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RESEARCH

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ABSTRACT. A 3-yr study (2009–2011) was conducted to examine the spatial and temporal dynamics of stink bugs in three commercial farmscapes. Study locations were replicated in South Carolina and Georgia, in an agriculturally diverse region known as the southeastern coastal plain. Crops included wheat, *Triticum aestivum* (L.), corn, *Zea mays* (L.), soybean, *Glycine max* (L.), cotton, *Gossypium hirsutum* (L.), and peanut, *Arachis hypogaea* (L.). Farmscapes were sampled weekly using whole-plant examinations for corn, with all other crops sampled using sweep nets. The predominant pest species of phytophagous stink bugs were the brown stink bug, *Euschistus servus* (Say), the green stink bug, *Chinavia hilaris* (Say), and the southern green stink bug, *Nezara viridula* (L.). Chi-square tests indicated a departure from a normal distribution in 77% of analyses of the variance to mean ratio, with 37% of slopes of Taylor's power law and 30% of coefficient β of Iwao's patchiness regression significantly greater than one, indicating aggregated distributions. Spatial Analyses by Distance IndicEs (SADIE) indicated aggregated patterns of stink bugs in 18% of year-end totals and 42% of weekly counts, with 80% of adults and nymphs positively associated using the SADIE association tool. Maximum stink bug densities in each crop occurred when the plants were producing fruit. Stink bugs exhibited greater densities in crops adjacent to soybean in Barnwell and Lee Counties compared with crops adjacent to corn or fallow areas. The diversity of crops and relatively small size of fields in the Southeast leads to colonization of patches within a farmscape. The ecological and management implications of the spatial and temporal distribution of stink bugs within farmscapes are discussed.

Key Words: sampling, Taylor's power law, patchiness regression, inverse distance weighted, SADIE

The widespread adoption of transgenic cultivars of cotton, *Gossypium hirsutum* (L.), expressing *Bacillus thuringiensis* (Bt) toxins to control the heliothine complex and the eradication of the boll weevil, *Anthonomus grandis grandis* Boheman, have decreased the need for the application of broad-spectrum insecticides on cotton in the southeastern United States (Greene et al. 1999, Bundy and McPherson 2000). This reduction in pesticide use has allowed stink bugs to greatly expand their damage on cotton (Greene et al. 1999, 2001). As Bt cultivars have become more widespread in Asia, South America, and the United States, documented stink bug damage on cotton has increased (Greene et al. 1999, Panizzi and Schaefer 2000, Zeng et al. 2009). Crop losses in U.S. cotton caused by stink bugs were estimated at $31 million in 2008 (Williams 2009). Significant yield losses from this pest complex are also frequent in soybean, *Glycine max* (L.), with up to $60 million in losses annually in the United States (McPherson and McPherson 2000). Stink bugs also can be serious pests in corn, *Zea mays* (L.) (Negron and Riley 1987, Ni et al. 2010).

Phytophagous stink bugs extract fluids from plant tissues with piercing and sucking mouthparts (McPherson and McPherson 2000). Crops can be damaged by the mechanical and chemical actions of stink bug feeding, resulting in a loss of turgor pressure and injection of digestive enzymes. Pathogens, introduced as opportunistic infections or by direct transmission during feeding, also contribute to cotton losses (Ragsdale et al. 1979, Barbour et al. 1990, Medrano et al. 2007). Feeding damage on a developing cotton boll ranges from stained lint and damaged seeds to pathogen-induced boll rot or boll abortion (Ragsdale et al. 1979, Barbour et al. 1990, Medrano et al. 2007). Stink bugs also transmit yeast-spot disease in soybean (Daugherty 1967). In grain and legume crops, stink bug feeding will decrease kernels or bean quality, and entire heads or fruiting bodies can be lost (Hall and Teetes 1982, Espino and Way 2008). Depending on growth stage, stink bug feeding on corn can cause low kernel weights, loss of kernel yield, and abortion of small ears (Ni et al. 2010). Edible plant parts may become distasteful as a result of stink bug feeding, with a bitter taste or pithy texture (Callahan et al. 1960). Alternative management strategies must be developed to reduce yield loss and the use of broad-spectrum insecticides currently applied.

The predominant pest species of phytophagous stink bugs in the southeastern coastal plain are the green stink bug, *Chinavia hilaris* (Say), the southern green stink bug, *Nezara viridula* (L.), and the brown stink bug, *Euschistus servus* (Say). Stink bugs are highly polyphagous and move between adjacent agricultural and wild hosts in the farmscapes; this movement is linked to crop phenology and the availability of suitable food sources (Jones and Sullivan 1982). Southeastern farmscapes are typically characterized by a mosaic of relatively small fields (<16 ha) of cotton, soybean, corn, wheat, *Triticum aestivum* (L.), and peanut, *Arachis hypogaea* (L.), providing stink bugs with a sequence of suitable hosts throughout the season (Jones and Sullivan 1982, Toews and Shurley 2009, Tillman et al. 2009, Reay-Jones et al. 2010, Reeves et al. 2010). A thorough understanding of stink bug spatial and temporal dynamics within farmscapes would assist in developing new management strategies that exploit predictable colonization events.

These studies are under way. For example, *N. viridula* was shown to have a clumped distribution in soybean fields in the United States (Todd and Herzog 1980). In Japan, the aggregated spatial patterns of male *N. viridula* in rice fields are partially caused by their attraction to females (Nakasuji et al. 1965). Aggregation is also caused by the

Table 1. Numbers of grid sampling points and sample dates per farmscape and year with yearly average densities of stink bug adults and nymphs per 50 sweeps (± SEM) in Lee and Barnwell Counties, SC, and Tift County, GA from 2009 to 2011

Year	Species	Barnwell County			Lee County			Tift County		
		Sample points/dates	Adult	Nymph	Sample points/dates	Adult	Nymph	Sample points/dates	Adult	Nymph
2009	*E. servus*	51/9	1.25 ± 0.21	0.10 ± 0.02	53/28	6.36 ± 0.87	5.92 ± 0.80	73/16	1.21 ± 0.19	0.62 ± 0.19
	C. hilaris	51/9	0.98 ± 0.34	0.14 ± 0.06	53/28	1.00 ± 0.20	0.79 ± 0.19	73/16	0.10 ± 0.04	0.01 ± 0.01
	N. viridula	51/9	0.16 ± 0.09	0.08 ± 0.06	53/28	1.58 ± 0.31	3.75 ± 0.63	73/16	0.34 ± 0.10	0.21 ± 0.08
	All	51/9	2.39 ± 0.46	0.24 ± 0.10	53/28	8.94 ± 1.04	10.47 ± 1.21	73/16	1.64 ± 0.22	0.84 ± 0.22
2010	*E. servus*	51/12	0.59 ± 0.16	0.12 ± 0.05	52/24	2.02 ± 0.35	2.09 ± 0.48	73/14	0.70 ± 0.11	0.53 ± 0.17
	C. hilaris	51/12	0.33 ± 0.11	0.22 ± 0.13	52/24	0.36 ± 0.14	0.19 ± 0.09	73/14	0.30 ± 0.07	0.15 ± 0.08
	N. viridula	51/12	0.02 ± 0.02	0.08 ± 0.05	52/24	0.34 ± 0.12	0.28 ± 0.12	73/14	0.15 ± 0.05	0.05 ± 0.03
	All	51/12	0.94 ± 0.23	0.41 ± 0.16	52/24	2.72 ± 0.51	2.57 ± 0.58	73/14	1.15 ± 0.15	0.74 ± 0.21
2011	*E. servus*	45/17	0.71 ± 0.31	0.09 ± 0.02	53/21	4.00 ± 1.08	3.09 ± 1.13	73/11	0.30 ± 0.08	0.37 ± 0.13
	C. hilaris	45/17	0.09 ± 0.04	0.04 ± 0.03	53/21	0.30 ± 0.10	1.13 ± 0.45	73/11	0.01 ± 0.01	0.01 ± 0.01
	N. viridula	45/17	0.00 ± 0.00	0.00 ± 0.00	53/21	0.00 ± 0.00	0.02 ± 0.02	73/11	0.00 ± 0.00	0.01 ± 0.01
	All	45/17	0.80 ± 0.31	0.07 ± 0.04	53/21	4.30 ± 1.08	4.25 ± 1.56	73/11	0.32 ± 0.08	0.40 ± 0.14

