Spatiotemporal Patterns and Dispersal of Stink Bugs (Heteroptera: Pentatomidae) in Peanut-Cotton Farmscapes

P. G. TILLMAN,1 T. D. NORTHFIELD,2 R. F. MIZELL,3 AND T. C. RIDDLE3

USDA–ARS, Crop Protection and Management Research Laboratory, Tifton, GA 31793


ABSTRACT In the southeast United States, a field of peanuts, *Arachis hypogaea* L., is often closely associated with a field of cotton, *Gossypium hirsutum* L. The objective of this 4-yr on-farm study was to examine and compare the spatiotemporal patterns and dispersal of the southern green stink bug, *Nezara viridula* L., and the brown stink bug, *Euschistus servus* (Say), in six of these peanut-cotton farmscapes. GS Version 9 was used to generate interpolated estimates of stink bug density by inverse distance weighting. Interpolated stink bug population raster maps were constructed using ArcMap Version 9.2. This technique was used to show any change in distribution of stink bugs in the farmscape over time. SADIE (spatial analysis by distance indices) methodology was used to examine spatial aggregation of individual stink bug species and spatial association of the two stink bug species in the individual crops. Altogether, the spatiotemporal analyses for the farmscapes showed that some *N. viridula* and *E. servus* nymphs and adults that develop in peanuts disperse into cotton. When these stink bugs disperse from peanuts into cotton, they aggregate in cotton at the interface, or common boundary, of the two crops while feeding on cotton bolls. Therefore, there is a pronounced edge effect observed in the distribution of stink bugs as they colonize the new crop, cotton. The driving force for the spatiotemporal distribution and dispersal of both stink bug species in peanut-cotton farmscapes seems to be availability of food in time and space mitigated by landscape structure. Thus, an understanding of farmscape ecology of stink bugs and their natural enemies is necessary to strategically place, in time and space, biologically based management strategies that control stink bug populations while conserving natural enemies and the environment and reducing off-farm inputs.

KEY WORDS southern green stink bug, brown stink bug, distribution, raster map

Stink bugs, mainly the southern green stink bug, *Nezara viridula* L., the brown stink bug, *Euschistus servus* (Say), and the green stink bug, *Acrosternum hilare* (Say), are an overarching issue in all types of agriculture throughout the tropical and subtropical regions of the world. They are primary pests responsible for millions of dollars in losses and cost of control in most fruit, vegetable, grain, and row crops. In cotton, *Gossypium hirsutum* L., stink bugs feed on developing seeds and lint causing shedding of newly formed bolls, yellowing of lint, and reduction in yields (Wene and Sheets 1964, Barbour et al. 1988, Roach 1988, Greene et al. 1999, Willrich et al. 2003). In the past, the status of peanuts, *Arachis hypogaea* L., as a host plant for stink bugs has been in question. Recent research, however, has shown that peanuts are a host plant for both *N. viridula* and *E. servus*. Females of *N. viridula* and *E. servus* oviposit on peanuts in the field and laboratory, and all subsequent nymphs and adults feed on leaves and/or stems of the plant (Tillman 2008a). In addition, seasonal occurrence of developmental stages of *N. viridula* and *E. servus* in on-farm peanuts indicated that these two stink bug species were developing on this crop (Tillman 2008b). Consequently, another study conducted in small field cages showed that *N. viridula* develop to adults from first instars on peanuts (unpublished data).

In the southeast United States, peanuts and cotton are two major crops in the agricultural landscape, and on many farms, peanut fields are adjacent to or near cotton fields. After the lead of Ehler (2000), we defined this within-farm configuration of patches of these two crops as a peanut-cotton farmscape. In an earlier study, Tillman (2006) determined that the density of *N. viridula* adults in cotton was much higher at the interface, or common boundary, of a peanut-cotton farmscape than at any other edge location for both crops, indicating that *N. viridula* adults were dispersing from peanuts into cotton. Because peanuts are potentially a source of populations of stink bugs in...
cotton, the spatiotemporal patterns of stink bugs in peanut-cotton farmscapes need to be ascertained to better understand how to manage these stink bug populations in these farmscapes.

There is a major lack of information on landscape ecology of stink bugs. Certainly, research from past studies has indicated that stink bug adults move from one crop to another crop to find food over the season (Toscano and Stern 1976; Todd and Herzog 1980, Hall and Teetes 1982, Jones and Sullivan 1982, Velasco and Walter 1992). However, except for the farmscape study conducted by Ehler (2000), detailed on-farm studies on distribution and dispersal of stink bugs have not been conducted at the landscape level. Because the host plant status of peanuts has been in question for stink bugs, research examining the impact of populations of stink bugs in peanuts on cotton has never been conducted.

Therefore, the primary goal of this 4-yr research project was to examine and compare the spatiotemporal patterns and dispersal of \textit{N. viridula} and \textit{E. servus} nymphs and adults in six on-farm peanut-cotton farmscapes. To accomplish this goal, spatially referenced counts of \textit{N. viridula} and \textit{E. servus} nymphs and adults were obtained for each crop in the farmscape over the growing season. This information was used to generate interpolated estimates of stink bug density. Interpolated stink bug population raster maps were constructed to visualize abundance and distribution of the stink bugs in the peanut-cotton farmscapes over time. Mark–recapture studies were conducted to determine whether individual stink bugs actually disperse from peanuts into cotton. Spatial analyses were conducted for stink bugs in individual crops to obtain a measure of spatial aggregation and species association within each crop over time.

\textbf{Materials and Methods}

\textbf{Study Sites.} Previous observations of behavior of stink bug populations in peanut-cotton farmscapes indicated that \textit{N. viridula} adults dispersed from peanuts into cotton (Tillman 2006). Based on this experience, we limited the study to examine spatiotemporal patterns of stink bugs in study sites with a field of peanuts associated with a field of cotton. In other words, the study was not conducted in randomly chosen landscapes about which absolutely no information was known about stink bug populations, but rather in landscapes in which new information on the seasonal occurrence and population behavior of stink bugs encouraged us to conduct a more in-depth study of these pests in these farmscapes. The study sites were located on Coastal Plain commercial farms near Mystic, GA. The Coastal Plain is intensively cropped to peanuts, cotton, and corn. Typically these crops are rotated with each other in this region. Each study site was managed as a conventionally tilled system.

