchard border row. A radar operator first attempted to locate the tree harboring the radar-tagged insect and then pinpointed the insect within the canopy of the selected tree. The search continued until either the radar operator recovered the insect, or until a maximum search time of 20 min had lapsed for each trial. Fifteen trials were conducted for tagged adults hidden at the inner third and at the outer third of each selected tree canopy. The data were analyzed using Fisher's exact test to compare the success rates of locating radar-tagged insects between the inner and outer tree canopies. The time duration to locate the insects was compared using the Wilcoxon/Kruskal-Wallis test (JMP Genomics 5.0, SAS Institute).

The second experiment was conducted using mature 'Bronze Beauty Bosc' pear [*Pyrus communis* L.; Rosales: Rosaceae] trees (~4 m tall; ~15 m canopy circumference) planted in 1996 at 3-m within row spacing that had fruit and foliage present. This plot was located in an orchard plot at the USDA-ARS Appalachian Fruit Research Station at Kearneysville, West Virginia. Within the pear tree canopy, the efficacy of the radar in detecting *H. halys* was evaluated by pinning radar-tagged *H. halys* adults in the exterior third of the canopy at lower, middle, and upper tree canopy heights. A radar operator attempted to locate the radar-tagged insect. A ladder was used to search the upper tree canopy if needed. The search continued

until either the radar operator located the insect, or until a maximum search time of 10 min had lapsed for each trial. Twenty trials were conducted at each of the 3 heights within the canopy. The time duration to locate the insects was log-transformed for normality and compared using ANOVA (JMP Genomics 5.0, SAS Institute).

## RESULTS

#### Reinforcement of Radar Tag Mechanical Resistance

The glue treatment itself did not affect the detectability of radar tags compared with the untreated tags ( $\chi^2 = 2.231$ ,  $df = 2$ ,  $P = 0.328$ ) (Fig. 2A). There was only one case in which the radar transponder fell off the radar wire while applying the glue strip. No transponder fell off with the glue dip method. The resistance of radar tags treated with glue to random mechanical collisions inflicted in the drop tests was significantly higher than that of untreated tags ( $\chi^2 = 39.543$ ,  $df = 4$ ,  $P < 0.0001$ ) (Fig. 2B). The percentage of detectable radar tags decreased by 85% in the drop tests when the radar tag was not treated with glue. By contrast, when glue strip was applied, the percentage of detectable radar tags decreased by only 30% in

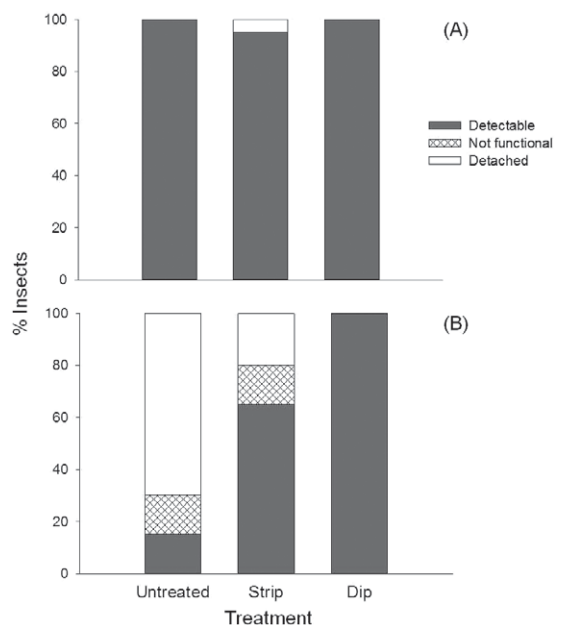


Fig. 2. Detectability of radar tags on *Halyomorpha halys* (A) before and (B) after the drop test. 'Detectable' indicates that the radar tag remained on the insect and was fully functional; 'Not functional' indicates that the radar tag remained on the insect but was not detectable; 'Detached' indicates that the radar tag was detached from the insect.

the drop tests. When glue dip treatment was applied, there was no decrease in the detectability of radar tags following the drop test (Fig. 2).