opipositional behavior of females laying eggs in masses (Hokyo and Kiritani 1962), with limited dispersal occurring until late instars (Kiritani et al. 1965). Aggregated patterns have been recorded for the conserpse stink bug, *Euschistus conspersus* (Uhler), in tomato, *Solanum lycopersicum* (L.), with greater numbers along the edge of fields (Zalom et al. 1996). Previous studies in the southeastern United States have demonstrated greater stink bug abundance along field borders in wheat (Reay-Jones 2010) and cotton (Reay-Jones et al. 2010, Reeves et al. 2010). Stink bug invasion of crop fields has been suggested to occur from alternate hosts surrounding fields, whereas within-field aggregation may be partially due to pheromones (Harris and Todd 1980, Tillman et al. 2010). *N. viridula* can disperse from corn and peanut to cotton in Georgia (Tillman 2006), whereas *E. servus* and *C. hilaris* disperse from wheat to corn in North Carolina (Blinka 2008).

Traditional spatial statistics, based on the relationship between mean and variance of pest counts, do not take sampling locations into account (Southwood and Henderson 2000). Two- and three-dimensional statistical methods use the spatial location of samples to allow for interpolation of population densities in unsampled areas (Leibhold et al. 1993). Spatial Analysis by Distance IndicEs (SADIE) red-blue methodology (Perry et al. 1999) is used to identify population clusters or low-density gaps represented by graphical displays of red and blue. This method has been used to describe distributions of *E. servus* and *N. viridula* in peanut-cotton farmscapes in Georgia (Tillman et al. 2009) and stink bugs and associated boll injury in southeastern cotton fields (Reay-Jones et al. 2010). Previously, stink bug emergence patterns were monitored at six different habitats in South Carolina (Jones and Sullivan 1981), and seasonal abundance and population structures of *E. servus*, *C. hilaris*, and *N. viridula* were studied in Georgia (Herbert and Toews 2011, 2012). Those data were collected from a limited number of crops, from experimental plots of relatively small scale, or without consideration for spatial analyses. Consequently, ecological studies are needed to better quantify stink bug population dynamics using georeferenced sampling points from commercial farmscapes. The objective of this study was to examine the spatial and temporal dynamics of stink bugs in mixed-crop commercial farmscapes over multiple years in South Carolina and in Georgia.

Materials and Methods

Fields Sampled. Stink bugs were sampled from 2009 to 2011 within three farmscapes, each consisting of portions of commercial farms with fields of wheat double-cropped with soybean, full-season soybean, cotton, peanut, and corn, as well as uncultivated fallow areas. Farmscapes were located in Lee County, SC; Barnwell County, SC; and Tift County, GA. Watermelon, *Citrullus lanatus* (Thunb.), and grain sorghum, *Sorghum bicolor* (L.), were also present at the Tift County

farmscape. The total field area sampled was 163.5 ha in Lee County, 166.6 ha in Barnwell County, and 208.5 ha in Tift County. Cooperating growers made their own decisions about crop placement, rotation, and insecticide applications. At the beginning of the project, GPS coordinates of all cultivated, and noncultivated field sampling points were recorded and maps created using geographical information systems (GIS) software ArcView 9.2 (Environmental Systems Research Institute [ESRI] 2006, Redlands, CA).

In 2009, insecticide applications were made with *beta*-cyfluthrin in Lee County (0.017 kg [AI]/ha) to cotton on 15 July, to full-season soybean on 27 July, and to double-crop soybean on 24 August. Applications were limited in 2010 to full-season soybean on 28 July and in 2011 to cotton on 20 July and to full-season soybean on 12 August. In Barnwell County, *beta*-cyfluthrin applications (0.017 kg [AI]/ha) were made to cotton on 1 July 2009, to cotton, peanut, and soybean on 27 July 2010, to peanut on 20 July 2011, and to cotton on 3 August 2011. In Tift County, in 2009, the grass borders between fields received an insecticide application on 20 July and were mown on 31 August and 2 October. In 2010, the borders were mown on 8 and 22 July. No data were available for insecticide applications in 2010 and 2011 or for mowing the field borders for 2011.

Stink Bug Sampling. A sampling plan following a grid (150 m) across each farmscape was used in all crops. Fallow areas located in the grid in Barnwell and Tift Counties were sampled, in addition to crops. The number of sampling dates (9–28) and points (45–73) varied slightly with year and county (Table 1). Each sampling point was marked by a vinyl flag attached to a 2.4-m tall fiberglass staff. Two subsamples of 25 sweeps (net diameter = 38 cm) were conducted at each sample point with the exception of corn, where two subsamples of 25 whole plants were visually examined. Adults and nymphs of each stink bug species were recorded from each sample. Crop growth stages were recorded for each crop, using vegetative and reproductive stages for corn and soybean, week of bloom (WOB) for cotton, and the Zadoks scale (Zadoks et al. 1974) growth stage for wheat. Weekly sampling began in each field when plants were large enough to be swept (or around V5 in corn) and ended at crop maturity or when sweep net sampling began to damage plants. Sampling therefore did not always occur in all flags on a given week. Fallow, peanut, grain sorghum, and watermelon stages were not recorded.

To determine the effect of distance from field edges on stink bug density, stink bugs in Lee and Barnwell Counties were also sampled along transects starting at the field edge (first two rows of the crop) and distances of 5, 10, and 25 m into the crop. In Tift County, transect samples were taken in the grass border adjacent to the agricultural crop, and then at distances of 5, 10, and 25 m into the fields. The number of transects varied with years and farmscapes from two to three per field. Sampling was conducted as previously described.

Statistical Analysis. Counts of adults and nymphs of the three primary pest species found in the two 25-sweep subsamples were summed at each sampling point prior to analysis. Aggregation indices were determined using the variance-mean ratio ($I_D = s^2/x$) where s^2 is the sample variance and x is the sample mean (Southwood and Henderson 2000) for individual and combined species for both life stages for weekly and cumulative annual counts for each farmscape. Departure from a ratio equal to one was tested by $\chi^2 = s^2(n-1)/\bar{x}$ with $n-1$ degrees of freedom, where n is the number of samples (Southwood and Henderson 2000). Coefficients of Taylor's power law and Iwao's patchiness regression for each species and farmscape were calculated in SigmaPlot (2006). Taylor's power law relates mean density to variance by the equation $s^2 = ax^b$ (Taylor 1961, 1984) where s^2 is the variance, x is the mean of the sample, and a and b are Taylor's coefficients, with a nonlinear regression used rather than log–log transformation to avoid overestimation of variances at low densities (Wilson 1985, 1994). Iwao's patchiness regression is defined as $\dot{X} = \alpha + \beta x$, where $\dot{X}$ is the mean crowding index calculated by $x = (s^2/x - 1)$ (Lloyd 1967), α is the index of basic contagion, and β is the density contagiousness coefficient. Slopes of Taylor's power law and Iwao's patchiness regression were compared with a value of one using t-tests [$t = (\text{slope} - 1)/$(SE of slope)], with $n-2$ df and a probability level of $P = 0.05$ (Zar 1999).