A total of six peanut-cotton farmscapes were studied over a 4-yr period. In each peanut-cotton farmscape, peanut and cotton rows were parallel to each other, and row width was 0.91 m in both crops. In cotton, a 12-row swath was planted around the edges of the field unassociated with the peanut field. At the beginning of the study in 2004, peanut-cotton Farmscape 1 was planted in Fibermax 960 cotton on 12 May and Georgia Green peanuts on 10 May. In 2005, Farmscape 2 was planted in Delta Pine 555 cotton on 19 May and Georgia Green peanuts on 8 May. In 2006, Farmscape three was planted in Delta Pine 555 cotton on 26 May and 02-C peanuts on 18 May. In 2007, Farmscape 4 was planted in Delta Pine 555 cotton on 11 June and Georgia Green peanuts on 21 May. Farmscapes 5 and 6 were both planted in 2007 in Delta Pine 555 cotton on 11 May and 02-C peanuts on 29 May.

\textbf{Insect Species.} Adult \textit{N. viridula} and \textit{E. servus} were identified using the species key in McPherson and McPherson (2000). Nymphs of these stink bugs were identified using the descriptions of Drake (1920) and Jones (1918) for all instars. Voucher specimens of the insects are held in the USDA-ARS, Crop Protection and Management Research Laboratory in Tifton, GA.

\textbf{Insect Sampling.} Nymphs and adults of \textit{N. viridula} and \textit{E. servus} were monitored weekly in cotton and peanuts throughout the growing season each year of the study. Whole plant sampling was used in cotton with a sample consisting of all \textit{N. viridula} and \textit{E. servus} found on all plants within 1.82 m of row. Insect species and developmental stage were identified and recorded in the field using a HP iPAQ rx1950 pocket personal computer (Hewlett-Packard, Palo Alto, CA). In peanuts, insects were sampled using sweep nets 38 cm in diameter. A sample consisted of all \textit{N. viridula} and \textit{E. servus} swept from 7.31 m of row in 2004, 2006, and 2007 and from 3.66 m of row in 2005. Once a sweep sample was collected, it was put in a 3.8-liter zippered plastic bag, which was placed in a cooler and transported to the laboratory. Insect species and developmental stage were identified and recorded in the laboratory.

For sampling purposes, a peanut-cotton farmscape plot was oriented so that the cotton field was north of the peanut field, and each field was divided into an \(x\) and \(y\) grid (Fig. 1). The common boundary of the two crops was called the interface of the farmscape. The other three sides of the field were referred to as sides b, c, and d. Side b was the eastern edge of the farmscape. Side c was the northern edge of the farmscape for cotton and the southern edge of the farmscape for peanuts. Side d was the western edge of the farmscape. \(x\) values referred to the distance along the width of the farmscape from the western edge of the farmscape \((x = 0 \text{ m})\) to the eastern edge of the farmscape. \(y\) values referred to the distance along the length of field away from the interface of the farmscape \((y = 0 \text{ m})\) toward the northern edge of the farmscape in cotton and the southern edge of the farmscape in peanuts. \(y\) values in cotton were positive, whereas \(y\) values in peanuts were negative. A sample location was one \(x, y\) coordinate on the peanut-cotton farmscape. All samples were spatially explicit replications; a single sample was obtained at one \(x, y\) coordinate. A range of 104–330 samples was obtained from a farmscape each week. A previous study indicated that over the season...
most *N. viridula* in cotton congregated on rows 1–4 from the outside edge of the interface of the two crops in the peanut-cotton farmscapes (Tillman 2006). A sampling scheme was used to ensure that all regions of the field were sampled but at unequal distances. This involved sampling the interface, sides b–d, and the interior of the field, but more samples were obtained near the interface of the two crops compared with other field locations.

**Farmscape 1.** The width of the field was 244 m, and the length of the field was 259 m for both cotton and peanuts (Fig. 1). For cotton, samples were obtained along the interface of the farmscape at two edge locations: rows 1 and 5 from the outside edge of the interface. The *x* values for the eight sample locations on row 1 were 23, 53, 84, 114, 145, 175, 206, and 236 m. The *y* values for the two sample locations on row 5 were 84 and 175 m. For the other three sides of the field, samples were obtained from two edge locations: 0.5 and 4.0 m from the outside edge of the interface. For side b, the *y* values for the six sample locations at *x*/H110050.5 m were 38, 76, 91, 122, 168, and 213 m. The *y* values for the two sample locations at *x*/H110054.0 m were 91 and 168 m. For side c, the *x* values for the six sample locations at *y*/H11005259 m were 23, 38, 76, 122, 168, and 206 m. The *x* values for the two sample locations at *y*/H11005255.5 m were 38 and 122 m. For side d, the *y* values for the six sample locations at *x*/H11005244 m were 38, 76, 91, 122, 168, and 213 m. The *y* values for the two sample locations at *x*/H11005240.5 m were 91 and 168 m. The interior of the field was subdivided into nine equally sized blocks, and two samples, 7.6 m apart, were obtained from near the center of each of these blocks for a total of 18 samples in the interior of the field. The number of independent samples per crop per week was 52, for a total of 104 samples per farmscape per week. The same sampling scheme was used for peanuts except the *y* values were negative.