#### Radar Efficacy in Various Landscapes

The success rates of locating radar-tagged *H. halys* were > 90% in all 4 landscapes with the comparable areas to be searched (~50 m long) ( $\chi^2 = 4.542$ ,  $df = 3$ ,  $P = 0.208$ ) (Table 1). In general, radar-tagged insects were detected and recovered within 2 min, despite the increasing complexity of the landscape and habitat. In the first experiment (open landscape), the distance of radar signal detection was of interest: the tagged insects were first detected at  $14.6 \pm 0.4$  m in the open landscape setting. There was no significant difference in the search time needed to locate the radar-tagged insects among the landscapes ( $F_{3,112} = 2.424$ ,  $P = 0.069$ ) (Table 1).

#### Radar Efficacy in Various Within-Tree Locations

There was no significant difference in the success rate of locating radar-tagged *H. halys* deployed in the inner or outer third of tree canopies (Fisher's exact test:  $P = 0.483$ ) (Table 2). However, it took significantly longer to locate *H. halys* in the inner tree canopy, compared with the outer canopy ( $\chi^2 = 7.262$ ,  $df = 1$ ,  $P = 0.007$ ). When radar-tagged *H. halys* were concealed at different heights within the outer tree canopy, the success rates of locating the insects were consistently 95% at the lower, middle and upper heights (Table 2). There was also no difference in the search time needed to locate the insects among the 3 heights ( $F_{2,52} = 0.703$ ,  $P = 0.499$ ).

### DISCUSSION

Although harmonic radar systems are a powerful tool to track individual target insects, it is not uncommon in most field studies that some tagged individuals remain undetected. It is difficult to pinpoint the exact cause, but many explanations have been suggested (Williams et al. 2004; Hall & Hadfield 2009; Gui et al. 2012). Gui et al. (2012) reported that 47% of tagged individuals were not recovered in their study in

which Colorado potato beetles were released and tracked in the field. Typically many of the missing individuals had dispersed out of the arena or had come to rest behind or within objects (e.g., soil cavity, rock, or vegetation) where micro-waves could not reach the diode (Boiteau et al. 2011b; Gui et al. 2012). Another potential cause includes lost or damaged radar tags (e.g., missing diode or wire) (Williams et al. 2004; Hall & Hadfield 2009). Lee et al. (2013b) demonstrated that a radar tag can be securely attached to the pronotum of a *H. halys* adult by gently sanding the pronotum and applying cyanoacrylate glue. With a strong adhesive bond of >150-g force, it is unlikely that the radar tag could be detached from *H. halys* due to self-generated motions when the tag is entangled in the field. However, the solder paste bond between transponder and wire often failed to hold the 2 parts together securely when the radar tag was subjected to mechanical impacts; and this is a major limitation of the radar system that caused the failure to recapture individuals (Hall & Hadfield 2009). To maximize the capacity of the harmonic radar to detect tagged insects, it is critical that the radar tags must not only be securely attached to the insect, but also to remain functional when exposed to a range of mechanical stresses in the field. In this study, we demonstrated that coating the solder paste bond with cyanoacrylate glue substantially increased the resistance of the bond to mechanical stresses, and that this protected the functionality of the radar tag. Applying cyanoacrylate glue as a protective shield did not affect the radar efficacy. The addition of this procedure to the assembly of tags should decrease the incidence of undetected individuals in the field due to non-functionality of radar tags.

Detection of tagged *H. halys* adults with the harmonic radar was highly effective (> 90%) when the insects were hidden on the exterior parts of trees or grasses in various landscapes with ~50-m row length to be searched. In particular, it took less than 2 min in most cases to detect and recover insects in diverse plant architectures within tree fruit orchards. In addition, within-tree locations of *H. halys* did not affect the success rate of locating the insects using the radar system. Success rates were 87% and 100% when insects were concealed in the inner and outer tree canopies,

TABLE 1. RADAR DETECTABILITY OF *HALYOMORPHA HALYS* CONCEALED IN VARIOUS LANDSCAPES IN WEST VIRGINIA.