The SADIE red-blue methodology of Perry et al. (1999) was used to identify clusters of high-density counts or gaps of low-density counts, using weekly and seasonal totals for each crop, by stink bug species and life stage. A local clustering index was assigned to each sample point, with either a positive cluster index ($\bar{v}_i$) for counts above the mean or a negative gap index ($\bar{v}_j$) for counts below the mean. Randomness is indicated by $\bar{v}_i = -\bar{v}_j = 1$. Nonrandomness was quantified by comparing the observed patterns with random rearrangements across the sampling area. The overall index of dispersion (I_a) can indicate an aggregated (>1), random ($=1$), or uniform distribution (<1). The null hypothesis of spatial randomness was rejected for $P < 0.025$ (aggregation) or $P > 0.975$ (uniformity).

The SADIE association tool was used to determine spatial associations between adults and nymphs for each species and for total counts of all species by farmscape and year. An overall index of association (X) was determined between each paired dataset, with positive associations for $X > 0$ ($P < 0.025$) or negative associations for $X < 0$ ($P > 0.975$). Mean X was determined from the local spatial associations (X_k) for each sampling point k. A positive association between two variables indicates a patch or gap for both variables, whereas a negative association indicates a patch of one variable and a gap of another (Perry 1997, 1998). Selected SADIE local aggregation indices were imported into the GIS software (ArcView 9.2, ESRI 2006) and the Inverse Distance Weighting (IDW) spatial statistical method was used to visualize stink bug aggregations. Cell values in IDW are interpolated using a linear weighted combination of data points around each cell. SADIE was chosen over more traditional geostatistical methods, such as kriging, because SADIE can illustrate local variability in spatial distribution and association among datasets sharing the same sampling points (Perry et al. 2002).

The influence of distance from the field edge and the effect of adjacent crop plantings on stink bug densities were analyzed separately for each farmscape. The response variables were the total numbers of each primary pest species and all species combined for each life stage averaged across sample dates. As the authors did not dictate crop plantings in the commercial farmscapes, not all crop and adjacent crop combinations occurred in all farmscapes. As such, crop and adjacent combinations were combined into a fixed "crop and adjacent crop" effect. "Crop and adjacent crop" effects in Lee County consisted of adjacent fields of corn and cotton, corn and wheat-double-crop soybean, cotton and soybean, cotton and woods, wheat and woods, corn and woods, wheat and cotton, and soybean and woods. Adjacent fields in Barnwell County consisted of cotton and corn, cotton and fallow,

cotton and soybean, corn and fallow, soybean and fallow, and soybean/peanut. In Tift County, where transects were separated by grass borders, adjacent fields consisted of cotton and pines, cotton and pecan, cotton and soybean, cotton and sorghum, and cotton and watermelon. These grass borders were considered to be adjacent to both fields on each side and were combined into a single value. Because only certain fields were used in certain years, an effect combining the two into "field and year" was created. The treatment arrangement of the study was a two-factor factorial of distance from edge and "crop and adjacent crop" combinations. The experimental design of the study was a split plot with subsampling. The whole plot factor was "crop and adjacent crop" arranged in a completely randomized design with "field and year" as replicates. The subplot factor was distance arranged in a randomized complete block design with "field and year" as blocks. The two to three transects within each field were subsamples. A linear model was developed to account for distance, "crop and adjacent crop," and their interaction as fixed effects, and "year and field" within "crop and adjacent crop" (i.e., whole plot error or error$_A$), interaction of distance with "year and field" (i.e., subplot error or error$_B$), and residual error (i.e., subsampling error or error$_C$) as random effects:

$$Y_{ijkl} = u + FY_i + C_j + FY(C)_{ij} + D_k + C*D_{ik} + D*FY(C)_{ijk} + T(D*FY(C))_{ijkl}$$

where Y_{ijkl} is the response variable in "year and field" i, "crop and adjacent crop" j, distance k, and transect l; u is the overall mean of the response; FY_i is the effect of "year and field" i; C_j is the effect of crop j; $FY(C)_{ij}$ is the effect of "year and field" i within "crop and adjacent crop" j (error$_A$); D_k is the effect of distance k; $C*D*_{ik}$ is the interaction effect of "crop and adjacent crop" j and distance k; $D*FY(C)_{ijk}$ is the interaction effect of distance k and "year and field" i within "crop and adjacent crop" j (error$_B$); and $T(D*FY(C))_{ijkl}$ is the effect of transect l within distance k and "year and field" i within "crop and adjacent crop" j (error$_C$).

PROC GLIMMIX (SAS Institute 2008) was chosen to estimate and test model terms, as the experimental design of the study involved multiple random effects, resulting in a split-plot design that required correction for the random effects and appropriate error terms for the level of the split plot. Examination of the count data using Proc FREQ determined that the data followed a normal distribution; therefore, no transformations or link functions in GLIMMIX were necessary. Stink bug counts for corn and woods and wheat and cotton adjacent crops were insufficient for analysis in Lee County and were omitted from the model. Significance for model terms was determined using a probability level of 95% ($P < 0.05$). Degrees of freedom were calculated using the Kenward–Roger degrees of freedom approximation (Kenward and Roger 1997). Because distance is a continuous variable and crop and adjacent crop combinations were considered a single effect, contrast statements were used to evaluate the impact of distance and crop and adjacent effects over traditional pairwise comparisons. As different treatment combinations were present in each farmscape, contrast coefficients were manually assigned as needed.

Results

Species Composition and Temporal Dynamics. Across all years and farmscapes, *E. servus* was the most abundant stink bug (64.7% of all individuals), with fewer *N. viridula* (12.9%) and *C. hilaris* (11.0%) counts. Densities of adults and nymphs varied with year and farmscape (Table 1). The rice stink bug, *Oebalus pugnax* (F.), was the most numerous noneconomic pest species of southeastern row crops, comprising 11.4% of total adults and nymphs of all species, and was found predominantly in wheat, with 84.2% found in wheat in 2009. The red-shouldered stink bug, *Thyanta custator* (F.), the dusky stink bug, *Euschistus tristigmus* (Say), and the spined soldier bug, *Podisus maculiventris* (Say), were < 1% of total captures. A range of host and nonhost weeds

and trees bordered all farmscapes. Woods along fields comprised a number of different species; main species were loblolly pine, *Pinus taeda* L., water oak, *Quercus nigra* L., southern red oak, *Quercus falcata* Michaux, black cherry, *Prunus serotina* Ehrhart, elderberry, *Sambucus canadensis* L., and American sweetgum, *Liquidambar styraciflua* L. Other weed hosts included vetch, *Vicia* spp., peppergrass, *Lepidium virginicum* L., coffee senna, and *Cassia occidentalis* L.