**Farmscape 2.** The width of the field was 365 m, and the length of the field was 243 m for cotton and 289 m for peanuts (Fig. 2). Samples were obtained along the interface of the farmscape at three edge locations: rows 1, 5, and 9 from the outside edge of the interface. For cotton, the *x* values for the nine sample locations on these rows were 53, 99, 114, 160, 206, 221, 267, 312, and 328 m. In peanuts, the *x* values for the nine sample locations on row 1 were the same as those for row 1 in cotton. The *x* values for the six sample locations on rows 5 and 9 were 53, 114, 160, 221, 267, and 328 m. For the other three sides of the field, samples were taken...
from two edge locations: 0.5 and 4.0 m from the outside edge of the field. For sides b and d in cotton, the y values for the nine sample locations at both edge locations were 23, 38, 53, 99, 114, 130, 160, 175, and 191 m. For side c in cotton, the x values for the nine sample locations at both edge locations were 38, 53, 99, 145, 160, 206, 251, 267, and 312 m. For sides b and d in peanuts, the y values for the three sample locations at both edge locations were −46, −145, and −244 m. For side c in peanuts, the x values for the three sample locations at both edge locations were 61, 183, and 305 m. For cotton, samples were obtained from five within-field locations (y values): 31, 61, 91, 122, and 183 m away from the outside edge of the interface. The x values for the six sampling locations were 53, 99, 160, 206, 267, and 312 m. For peanuts, the interior of the field was subdivided into nine equally sized blocks, and one sample was obtained from near the center of the field.

Fig. 2. Raster maps showing interpolated values of E. servus density produced by inverse distance weighting for farmscape 2 on (A) 10 August 2005, (B) 17 August 2005, and (C) 24 August 2005. Sample locations are shown on A; row 1 in cotton and peanuts overlap at the interface.
each of these interior blocks for a total of nine samples in the interior of the field. The total number of independent samples per week was 111 for cotton and 48 for peanuts.

**Farmscape 3.** The width of the field was 609 m, and the length of the field was 365 m for cotton and 243 m for peanuts (Fig. 3). In cotton, samples were obtained along the interface of the farmscape at four edge locations: rows 1, 2, 5, and 9 from the outside edge of the interface. The \( x \) values for the 18 sample locations on rows 1, 2, and 5 were 23, 69, 99, 114, 145, 175, 206, 221, 251, 282, 312, 328, 373, 404, 465, 511, 556, and 602 m. The \( x \) values for the six sample locations on row 9 were 99, 175, 251, 328, 404, and 511 m. Samples were taken from three edge locations, 0.5, 1.4, and 4 m from the outside edge of the field, for the other three sides of the field. For sides b and d, the \( y \) values for the nine sample locations at the three edge locations were 15, 31, 61, 91, 122, 152, 213, 251, and 282 m. For side c, the \( x \) values for the nine sample locations at the three edge locations were 38, 53, 69, 99, 114, 160, 221, 251, and 282 m. For side c, the \( x \) values for the nine sample locations at the three edge locations were 8, 38, 69, 160, 191, 221, 450, 480, and 511 m. In peanuts, samples were obtained along the interface of the farmscape at three edge locations: rows 1, 5, and 9. The \( x \) values for the 18 sample locations on these rows were the same as those for row 1 in cotton. For the other three sides of the field, samples were taken from two edge locations: 0.5 and 4 m from the outside edge of the field. For sides b and d in peanuts, the \( y \) values for the nine sample locations at both edge locations were –38, –53, –69, –99, –114, –130, –160, –191, and –236 m. For side c in peanuts, the \( x \) values for the nine sample locations at both edge locations were 191, 206, 221, 267, 312, 358, 450, 480, and 511 m. Cotton samples were obtained from nine within-field locations (\( y \) values): 15, 31, 61, 91, 122, 152, 213, 274, and 335 m from the outside edge of the interface. Peanut samples were obtained from seven within-field locations (\( y \) values): –15, –31, –61, –91, –122, –152, and –213 m from the outside edge of the interface. The \( x \) values for the six sampling locations were 99, 175, 251, 328, 404, and 511 m for both crops. The total number of independent samples per week was 195 for cotton and 150 for peanuts.

**Farmscape 4.** The width of the field was 488 m, and the length of the field was 244 m for both cotton and peanuts (Fig. 4). In cotton, samples were obtained along the interface of the farmscape at four edge locations: rows 1, 2, 5, and 9. The \( x \) values for the 18 sample locations on these rows were 38, 53, 114, 160, 175, 221, 251, and 282 m. For side c, the \( x \) values for the nine sample locations at the three edge locations were 8, 38, 69, 160, 191, 221, 450, 480, and 511 m. In peanuts, samples were obtained along the interface of the farmscape at three edge locations: rows 1, 5, and 9. The \( x \) values for the nine sample locations on these rows were the same as those for row 1 in cotton. For the other three sides of the field, samples were taken from two edge locations: 0.5 and 4 m from the outside edge of the field. For sides b and d, the \( y \) values for the nine sample locations at the two edge locations were 15, 31, 46, 61, 91, 122, 152, 183, and 213 m. For side c, the \( x \) values for the nine sample locations at the three edge locations were 15, 31, 46, 61, 91, 122, 152, 183, and 213 m. For side c, the \( x \) values for the nine sample locations at the three edge locations were 8, 38, 69, 160, 191, 221, 450, 480, and 511 m. In peanuts, samples were obtained along the interface of the farmscape at three edge locations: rows 1, 5, and 9. The \( x \) values for the 18 sample locations on these were the same as those for row 1 in cotton. For the other three sides of the field, samples were taken from two edge locations:...
0.5 and 4 m from the outside edge of the field. For sides b and d, the y values for the nine sample locations at both edge locations were \(-15, -31, -61, -91, -122, -152, -183, -213, \) and \(-222, 229\) m. For side c, the x values for the nine sample locations at both edge locations were 38, 84, 130, 191, 251, 297, 358, 404, and 450 m.
Cotton samples were obtained from eight within-field locations \((y)\) values: 15, 31, 61, 91, 122, 153, 183, and 213 m from the outside edge of the interface. Peanut samples were obtained from eight within-field locations \((y)\) values: 15, 31, 61, 91, 122, 153, 183, and 213 m from the outside edge of the interface. The \(x\) values for the six sample locations were 53, 114, 175, 267, 373, and 434 m for both crops. The total number of independent samples per week was 174 for cotton and 156 for peanuts.