Landscape	Success rate (%) of locating insects	Time duration to locate insects (sec)
Open	100	120.00 ± 11.20
Mowed grass	93	141.14 ± 17.58
Exterior tree-canopy I	97	118.55 ± 31.36
Exterior tree- canopy II	100	94.24 ± 15.63

Values within a column are not statistically different (success rate:  $P = 0.208$ ; time duration:  $P = 0.069$ ).

TABLE 2. RADAR DETECTABILITY OF *HALYOMORPHA HALYS* CONCEALED AT VARIOUS LOCATIONS WITHIN TREES IN WEST VIRGINIA.

Experiment	Insect location within tree	Success rate (%) of locating insects	Time duration to locate insects (sec)
1	Inner	87 a	372.69 ± 95.00 a
	Outer	100 a	148.40 ± 38.60 b
2	Lower	95 a	61.67 ± 13.03 a
	Middle	95 a	76.68 ± 19.21 a
	Upper	95 a	110.47 ± 28.91 a

Values followed by the same letter within a column are not statistically different in each experiment ( $P = 0.05$ ).

respectively. Nevertheless it took twice as long, on average, to locate the insects concealed within the inner parts of tree canopies, compared with those concealed within the outer parts. The efficacy of the harmonic radar at detecting tagged insects can be significantly affected by the amount of plant material blocking 'microwave sightlines' between the transceiver and the tag (e.g., Lövei et al. 1997; Boiteau et al. 2011b). When radar tags were placed behind a tree, maximum detectable distance by radar was substantially decreased, compared with tags in open sight locations (Lövei et al. 1997). Boiteau et al. (2011b) also found that detection rates declined by up to 70% when radar tags were placed in the second row compared with the first row of a corn field. In this study, it required more time to achieve clear microwave sightlines through foliage when the insects were located at the inner canopies of apple trees, compared with those located in the outer canopies. Various levels of search effort are needed to locate clear microwave sightlines that allow the detection of the radar-tagged insects that may be concealed by vegetation, or that are oriented away from optimal polarization (i.e., angle of tag relative to the angle of incipient microwaves) (Lövei et al. 1997; Boiteau et al. 2011b). In this study, radar tag orientation was randomly decided when concealing the tagged insects. In general, clearer and wider radar detection zone was achieved when the angle of tag relative to the microwave was close to perpendicular.

Accurate and quick detection are the 2 fundamental reasons for researchers to use the radar system in the field to track the movement of target insects. Portable harmonic radar systems have benefited from technological developments and have become more compact, while providing more reliable detection. The radar system used in this study was the fourth generation of a harmonic radar system developed by B. Colpitts, University of New Brunswick, Fredericton, New Brunswick, Canada. This new system provided better detection capacity when the radar-tagged insects were covered by soft vegetation such as twigs and leaves within a tree canopy compared with previous systems (e.g., see Boiteau et al. 2011b). This

reliable detection also was due to very few false positive signals received during searches. With proper calibration, it was possible to minimize most of the potential false positive signals typically created by the high water contents of dense vegetation as well as the soil surface. However, while decreasing the transmitted microwave power reduces the incidence of false positives, it also reduces the detectable range, a trade-off that the operator must consider.

Radar tracking provides advantages over traditional mass mark-recapture approaches (e.g., painting, dust marking and protein marking) such as higher recapture rates and individual tracking of target insects (Hagler & Jackson 2001; Williams et al. 2004; Hall & Hadfield 2009; Chapman et al. 2011). Indeed, recovery of radar-tagged southern green stink bugs in and around cotton fields was much higher for tagged bugs (up to 75%) compared with the recovery of marked bugs using sweep net and drop cloth sampling (up to 35%) after 24 h (Pilkay et al. 2013). However, harmonic radar tracking typically requires more time, training and resources compared with typical mark-release-recapture approaches. Therefore, the best tracking technique will likely vary according to the scientific question being posed.

This study reports a new method to increase the resistance of radar tags to mechanical stresses by shielding and bolstering the bond between the transponder and the radar wire. Our results also demonstrated that radar-tagged *H. halys* can be detected with sufficiently high success rates for field operation in various agricultural landscapes. The radar technique will help researchers elucidate dispersal behaviors and distribution patterns of *H. halys* in the field.

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