In wheat (present only in Lee County), stink bugs were first detected in early April, with *E. servus* sampled when flag leaves were visible (Zadoks stage 37). Numbers of adult *E. servus* increased rapidly as wheat entered the boot stage, with adult *N. viridula* first collected in wheat during heading (stage 50). Nymphs of either species were not collected in wheat in any year before the dough stage (Fig. 1A–C for *E. servus*). *C. hilaris* was not collected in wheat. The numbers of stink bugs collected decreased in wheat as the grain matured.

Stink bugs were next detected in corn, with *E. servus* found in the V10 stage in Lee (Fig. 1A–C) and Barnwell Counties. *C. hilaris* was also found for the first time in Barnwell County in corn at V10 in 2009 (Fig. 2D), though this species was not found in corn in Lee County in any year, and corn was not available for sampling in Tift County. *N. viridula* was not found in corn in Lee County in 2009 and 2011, though 0.1 insects per 50 plants sampled were found only at V10 in 2010. In Barnwell County, where wheat was not present, adult *E. servus* were found in corn, with a maximum density of 1.5 insects per 50 sweeps in the milk stage, with densities decreasing as the corn matured (data not shown due to low densities).

Stink bugs were first detected in cotton during squaring, and all three major species were found from stage V10 to R1 in soybean at approximately the same time in all locations where both crops were present. The first adult population peaks in cotton for *E. servus* and *N. viridula* occurred in the first WOB in all locations, with *C. hilaris* also peaking in the first WOB in Tift County in 2010 (data not shown). Peak populations for all three species in soybean did not occur until R4 for adults, with a sharp increase in nymphs for all species in soybean at R6, typically 3–4 wk after adult peaks (Figs. 1 and 2). Double-cropped soybean (Fig. 1A–C), planted after wheat had been harvested, also had adult peaks around R4, with a nymph stage peak at R6. *C. hilaris* was rarely detected in peanut (Fig. 2D), whereas densities of *E. servus* in peanut were also low (Fig. 2A–C). *N. viridula* was not found in peanut (Fig. 1D).

Examining densities of adults and nymphs by species at all sampled farmscapes, *E. servus* showed two distinct peaks (one in wheat and one in soybean) (Fig. 1A–C). A single peak of *E. servus* occurred in 2011 in mid-summer in Lee County. No clear pattern could be detected for *E. servus* in Tift County, likely due to low densities (Fig. 2). In Tift County in 2011, where sampling was not undertaken until August, a limited number (0.02 per 50 sweeps) of nymphs were found in the first WOB in cotton, as cotton had been replanted due to severe drought.

C. hilaris, found in lower numbers than *E. servus*, showed two adult peaks in Barnwell County in 2009, with one occurring in corn at R1 and soybean at V10, concurrently, and the other occurring at R4 in soybean, with low numbers of nymphs in both cases (Fig. 2D). Adult peaks in full-season soybean and peanut were recorded 2 wk after the application of insecticide (Fig. 2). Two peaks for *C. hilaris* adults were recorded at R1 and R6 and one peak for nymphs at R6 in Lee County in soybean in 2009 (data not shown). Densities were low for *C. hilaris* in 2010 and 2011, with only single peaks of adults and nymphs each year occurring at R6 in soybean and in the eighth WOB in cotton in Lee County.

Data for *N. viridula* are shown only for Tift County in 2009 due to low densities and no clear patterns in all years and farmscapes (Fig. 1D). Nymphs of *N. viridula* increased in wheat in Lee County in 2009 at stage 87 (hard dough), following a smaller adult peak during stage 73 (early milk). A peak of adults was found in cotton in 2010, in the sixth WOB, 5 wk after the field received the only insecticide application of the year. A peak in nymphs at the first WOB in cotton was also recorded in Tift County in 2009, though densities never increased beyond 0.03 insects per 50 sweeps in cotton samples (Fig. 1D).

Spatial Patterns. Indices of dispersion are presented for farmscapes by crop and year where adequate data were available (Table 2). Populations in watermelon or sorghum were insufficient for analysis. Adults were significantly aggregated in 43 of 56 comparisons (variance to mean ratio >1, Table 2). *E. servus* was aggregated 39.5% of the time. Aggregated distributions for *N. viridula* (11.6%) and *C. hilaris* (9.3%) occurred less often, with the remaining 16.4% for the combined totals of adults of all species. Most aggregated distributions were found in soybean (32.6%), with cotton (20.9%), corn (18.6%), fallow (4.7%), and peanut (2.3%) showing lower percentages. Adult stink bugs had aggregated distributions in 9.3% of farmscape-date combinations in both wheat and double-cropped soybean. Lee County held 39.3% of aggregated distributions for adults, with 19.6% in Barnwell County and 16.1% in Tift County (Table 2). Nymphs were aggregated in 27 of 30 distributions (90.0%), with 33.3% for *E. servus*, 14.8% for *N. viridula*, 3.7% for *C. hilaris*, and the remaining 38.6% of aggregated distributions found for the combined totals of adults of all species. Nymphs were most often aggregated in soybean (48.1%), with fewer aggregated distributions in fallow (18.5%), wheat (14.8%), double-cropped soybean (11.1%), cotton (3.7%), and peanut (3.7%). The majority of significant indices for nymphs were found in Lee County (53.3%), with 6.7% in Barnwell County and 30.0% in Tift County (Table 3).

Data were sufficient for analysis using Taylor's power law and Iwao's patchiness regression in 86 year-farmscape-crop combinations (56 for adult stink bugs and 30 for nymphs) (Tables 2 and 3). Slopes for Taylor's power law were significantly ($P < 0.05$) different from one, indicating a nonrandom distribution, for adults in 22 of 56 year-farmscape-crop combinations (39.3%) in Lee (19.6%), Barnwell (5.4%), and Tift (14.3%) counties (Table 2), whereas slopes were significantly different from one for nymphs in 10 of 30 regressions (33.3%) for Lee (26.6%), Barnwell (3.3%), and Tift (3.3%) (Table 3). For nymphs, slopes of Taylor's power law were generally >1, indicating aggregated distributions with the exception of two in Lee County in 2009, where nymphs of all species combined in cotton and *N. viridula* nymphs in double-cropped soybean had uniform distributions. The density contagiousness coefficient β of Iwao's patchiness regression was significantly different from one in 20 of 56 cases (35.7%) for adults in Lee (19.6%), Barnwell (1.8%), and Tift Counties (14.3%) (Table 2), and six of 30 cases (20.0%) for nymphs in Lee County (13.3%), with 3.3% each in Barnwell and Tift Counties (Table 3). All significant density contagiousness coefficients indicated aggregation, with the exception of one for nymphs of *E. servus* in wheat in Lee County in 2010, which indicated a uniform distribution.