**Farmscape 5.** The width of the field was 274 m, and the length of the field was 305 m for cotton and 244 m for peanuts (Fig. 5). In cotton, samples were obtained along the interface of the farmscape at four edge locations: rows 1, 2, 5, and 9. The \(x\) values for the 15 sample locations on these rows were 8, 23, 38, 53, 69, 99, 114, 130, 145, 160, 191, 206, 221, 236, and 251 m. For the other three sides of the field, samples were taken from two edge locations: 0.5 and 4 m from the outside edge of the field. For sides b and d, the \(y\) values for the nine sample locations at the two edge locations were 15, 31, 61, 91, 122, 153, 183, and 213 m. For side c, the \(x\) values for the nine sample locations at both edge locations were \(-15, -31, -61, -91, -122, -153, -183, and -213\) m. For side c, the \(x\) values for the nine sample locations at both edge locations were 38, 84, 114, 130, 160, 175, 206, 221, and 267 m. Cotton samples were obtained from eight within-field locations \((y)\) values: 15, 31, 61, 91, 122, 153, 183, and 244 m from the outside edge of the interface. Peanut samples were obtained from eight within-field locations \((y)\) values: \(-15, -31, -61, -91, -122, -153, -183, and -213\) m from the outside edge of the interface. The \(x\) values for the six sample locations were 23, 53, 99, 145, 191, and 236 m for both crops. The total number of independent samples per week was 162 for cotton and 141 for peanuts.

**Farmscape 6.** The width of the field was 427 m, and the length of the field was 229 m for cotton and 168 m for peanuts (Fig. 6). In cotton, samples were obtained along the interface of the farmscape at four edge locations: rows 1, 2, 5, and 9 from the outside edge of the interface. The \(x\) values for the 18 sample locations on these rows were 23, 38, 53, 69, 99, 114, 130, 145, 160, 191, 206, 221, 236, and 251 m. For the other three sides of the field, samples were taken from two edge locations: 0.5 and 4 m from the outside edge of the field. For sides b and d, the \(y\) values for the nine sample locations at the two edge locations were 15, 31, 61, 91, 122, 153, 183, and 213 m. For side c, the \(x\) values for the nine sample locations at the three edge locations were 23, 53, 99, 145, 191, and 236 m for both crops. The total number of independent samples per week was 162 for cotton and 141 for peanuts.
The \( x \) values for the 18 sample locations on these were the same as those for row 1 in cotton. For the other three sides of the field, samples were taken from two edge locations: 0.5 and 4 m from the outside edge of the field. For sides b and d in peanuts, the \( y \) values for the nine sample locations at both edge locations were \(-15, -31, -46, -61, -76, -91, -122, -137, \) and \(-152 \) m. For side c in peanuts, the \( x \) values for the nine sample locations at both edge locations were \( 23, 69, 114, 175, 206, 251, 312, 358, \) and \( 404 \) m. Cotton samples were obtained from seven within-field locations (\( y \) values), \( 15, 31, 61, 91, 122, 153, \) and \( 213 \) m from the outside edge of the interface, and peanut samples were obtained from six within-field locations (\( y \) values): \(-15, -31, -61, -91, -122, \) and \(-153 \) m from the outside edge of the interface. The \( x \) values for the six sample locations were \( 69, 114, 206, 251, 343, \) and \( 389 \) m for both crops. The total number of independent samples per week was 168 for cotton and 144 for peanuts.

**Dispersal.** In 2007, all \( N. \) viridula and \( E. \) servus fifth instars and adults found in peanuts during the sampling process were marked to examine the propensity of individual stink bugs to disperse from peanuts into cotton. Stink bugs collected from peanuts were marked, either in the laboratory or the field, with a specific color to designate the date the captured insect was found (Tillman 2006). In addition, a permanent marker was used to designate the \( x, y \) sampling location in which the insect was found. Generally, \( N. \) viridula and \( E. \) servus nymphs and adults were only sampled once a week in cotton. However, to closely observe dispersal of marked insects, extra sets of interface samples (rows 1, 2, 5, and 9) were obtained as available from cotton in each peanut-cotton farm-scape in 2007. In farmscape 4, the extra samples were obtained on 28 July and 3 August. In farmscape 5, an additional sample was acquired on 6 September. In farmscape 3, cotton was sampled on four extra dates: 29 and 30 August and 5 and 6 September. When marked insects were located in subsequent sampling events, the date and sampling location of the insect when marked were recorded. We were only able to recapture marked stink bugs for up to 9 d after marking them because an insecticide (dicrotophos [Bidrin 8], 3,806 \( \mu \)g/ml; Amvac, Los Angeles, CA) was applied for
control of these stink bugs when their populations built up in cotton.

Data Analyses. Interpolation estimates predictions at unsampled locations based on values at sampled locations (Kopp et al. 2002). One of the commonly used techniques for interpolation of scatter points is inverse distance weighted interpolation. Inverse distance weighting (IDW) is based on the assumption that nearby points ought to be more closely related than distant points to the value at the interpolation location (GS+ Version 9; Gamma Design Software, Plainwell, MI). The interpolating surface is a weighted average of the scatter points, and the weight assigned to each scatter point diminishes as the distance from the interpolation point to the scatter point increases. The rationale for using the IDW method to estimate stink bug density was that cursory examination of stink bug density data showed that many of the stink bugs occurred near the interface of the peanut-cotton farmscape. The IDW algorithm is appropriate for aggregated data and allows for rapid calculation (Krajewski and Gibbs 2001). Before interpolation for each raster map, 10% of the sample points were randomly selected and retained for accuracy assessments. With the remaining points, GS+ Version 9 (Gamma Design Software, Plainwell, MI) was used to generate interpolated estimates of insect density by IDW. The most commonly used weighting power of two was used. A fixed search radius of 200 points and a minimum and maximum number of neighbors of 1 and 10, respectively, were used. Preliminary analyses using GS+ showed that there was no significant anisotropy for each data set. For these and subsequent analyses, insect counts in peanuts were converted to number per 1.82 m for every data set.

To visually characterize abundance and distribution of stink bugs in peanut-cotton farmscapes, the IDW interpolated estimates of insect density were mapped using ArcMap Version 9.2 ESRI (Environmental Systems Research Institute, Redlands, CA). Using samples retained for accuracy assessments, root mean square errors (RMSEs) were calculated between measured and interpolated values of insect density for each peanut-cotton farmscape.

SADIE (spatial analysis by distance indices) methodology was used to examine spatial aggregation of individual species and spatial association of the two stink bug species in individual crops in the peanut-cotton farmscapes over time (Perry et al. 1999, Perry and Dixon 2002). This was done to provide information on the dispersal behavior of stink bugs within each crop and in turn to obtain insight into dispersal and distribution of the stink bugs in the whole peanut-cotton farmscape. For each peanut-farmscape studied, SADIE analyses were performed for the week stink bugs were found only or mostly in peanuts and the following week when many of these insects were found in cotton. Raster mapping and SADIE analyses were performed for a single species because the two species generally behaved similarly.

SADIE methodology has been used successfully to describe and quantify spatial patterns of other insects (Holland et al. 1999, 2005; Ferguson et al. 2000; Sciarretta and Trematerra 2006). SADIE analyses use the actual counts at the sampled locations, expressed as spatially referenced point counts (as described by Perry et al. 1999). The clustering index gives a measure of the proportion of the data that fit into patch clusters (groups of counts higher than the means) and gap clusters (groups of counts lower than mean). In this study, we used the positive (patch) cluster indices because we were more interested in aggregates of insects rather than gaps of insects. Randomization tests are used to calculate the number of times that the random data are more clustered than the actual data. This clustering test is one-tailed and determines whether the data are significantly clustered. Cluster indices were considered significant when P, the proportion that the random data were more clustered than the observed data, was <0.05. The association index compares the amount of overlap between the clusters (from the clustering tests) of the two species. The association test is two-tailed and determines whether the clusters of the two species are associated (P < 0.025), unassociated (0.025 > P > 0.975), or disassociated (P > 0.095). SADIEShell (Conrad 2006), a graphic user interface, was used for SADIE analyses. In this study, results from the IDW tests were considered in the interpretation of SADIE statistics.

χ² analyses (PROC FREQ; SAS Institute 2003) were used to compare frequency of occurrence of recaptured N. viridula and E. servus on rows 1, 2, 5, and 9 in cotton. The distance (in m) an adult in cotton had traveled away from its original interface location (x-axis position) in peanuts was determined for each recaptured adult. Then all adult stink bugs were placed into three distance groups: 0–15, 15–60, and 76–120 m away from the original interface location in peanuts. χ² analyses (PROC FREQ, SAS Institute 2003) were used to compare frequency of occurrence of recaptured N. viridula and E. servus adults in each of the three distance groups. The distance that recaptured N. viridula and E. servus adults traveled across rows and the distance adults traveled down the farmscape interface were compared using one-tailed t-tests.

Results

Farmscape 1. Raster maps of stink bug density were constructed for N. viridula on 30 July 2004 and 6 August 2004 for peanut-cotton farmscape 1 (Fig. 1). The RMSEs of the estimates for the 2 wk were close to zero (Table 1), indicating a good representation by the estimate. By visually inspecting the interpolated stink bug population raster map, it is evident that these stink bugs were present in the farmscape only in peanuts on 30 July. Both nymphs and adults of this stink bug species were observed in peanuts on this date. On 6 August, the spatial distribution of stink bugs in the farmscape was concentrated near the interface of the farmscape, although some N. viridula were present in the interior of the cotton field. Nymphs and adults of N. viridula were observed feeding on newly developed cotton bolls on 6 August, indicating that the stink
bugs had dispersed into cotton to begin feeding on the bolls.

SADIE analyses of *N. viridula* counts showed that the distribution of these stink bugs was not significantly different from a random distribution in peanuts and *N. viridula* and *E. servus* did not occur together in this crop on 30 July (Table 2). For the following sampling week, SADIE analysis showed a very strong aggregation of *N. viridula* in cotton (Table 2). The analysis also showed that both stink bug species occurred together in the same part of the cotton field on this date (Table 2). Aligned results for the first season of the study indicated that stink bug adults dispersed from peanuts into cotton and aggregated in cotton near the interface of the farmscape while feeding on cotton bolls.

**Farmscape 2.** Raster maps of stink bug density were constructed for *E. servus* on 10, 17, and 24 August 2005 for peanut-cotton farmscape 2 (Fig. 2). The RMSE of the estimate for the second and third week was found to be moderately low (Table 1) indicating a good representation by the estimate. Visual inspection of the interpolated stink bug population raster maps for 10 and 17 August showed that stink bugs were present in the farmscape only or mostly in peanuts on these sampling dates. On 17 August, *E. servus* nymphs and adults were observed in peanuts, whereas only adults were observed in cotton feeding on bolls. On this sampling date, a group of *E. servus* occurred along side *N. viridula* on 24 August (Table 2). SADIE analysis of the cluster indices showed that these stink bugs were strongly aggregated in cotton on 24 August (Table 2). The raster map for the *E. servus* population on 24 August showed that the stink bugs in the farmscape mainly were concentrated near the interface of the farmscape.