SADIE aggregation indices for year-end summary data were significant in 11 of 60 analyses (18.3%) for the three main pest species and all species summed with six (54.5%) significant indices for adults and five (45.5%) for nymphs (Table 4). Significant year-end SADIE indices indicated aggregated distributions in adults and nymphs, and all 22 significant associations between adults and nymphs were positive out of 28 paired datasets (Table 4). SADIE also was used in 608 separate sample datasets for weekly totals separated by species for all three farmscapes and years. Of those, 258 adult and 127 nymph datasets contained captures at two or more sampling locations, permitting analysis. Adults and nymphs had significant patches or gaps in 11.2% and 22.8% of analyzed weekly datasets, respectively (see weekly indices in Figs. 1 and 2). Adults and nymphs of *E. servus* (41.4% and 48.3%, respectively) and *C. hilaris* (10.3%, 6.9%) had more significant indices than *N. viridula* (3.4% and 3.4%). The majority of significant indices were from combined totals of adults (44.9%) and nymphs (41.4%). All significant SADIE indices indicated aggregation with the exception of uniform distributions for adult *N. viridula* in Lee County on 22 March 2009, *E. servus* nymphs in Lee County on 12 May 2009, and adult *E. servus* in Tift County on 22 July 2010. The SADIE association tool detected significant associations between adult and nymph stink bugs in 80.0% of 96 paired weekly datasets, with 20.8% of all significant
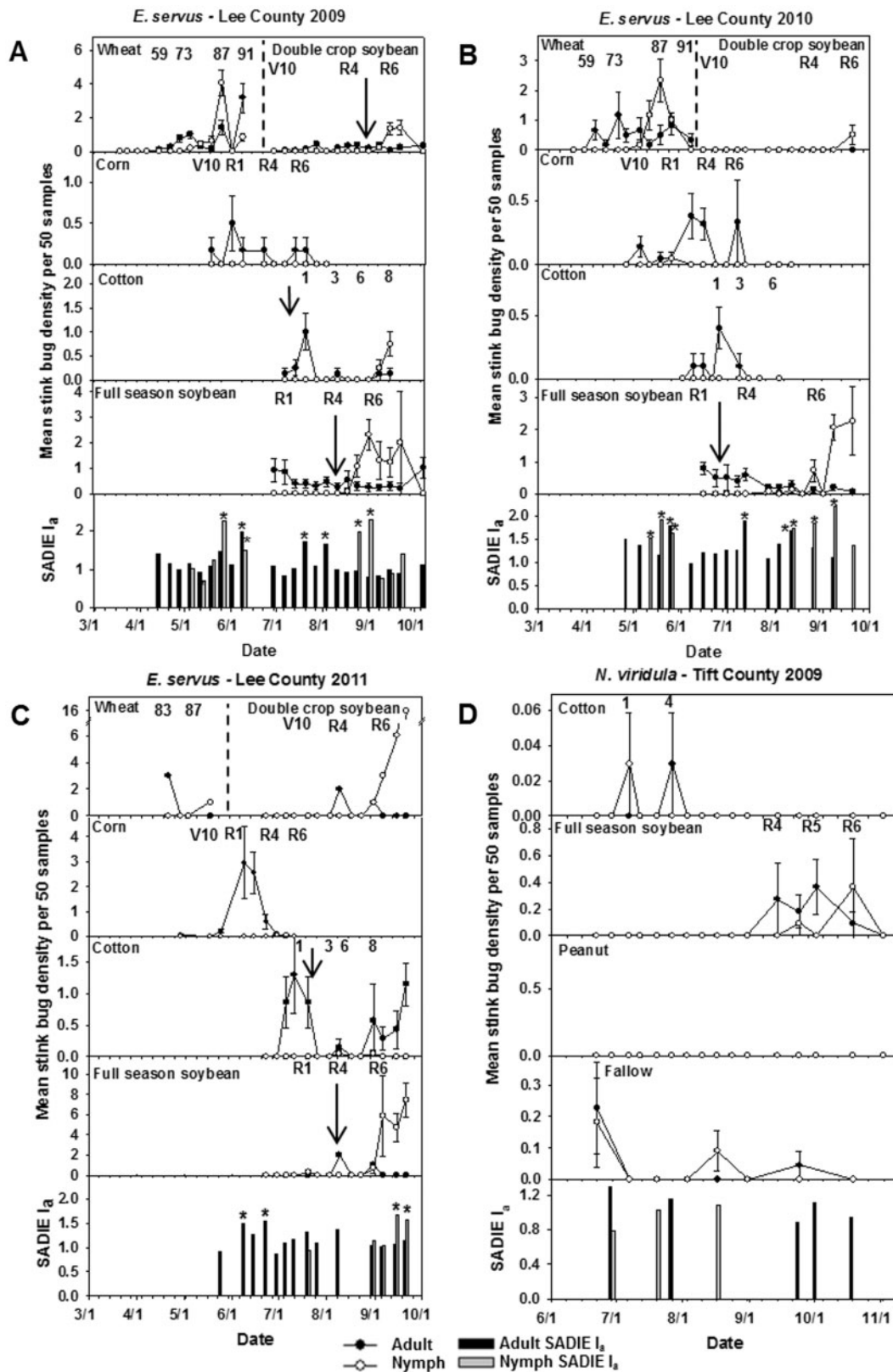
Fig. 1. Average densities for selected stink bug species ($\pm$ SEM) and daily SADIE indices of dispersion in mixed crop farmscapes in Lee County, SC (A–C, 2009–2011), and Tift County, GA (D, 2009). Arrows indicate insecticide applications. Crop phenology indicated by vegetative (V) and reproductive stages (R) in soybean and corn. Cotton stages are indicated by WOB. Wheat stages follow Zadoks scale. Peanut remained reproductive throughout the sampling periods. Asterisks indicate significant ($P < 0.025$) aggregations.
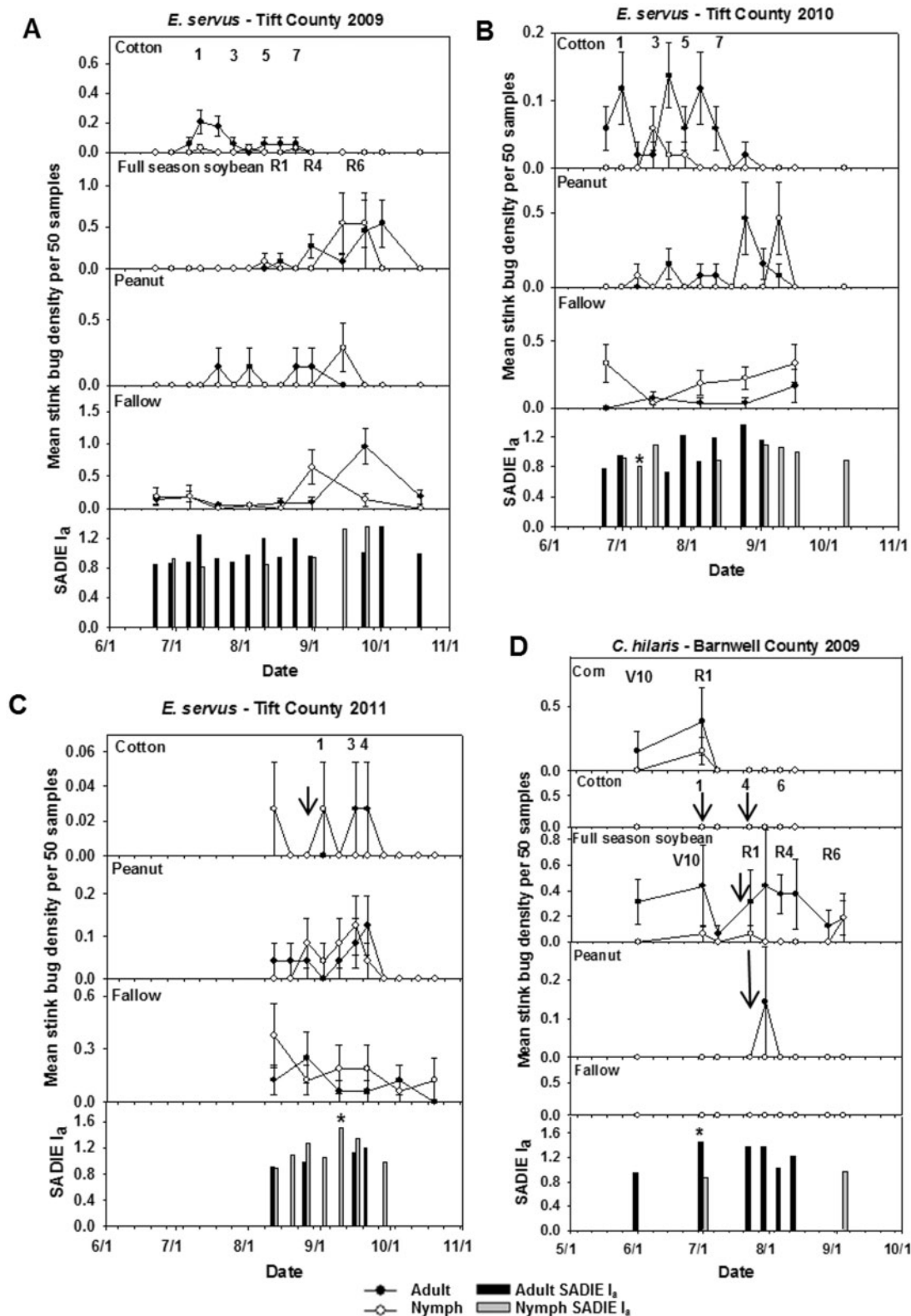
Fig. 2. Average densities (± SEM) and daily SADIE indices of dispersion for selected stink bug species in mixed crop farmscapes in Tift County, GA (A–C, 2009–2011), and Barnwell County, SC (D, 2009). Arrows indicate insecticide applications. Crop phenology indicated by vegetative (V) and reproductive stages (R) in soybean and corn. Cotton stages are indicated by WOB. Peanut remained reproductive throughout the sampling periods. Asterisks indicate significant (*P* < 0.025) aggregations.