**Farmscape 3.** Raster maps of stink bug density were constructed for *N. viridula* on 3, 10, 17, 24, and 31 August 2006 for peanut-cotton farmscape 3 (Fig. 3). The RMSE of the estimate for the different weeks was found to be very low to moderately low (Table 1). On the first sampling date, all stink bugs in the farmscape were present in peanuts. Both adults and nymphs of *N. viridula* were observed in this crop at this time. By 10 August, the majority of *N. viridula* in the farmscape still were present in peanuts. On 17 August, the spatial distribution of stink bugs in the farmscape was concentrated in cotton near the interface of the two crops. Adults and nymphs of *N. viridula* were observed feeding on cotton bolls indicating that the insects dis-
persed into cotton to begin feeding on bolls. On 24 August, the population density of *N. viridula* in cotton was higher than the previous week, but the stink bugs were still concentrated at the interface of the farmscape. The *N. viridula* population peaked in cotton on 31 August, and the pests remained mainly concentrated at the interface of the farmscape.

SADIE analysis indicated that *N. viridula* were not aggregated in peanuts on 10 August (Table 2). However, this analysis showed aggregation of this stink bug species in cotton on 17 August (Table 2). Also, the association tests indicated that both species occurred in the same part of the cotton field on this date (Table 2). Therefore, key dispersal activity of the stink bugs again occurred at the interface of the farmscape.

**Farmscape 4.** Raster maps of stink bug density were constructed for *E. servus* on 4, 11, 18, and 25 July 2007, and 1 and 8 August 2007 for peanut-cotton farmscape 4 (Fig. 4). The RMSE of the estimates for the different weeks was found to be very low to moderately low (Table 1). By visually inspecting the interpolated stink bug population raster map, it is evident that these stink bugs were present in the farmscape only or mostly in peanuts on 4, 11, 18, and 25 July. Adults of *E. servus* peaked in peanuts on 25 July. Nymphs were also observed in this crop on this date. The raster map for the *E. servus* population on 1 August shows that this insect species occurred along the interface of the farmscape on this sampling date. A few adults of this stink bug species were observed feeding on cotton bolls at this time. The *E. servus* population peaked in cotton on 8 August. The raster map for the *E. servus* population on this sampling date shows that stink bugs in the farmscape remained concentrated in cotton near the interface of the farmscape, but stink bugs were also present in the other locations in the peanut field.

SADIE analyses showed that *E. servus* were not aggregated in peanuts and *E. servus* and *N. viridula* were not spatially associated in this crop on 25 July (Table 2). For the following sampling week, these analyses showed that *E. servus* was significantly aggregated in cotton, and the two stink bug species occurred in the same part of the cotton field (Table 2).

Adults of *E. servus* that had been marked in peanuts were recaptured in cotton on four dates from 28 July to 8 August (Table 3). Similarly, *N. viridula* adults marked in peanuts were recaptured in cotton. In addition, on the interface of the farmscape, one *E. servus* female was visually observed walking from peanuts on row 1 onto cotton on row 1. These results clearly showed that individuals of both stink bug species dispersed from peanuts into cotton.

**Farmscape 5.** Raster maps of stink bug density were constructed for *E. servus* on 21 and 28 August 2007 and 4 September 2007 for peanut-cotton farmscape 5 (Fig. 5). The RMSE of the estimate for the different weeks was found to be very low to moderately low (Table 1). By visually inspecting the interpolated stink bug population raster map, it is evident that these stink bugs were present in the farmscape only in peanuts on 21 August. The raster map for the *E. servus* population on 28 August shows that some individuals occurred in cotton at the interface of the farmscape, but most of the stink bugs were found in peanuts. Indeed, adults of *E. servus* peaked in peanuts on 28 August. Stink bugs were observed feeding on cotton bolls on this sampling date. On 4 September, the spatial distribution of stink bugs in the farmscape was concentrated in cotton near the interface of the two crops. The population of *E. servus* peaked in cotton on this sampling date.

SADIE analyses showed that *E. servus* were not aggregated in peanuts, and the two stink bug species were not spatially associated in the peanut field on 28 August (Table 2). SADIE analyses detected a very strong aggregation of *E. servus* in cotton and a significant association between the spatial patterns of the two stink bug species in cotton on 4 September (Table 2). A couple of *N. viridula* males and females that had been marked in peanuts were recaptured in cotton on 6 September (Table 3).

**Farmscape 6.** Raster maps of stink bug density were constructed for *N. viridula* on 21 and 28 August 2007 and 4 September 2007 for peanut-cotton farmscape 6 (Fig. 6). The RMSE of the estimate for the different weeks was found to be very low to moderately low (Table 1). Visual inspection of the interpolated *N. viridula* population raster maps showed that the majority of stink bugs of this species were present in the farmscape in peanuts on 21 and 28 August. Nymphs and adults of *N. viridula* were observed in peanuts on these dates. By 28 August, some *N. viridula* nymphs and adults were observed feeding on cotton bolls along the interface of the farmscape. There was also a group of *N. viridula* in cotton along side b at this time. A small noncommercial grove of pecan [*Carya illinoensis* (Wangenh. K. Koch) trees occurred =15 m from this field edge]. Adults of *N. viridula* were observed feeding on pecan fruit in these trees at this time, and none of the insects marked in peanuts were recaptured at this site on any sampling date. Therefore, it is highly likely that at this site some of the *N. viridula* adults in the cotton field had dispersed from pecan trees to feed on cotton bolls. On 4 September,
the spatial distribution of stink bugs in the farmscape mainly was concentrated near the interface of the farmscape, although some *N. viridula* also were present in the interior of the field for both crops. Again, some *N. viridula* were located along side b next to the pecan grove. The *N. viridula* population peaked in cotton on 4 September.

SADIE analyses showed that *N. viridula* were not aggregated in peanuts and the two stink bug species did not occur in the same part of the peanut field on 28 August (Table 2). For the following sampling week, SADIE analysis detected that *N. viridula* was strongly aggregated in cotton (Table 2). Also, a significant association was shown between the spatial patterns of the two species in cotton on this date.