associations for *E. servus*, 3.1% for *C. hilaris*, and 4.2% for *N. viridula*. Associations between the combined total adults and nymphs represented 71.9% of the significant associations. All associations of adults and nymphs were positive, with the exception of a limited number in

2009, with *E. servus* on 19 May, *N. viridula* on 12 July, and all species combined on 19 May and 24 August negatively associated in Lee County, and 31 August in Tift County, where *E. servus* adults and nymphs were negatively associated. The limited number of negative

Table 2. Dispersion indices for stink bug adults in selected crops from Lee and Barnwell Counties, SC, and Tift County, GA

Location	Year	Crop	Species	Taylor's power law				Iwao's regression				I_D
				a	b	R^2	t-value for slope = 1	α	β	R^2	t-value for slope = 1	
Barnwell	2009	Corn	*E. servus*	1.386	1.239	0.98	1.759	−0.061	1.448	0.87	1.363	1.371[a]
Barnwell	2009	Corn	All	1.163	1.001	1.00	0.018	0.020	1.185	0.93	0.988	1.487[a]
Barnwell	2009	Cotton	*E. servus*	1.566	0.681	0.71	−0.797	0.351	3.026	0.19	0.578	2.267[a]
Barnwell	2009	Cotton	All	1.566	0.681	0.71	−0.797	0.351	3.026	0.19	0.578	2.267[a]
Barnwell	2009	Soybean	*E. servus*	0.771	0.773	0.76	−0.757	0.089	1.000	0.09	0	0.917
Barnwell	2009	Soybean	*C. hilaris*	92.073	4.501	0.67	1.874	−0.360	8.596	0.37	1.791	3.159[a]
Barnwell	2009	Soybean	All	4.724	1.773	0.62	0.932	−0.991	6.327	0.50	2.245	2.842[a]
Barnwell	2010	Cotton	*E. servus*	3.506	1.491	0.98	**3.186***	−0.162	3.940	0.59	1.554	1.154[a]
Barnwell	2010	Cotton	All	1.672	1.126	0.98	1.297	−0.004	2.958	0.65	**2.831***	1.346[a]
Barnwell	2010	Soybean	All	0.954	0.557	0.69	−1.125	0.464	0.608	0.05	−0.624	1.247
Barnwell	2011	Corn	*E. servus*	1.251	3.681	0.81	**3.023***	−0.406	2.677	0.67	2.173	2.083[a]
Barnwell	2011	Corn	All	1.251	3.681	0.81	**3.023***	−0.406	2.677	0.67	2.173	2.084[a]
Barnwell	2011	Cotton	*E. servus*	7.092	1.926	0.98	2.555	−0.063	2.670	0.58	1.353	1.210[a]
Barnwell	2011	Cotton	All	3.080	1.479	0.97	2.174	−0.156	3.271	0.59	1.818	1.123
Lee	2009	Cotton	*E. servus*	1.141	1.108	1.00	**4.750***	−0.051	1.174	0.98	2.155	1.429[a]
Lee	2009	Cotton	All	1.122	1.319	0.98	**4.132***	−0.117	1.044	0.75	0.216	1.001
Lee	2009	Soybean	*E. servus*	2.248	1.322	0.56	0.75	−0.259	2.740	0.48	2.11	1.936[a]
Lee	2009	Soybean	*N. viridula*	1.947	1.101	0.78	0.25	−0.245	4.931	0.30	1.877	1.639[a]
Lee	2009	Soybean	*C. hilaris*	0.720	0.677	0.83	−1.707	0.103	1.121	0.17	0.17	1.216[a]
Lee	2009	Soybean	All	2.379	1.750	0.66	1.597	−0.317	2.663	0.52	**2.266***	2.354[a]
Lee	2009	Wheat	*E. servus*	1.927	2.010	1.00	**14.064***	−0.455	2.680	0.96	**8.671***	5.099[a]
Lee	2009	Wheat	*N. viridula*	2.301	0.981	0.63	−0.035	−0.255	6.503	0.23	1.552	2.364[a]
Lee	2009	Wheat	All	1.530	2.179	0.99	**7.371***	−0.226	2.457	0.88	**4.730***	4.869[a]
Lee	2009	DSB	*E. servus*	7.467	2.241	0.82	2.057	−0.326	3.677	0.49	**2.841***	1.303[a]
Lee	2009	DSB	*N. viridula*	1.756	0.987	0.99	−0.182	−0.011	2.507	0.83	**3.184***	2.017[a]
Lee	2009	DSB	*C. hilaris*	7.151	1.708	0.98	**4.252***	−0.413	9.266	0.91	**9.611***	1.899[a]
Lee	2009	DSB	All	1.913	1.131	0.92	1.028	−0.104	2.291	0.76	**3.518***	1.908[a]
Lee	2010	Corn	*E. servus*	26.174	3.863	0.96	**4.335***	−0.135	2.118	0.63	1.934	1.381[a]
Lee	2010	Corn	All	12.701	3.230	0.99	**10.216***	−0.321	3.401	0.66	**2.672***	1.767[a]
Lee	2010	Soybean	*E. servus*	0.980	0.719	0.40	−0.648	0.035	1.392	0.16	0.44	1.265[a]
Lee	2010	Soybean	*C. hilaris*	1.846	1.318	1.00	**6.094***	0.265	1.534	0.91	1.341	2.246[a]
Lee	2010	Soybean	All	2.022	0.776	0.60	−0.828	0.205	1.790	0.42	1.241	2.222[a]
Lee	2010	Wheat	All	2.255	2.955	0.97	**6.498***	−1.073	3.693	0.74	**4.005***	2.224[a]
Lee	2011	Corn	*E. servus*	0.016	7.449	1.00	**18.622***	−0.561	5.293	0.86	**4.158***	12.201[a]
Lee	2011	Corn	All	0.016	7.449	1.00	**18.622***	−0.561	5.293	0.86	**4.158***	12.201[a]
Lee	2011	Cotton	*E. servus*	1.605	1.183	0.90	0.571	−0.095	2.485	0.17	1.021	1.113
Lee	2011	Cotton	All	1.219	0.960	0.63	−0.088	−0.038	3.363	0.09	0.756	1.314[a]
Lee	2011	Soybean	*E. servus*	1.545	0.779	0.67	−0.605	0.497	1.121	0.16	0.179	1.904[a]
Lee	2011	Soybean	All	1.649	0.645	0.76	−1.776	0.538	1.113	0.30	0.224	2.117[a]
Tift	2009	Cotton	*E. servus*	1.126	1.066	0.98	0.972	−0.050	1.233	0.54	0.603	1.047
Tift	2009	Cotton	All	0.828	0.900	0.94	−0.901	0.073	0.629	0.03	−0.331	1.074
Tift	2009	Fallow	*E. servus*	1.760	1.226	0.99	3.167	0.086	1.668	0.64	1.299	1.794[a]
Tift	2009	Fallow	All	2.004	1.223	1.00	**3.783***	0.132	1.923	0.72	1.906	1.988[a]
Tift	2009	Soybean	*E. servus*	3.223	1.239	0.67	0.386	−0.492	5.717	0.39	1.845	2.548[a]
Tift	2009	Soybean	*N. viridula*	1.708	0.994	0.77	−0.014	−0.175	4.135	0.22	1.229	1.753[a]
Tift	2009	Soybean	All	2.311	1.002	0.86	0.01	−0.026	2.992	0.57	**2.204***	2.482[a]
Tift	2010	Cotton	*E. servus*	1.169	1.040	0.96	0.328	−0.040	1.984	0.38	1.133	1.087
Tift	2010	Cotton	*N. viridula*	0.593	0.775	0.87	−1.348	0.170	1.510	0.01	0.068	1.211[a]
Tift	2010	Cotton	*C. hilaris*	1.056	1.008	0.95	0.06	−0.026	1.671	0.17	0.53	1.062
Tift	2010	Cotton	All	1.477	1.063	0.98	0.81	0.032	2.427	0.72	**2.676***	1.399[a]
Tift	2010	Fallow	*E. servus*	3.543	1.451	1.00	**4.676***	−0.226	5.623	0.92	**4.656***	1.240[a]
Tift	2010	Fallow	All	4.262	1.553	1.00	**6.598***	−0.326	6.163	0.90	**4.579***	1.196
Tift	2010	Peanut	*E. servus*	2.331	1.438	1.00	**10.985***	−0.214	2.783	0.93	**6.306***	1.398[a]
Tift	2010	Peanut	All	2.293	1.418	1.00	**10.377***	−0.195	2.733	0.93	**6.480***	1.359
Tift	2011	Fallow	*E. servus*	2.212	1.374	0.99	**4.220***	1.145	1.333	0.59	**−3.650***	1.099
Tift	2011	Fallow	All	2.212	1.374	0.99	**4.220***	1.145	1.333	0.59	**−3.650***	1.069