Males, females, and fifth instars of both species that had been marked in peanuts were recaptured in cotton at the interface of the farmscape from 28 August through 6 September (Table 3). Also, on the interface of the farmscape, one fifth instar and one female of *N. viridula* were observed walking from peanuts on row 1 onto cotton on row 1 on 4 September. Thus, it is evident that the increase of stink bugs in cotton at the interface of the farmscape from 28 August to 4 September was mainly caused by the dispersal of these insects from peanuts.

The spatiotemporal analyses for each of the three farmscapes in 2007 season. Apparently, these nymphs were searching for food, and once they found fruit to feed on, they remained in the location where this food was readily available.

To detect any changes in dispersal behavior over time, adult stink bugs were placed into two recapture groups. Group 1 included adults recaptured in cotton 1–3 d after being marked in peanuts, and group 2 included adults recaptured in cotton 7–9 d after being marked in peanuts. The frequency of occurrence of adults recaptured in rows 1, 2, 5, and nine was not significantly different between the two recapture groups, and so both groups were combined for analysis (Table 4). Most (62.75%) of the adult stink bugs dispersed from peanuts into row 1 of cotton. Marked stink bugs were recaptured as far as row 9 away from the edge of the interface. Regarding the scouting samples, stink bugs were found only as far as row 16 by the last day of the study. Dispersal of stink bugs could only be observed for 9 d because the influx of these insect pests into the interface of cotton caused severe economic damage to the crop in that location of the field. Nevertheless, it is apparent that stink bug adults dispersed from peanuts in search of food and remained in the location in which food was available long enough to cause economic injury to cotton bolls. The fact that most of the stink bugs were present on row 1 of cotton over time supports the conclusion that stink bugs were congregating at the first location where they found suitable food.

Table 4. Frequency of occurrence of recaptured adults of *N. viridula* and *E. servus* in specific locations in cotton in peanut-cotton farmscapes in 2007

<table>
<thead>
<tr>
<th>Recapture location in cotton</th>
<th>Group 1a</th>
<th>Group 2b</th>
<th>Frequency (% of occurrence of marked adults)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Row for all adultsc</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>14</td>
<td>62.75</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>8</td>
<td>27.45</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>1</td>
<td>7.84</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>0</td>
<td>1.96</td>
</tr>
<tr>
<td>Interface distance (m) groupd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-15</td>
<td>18</td>
<td>14</td>
<td>62.75</td>
</tr>
<tr>
<td>15-60</td>
<td>7</td>
<td>6</td>
<td>5.88</td>
</tr>
<tr>
<td>76-120</td>
<td>2</td>
<td>1</td>
<td>5.88</td>
</tr>
</tbody>
</table>

Group comparison: $\chi^2 = 3.23, df = 3, P = 0.5989$
Row comparison: $\chi^2 = 46.02, df = 3, P < 0.0001$
Frequency (%) of occurrence

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a Recaptured 1–3 d after being marked.

b Recaptured 7–9 d after being marked.

c Cotton row where recaptured adults were located for all recaptured adults.

d Distance (m) recaptured adults traveled away from their original interface location (x-axis position).
The frequency of occurrence of recaptured adults in the three distance groups, 0, 15–60, and 76–120 m away from the original interface location (x-axis position), was not significantly different between the two recapture groups and so both groups were combined for analysis (Table 4). Obviously, the farthest distance that recaptured stink bug adults traveled away from their original interface position was 120 m. However, most (62.75%) of the stink bug adults dispersed from peanuts into cotton at the same interface location in which they originally occurred in peanuts. These results indicated that the stink bug adults were mostly interested in searching for an available food source.

In this study, 19 *N. viridula* and *E. servus* adults moved across cotton rows (y-axis position), whereas the same number of adults moved down the interface (x-axis position) of the farmscape. The mean distance adults traveled down the interface (47.34 ± 6.48 m) was significantly higher than the mean distance adults traveled across cotton rows (2.74 ± 0.41 m; \( t = 6.87; \) df = 36.52; \( P = 0.0001 \)). These results indicated that the stink bug adults moved along a path of least resistance, because plants along a row are closer in proximity than plants between rows.

**Discussion**

Generally, in the southeastern United States peanut fields can be closely associated with cotton fields. Recent research has shown that *N. viridula* and *E. servus* adults move into peanuts early in the season and then oviposit on leaflets of this plant (Tillman 2008b). Stink bug nymphs then feed and develop into adults on this crop (P.G.T., unpublished data). This study on spatiotemporal patterns and dispersal of *N. viridula* and *E. servus* in peanut-cotton farmscapes has shown that some nymphs and adults that develop in peanuts disperse into cotton. When *N. viridula* and *E. servus* nymphs and adults disperse from peanuts into cotton, they aggregate in cotton at the interface of the farmscape while feeding on cotton bolls. Therefore, there is a pronounced edge effect observed in the distribution of stink bugs as they colonize the new crop cotton. Similar results have been reported for other insects.

The spatiotemporal distribution of *Ceutorhynchus assimilis* Payk. adults in a crop of winter oilseed rape was mapped and analyzed using SADIE analyses (Fergu-son et al. 2000). The distribution of immigrating *C. assimilis* adults was consistent with their arrival at the crop boundaries and movement within the crop toward its center, and adult *C. assimilis* were aggregated at all times within the crop.

The spatiotemporal dynamics and behavior of *N. viridula* and *E. servus* at the interface of the peanut-cotton farmscape generally is very predictable because peanuts are the only source of stink bugs for cotton at this location in the field. Stink bugs predictably disperse from peanuts into cotton when cotton bolls become present on cotton plants. Stink bugs may oviposit on cotton leaves before bolls are present on the plants, but generally the stink bugs seem to prefer to oviposit on peanuts (P.G.T., unpublished data). Agronomic practices, however, can impact stink bug dispersal. For example, we observed that when a tractor applies a fungicide from the back of the peanut field toward the interface of a peanut-cotton farmscape, stink bugs can be flushed from peanuts into cotton. This dispersal activity, however, is also very predictable and even avoidable.