Locations and crops with insufficient samples for analysis have been omitted. Double-crop soybeans are indicated by "DSB." I_D, overall index of dispersion, aggregated (> 1), random (1), or uniform (< 1).
[a] χ^2 test indicated significant difference from 1 ($P < 0.05$; in bold).
**$P < 0.05$ (in bold).

associations suggested significant clusters of adults and nymphs were generally found in the same area of the farmscape.

IDW interpolation maps for weekly SADIE aggregation indices are presented for *E. servus* adults and nymphs in Lee County in 2009 (Fig. 3). In Lee County in 2009, *E. servus* nymphs were aggregated in four weeks of sampling, as opposed to three for adults (Fig. 3). Clusters of adults were located in wheat on 6/9, in double cropped soybean, cotton, and full season soybeans on 7/21, and in full season soybeans on 8/4. Clusters of nymphs were located in wheat on 5/26 and 6/9, and

in full season soybeans on 8/24 and 9/1. Peak populations in corn were rarely above 0.5 stink bugs per 50 plants, and clustering was not observed. Soybean and cotton adjacent to one another demonstrated adult clustering in late July (Figs. 1 and 3). In Barnwell County in 2009, *C. hilaris* demonstrated significant adult clustering in fields of cotton and soybean adjacent to one another on 1 July 2009.

Distance From Field Borders and Landscape Effects. Distance from field edges did not have a significant effect on stink bug densities in any farmscape sampled ($P > 0.05$) (Table 5). However, crop and adjacent

Table 3. Dispersion indices for stink bug nymphs in selected crops from Lee and Barnwell Counties, SC, and Tift County, GA

Location	Year	Crop	Species	Taylor's power law				Iwao's regression				I_D
				a	b	R^2	t-value for slope $= 1$	α	β	R^2	t-value for slope $= 1$	
Barnwell	2009	Soybean	All	1.499	1.044	0.93	0.282	−0.030	3.424	0.34	1.353	**1.339**[a]
Barnwell	2010	Soybean	All	3.734	2.391	1.00	**8.652***	−1.733	5.533	0.94	**7.519***	**3.489**[a]
Lee	2009	Cotton	All	0.615	0.326	0.51	**−2.319***	0.540	0.294	0.02	−0.749	1.478
Lee	2009	Soybean	*E. servus*	4.799	1.064	0.60	0.091	0.293	3.076	0.41	1.915	**4.631**[a]
Lee	2009	Soybean	*N. viridula*	3.958	0.780	0.93	−1.742	2.746	1.168	0.11	0.107	**4.823**[a]
Lee	2009	Soybean	*C. hilaris*	2.174	0.851	0.70	−0.389	0.174	3.988	0.22	1.154	**2.691**[a]
Lee	2009	Soybean	All	12.925	0.482	0.68	−1.762	3.906	1.966	0.25	0.835	**8.437**[a]
Lee	2009	Wheat	*E. servus*	2.653	1.260	0.99	3.013	0.976	1.467	0.82	1.405	**5.646**[a]
Lee	2009	Wheat	*N. viridula*	4.163	0.868	0.99	**−2.431***	0.452	2.311	0.78	1.887	**5.218**[a]
Lee	2009	Wheat	All	3.367	1.005	1.00	0.181	1.313	1.218	0.91	1.187	**7.118**[a]
Lee	2009	DSB	*E. servus*	1.840	8.317	1.00	**10.498***	−0.358	2.468	0.96	**5.163***	**2.781**[a]
Lee	2009	DSB	*N. viridula*	3.066	1.495	1.00	**6.972***	0.088	2.591	0.94	**4.612***	**5.135**[a]
Lee	2009	DSB	All	1.171	1.945	1.00	**11.779***	0.123	1.741	0.94	**3.707***	**5.433**[a]
Lee	2010	Soybean	*E. servus*	0.000	21.453	0.99	**8.174***	−0.223	2.735	0.64	1.955	**5.274**[a]
Lee	2010	Soybean	*N. viridula*	4.755	1.554	0.98	**2.829***	0.399	3.946	0.35	1.837	**2.073**[a]
Lee	2010	Soybean	All	4.670	0.906	0.62	−0.139	0.096	2.336	0.61	1.669	**5.709**[a]
Lee	2010	Wheat	*E. servus*	1.399	0.000	0.24	0.005	6.684	−2.863	0.41	**−2.462***	2.18
Lee	2010	Wheat	All	0.757	1.649	0.96	**2.948***	−0.196	1.156	0.90	0.924	**2.179**[a]
Lee	2011	Soybean	*E. servus*	12.767	0.733	0.46	−0.354	1.020	1.989	0.46	1.158	**11.413**[a]
Lee	2011	Soybean	All	20.965	0.452	0.56	−1.863	3.700	1.233	0.47	0.409	**13.871**[a]
Tift	2009	Fallow	*E. servus*	2.439	0.944	0.96	−0.448	0.980	2.359	0.20	0.586	**2.714**[a]
Tift	2009	Fallow	All	2.498	1.024	0.95	0.149	0.560	3.000	0.29	0.926	**2.520**[a]
Tift	2009	Soybean	*E. servus*	2.786	1.427	0.93	0.613	−0.230	3.530	0.74	2.29	**2.324**[a]
Tift	2009	Soybean	All	1.882	0.614	0.89	−1.833	0.762	2.411	0.17	0.742	**2.691**[a]
Tift	2010	Cotton	All	240.718	2.882	1.00	**10.926***	−1.047	34.257	0.84	**5.273***	**2.524**[a]
Tift	2010	Fallow	*E. servus*	2.223	1.476	0.83	0.728	−0.092	2.081	0.46	0.831	**1.240**[a]
Tift	2010	Fallow	All	2.647	1.694	0.91	1.196	−0.069	1.822	0.66	1.082	**1.215**[a]
Tift	2010	Peanut	All	1.341	0.885	0.99	−1.939	0.438	1.150	0.24	0.11	**1.755**[a]
Tift	2011	Fallow	*E. servus*	1.558	1.092	0.95	0.627	−0.032	2.558	0.55	1.335	**1.333**[a]
Tift	2011	Fallow	All	1.516	1.133	0.95	0.769	−0.051	2.143	0.60	1.301	1.254