Unfortunately, other host plants sometimes occur near the other field edges of a peanut-cotton farmscape, and they may serve as sources of stink bugs. In this study, wild cherry trees and noncommercial pecan trees apparently served as sources of adult stink bugs along the edges of some of the peanut-cotton farmscapes. Therefore, the spatiotemporal dynamics of stink bugs along field edges can be dependent on the availability/abundance of other species of plants that stink bugs are feeding on. Therefore, it is imperative that we identify all hosts plants of stink bugs and determine the extent to which these plant species may impact the occurrence and abundance of stink bugs in cotton field edges.

Clearly, late instars and adults of *N. viridula* and *E. servus* switched from peanuts to cotton as a host plant, even when peanuts were still available as a food source. Previous studies have shown that stink bug adults emerge in early spring, and as the season progresses, the adult population moves from crop to crop for food and oviposition hosts (Toscano and Stern 1976, Todd and Herzog 1980, Hall and Teetes 1982, Jones and Sullivan 1982, Velasco and Walter 1992, Ehler 2000). Stink bugs generally prefer to feed on fruit/seeds of host plants such as grain sorghum, soybean, corn, cotton, and rice (Hall and Teetes 1982, Panizzii et al. 1995, Riley et al. 1987, Barbour et al. 1988, Patel et al. 2006). The fruit of a peanut plant generally is not available to stink bugs as a source of nutrition because the fruit grows underground, so older nymphs and adults may be continuously moving within peanuts in search of available fruit. A constant searching for fruit may partially explain why stink bugs do not aggregate in peanuts. The difference in aggregation between the two plant species may also be that there are generally multiple sources of stink bugs in peanuts, but for cotton, peanuts generally are the main or only source of stink bugs.

As previously mentioned, late instars of both *N. viridula* and *E. servus* host switch from peanuts to cotton at the interface of the farmscape. Host switching is an indication that food quality may be higher for cotton bolls compared with peanuts. Adults may be switching from feeding on peanuts to cotton bolls to acquire additional nutrients for reproduction. In general, reproductive performance and proportional gain in adult body weight was greater for *N. viridula* when they fed exclusively on soybean rather than on radish (Panizzi and Saraiva 1993). In addition, these biological parameters were better for those stink bugs that switched from feeding on radish as nymphs to feeding on soybean as adults compared with those that were fed solely on radish. Because late instars of *N. viridula* and *E. servus* do not have to switch from feeding on...
peanuts to feeding on cotton bolls to develop to adults, host switching also may indicate a preference for cotton bolls over peanuts.

Plant structure for peanuts can be described as low (≈43 cm in height) and bushy. Fully developed peanut plants spread over the ground uniformly covering the field in peanuts. Our results indicated that stink bug adults moved along a path of least resistance, along, rather than across rows. Similarly, Panizzi et al. (1980) determined that N. viridula nymphs moved more along rows than across rows in soybeans. In peanuts, there is little to no structural barrier to movement. Thus, the plant structure and growth habit of peanuts may have enabled stink bug nymphs and adults to move quickly across a peanut field.

Nymphs and adults of N. viridula and E. servus disperse from peanuts into cotton when cotton bolls are available as a food source. Apparently cotton is a suitable host plant for stink bug development and reproduction, because eggs, all instars, and males and females of both stink bug species were observed in cotton in each farmscape studied. In addition, adults were observed mating and feeding on cotton, and females were observed ovipositing on cotton. For each peanut-cotton farmscape we studied, the cotton field abutted the peanut field for the full length of the interface of the two crops. Thus, the whole edge of cotton adjacent to peanuts was exposed to stink bugs dispersing from peanuts, and so cotton bolls were easily accessible and available. Similarly, Velasco and Walter (1992) reported that N. viridula moved into soybean in late summer because it was an available, easily accessible and available. Similarly, Velasco and Walter (1992) reported that N. viridula moved into soybean in late summer because it was an available, suitable host plant at that time.

Nymphs and adults of N. viridula and E. servus dispersed from peanuts into row 1 of cotton at the interface of the peanut-cotton farmscape. Thus, the bugs moved directly into the next host plant at the nearest point of contact. Kiritani and Sasaba (1969) reported that within 24 h, N. viridula females migrated at least 1 km from the place where they developed, over a low mountain, and into a rice paddy field at a susceptible stage for feeding and reproduction. Even though the stink bugs traveled over the distance of the low mountain range, they still moved directly from one host plant into the closest available suitable host plant. Therefore, although stink bugs apparently can travel long distances, they probably only travel as far as necessary to locate the nearest host plant.

The important factor did not seem to be the distance the stink bugs traveled to find another host plant but how far the first host plant was from the second one. In peanut-cotton farmscapes, N. viridula and E. servus generally move from rows 1 to 16 of peanuts into row 1 of cotton. However, in 2008, we found an E. servus female that had dispersed ≈400 m across a newly planted field of peanuts into field of corn with ears (P.G.T., unpublished data). It seems that when adult stink bugs are searching for another host plant for food and/or reproduction, they disperse only as far as they need to find food or an oviposition site.

In cotton, nymphs and adults of N. viridula and E. servus aggregate at the food site, and both species are aggregated in the same parts of the field. Both of these stink bug species disperse en mass from the peanut field into row 1 of cotton at the interface of the two crops. Cotton is a relatively high (1–2 m in height) shrubby bush, and the cotton rows are distinctly separated even though there may be some overlapping of plants across rows. Stink bug nymphs and adults in this study probably remained mostly in row 1 because a suitable food was available in the quantity they needed. Also, it is likely that they stayed in the plants on the first row of cotton partly because plant structure provided a barrier/gap between row 1 and the following rows.

In conclusion, what seems to be driving the spatio-temporal distribution of these two stink bug species in peanut-cotton farmscapes is availability of suitable food in time and space mitigated by landscape structure. Thus, we must understand the farmscape ecology of stink bugs and their natural enemies to strategically place, in time and space, biologically based management strategies that control stink bug populations.

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