Locations and crops with insufficient samples for calculation have been omitted. Double-crop soybeans are indicated by "DSB." I_D, overall index of dispersion, aggregated (> 1), random (1), or uniform (< 1).
[a] χ^2 test indicated significant difference from 1 ($P < 0.05$; in bold).
*$P < 0.05$ (in bold).

crop effects were often significant and contrasts were developed to compare insect densities in sets of similar crop and adjacent crop combinations with densities in other sets of crop and adjacent crop combinations. For example, in Lee County, crop and adjacent crop effects were significant ($P < 0.05$) and densities in crop and adjacent crop combinations with full-season soybean or woods (consisting of cotton fields adjacent to soybean fields, cotton fields adjacent to woods, soybean fields adjacent to cotton fields, wheat fields adjacent to woods, and soybean fields adjacent to woods) were significantly higher than densities in the other combinations (i.e., corn and cotton, corn and wheat-double-crop soybean, corn and woods, wheat and cotton). Specifically, average stink bug density was higher by 0.20 ± 0.07 (SEM) ($t = 2.74$; df $= 13.2$; $P = 0.0167$), adults of *E. servus*, *N. viridula* were higher by 0.11 ± 0.03 ($t = 3.64$; df $= 11.78$; $P = 0.0035$), and combined adults of all species were higher by $0.46 \pm .11$ ($t = 4.04$; df $= 13.83$; $P = 0.0012$).

Densities of nymphs of *E. servus* were higher by 1.04 ± 0.28 ($t = 3.70$; df $= 12.11$; $P = 0.0030$) in soybean versus cotton fields. This also occurred for nymphs of *C. hilaris* (0.57 ± 0.08; $t = 7.14$; df $= 12.76$; $P < 0.0001$) and combined nymphs of all species (1.83 ± 0.31; $t = 5.88$; df $= 12.38$; $P < 0.0001$). Adults of *C. hilaris* and nymphs of *N. viridula* were not significantly influenced by crop and adjacent crop effects ($P > 0.05$). Barnwell County, lacking woods transects, still exhibited higher estimated densities on soybean fields adjacent to cotton or peanut fields and cotton fields adjacent to soybean or peanut fields for *C. hilaris* adults (0.31 ± 0.03; $t = 10.53$; df $= 41$; $P < 0.0001$), as well as adults (0.46 ± 0.08; $t = 6.09$; df $= 25.66$; $P < 0.0001$) and nymphs (0.03 ± 0.01; $t = 2.98$; df $= 164$; $P < 0.0033$) of all species combined. In Tift County, no crop and adjacent crop effect of any crop combination influenced stink bug densities for any species. Interactions between crop and adjacent crop effects and distance were

detected in Lee County for *E. servus* adults, adults and nymphs of *N. viridula*, nymphs of *C. hilaris*, and the combined nymphs of all species (Table 5). However, post-hoc analyses using contrast statements and mean separation tests did not reveal any biologically meaningful trends.

Discussion

Although SADIE and IDW of local aggregation indices have been used previously to describe the spatial dynamics of stink bugs (Tillman et al. 2009, Reay-Jones et al. 2010), this study is the first to attempt to use these techniques to quantify the spatial and temporal dispersal of adults and nymphs of multiple species across multiple years and farmscapes in different states. SADIE detected fewer aggregations than the variance-to-mean ratio, Taylor's power law, or Iwao's patchiness regression, with 82% of SADIE analyses indicating randomness. Slopes of Taylor's power law were greater than 1 in 31% of analyses, indicating a clumped distribution for adult and nymph stink bugs. Fit of Iwao's patchiness regression also generally indicated clumped distributions for adult and nymph stink bugs ($\beta > 1$) when β was significantly different from one, but distributions were random in 64% of analyses, supporting the results of Taylor's power law. The majority of significant slopes for both regressions were found in areas of highest densities, such as in Lee County or in soybean.

Many arthropod species, including stink bugs, are spatially aggregated in fields of crops (Taylor et al. 1978; Reay-Jones et al. 2009, 2010; Reay-Jones 2012). The degree of aggregation can vary with species and life stage. Based on SADIE, nymphs were slightly more frequently aggregated than adults. Stink bug eggs are laid in masses, and nymphs do not disperse from ovipositional sites until maturation to late instars (Kiritani et al. 1965), as illustrated by the high counts in soybean in Lee County, with up to 16 nymphs in a single sample. However,

Table 4. SADIE summary data analyses for year-end total stink bug dispersion indices across all crops by location for 2009–2011

Location	Year	Species	Adult I_a	Adult P_a	Nymph I_a	Nymph P_a	Association X	Association $P(X)$
Barnwell	2009	E. servus	**2.022***	**0.0002**	—	—	—	—
Barnwell	2009	C. hilaris	1.195	0.1421	1.037	0.3476	**0.464**[†]	**0.0089**
Barnwell	2009	N. viridula	1.058	0.3204	1.418	0.0273	**0.367**[†]	**0.0151**
Barnwell	2009	All	**1.825***	**0.0007**	1.156	0.1820	**0.598**[†]	**<0.0001**
Barnwell	2010	E. servus	1.175	0.1584	1.116	0.2247	**0.485**[†]	**0.0010**
Barnwell	2010	C. hilaris	1.180	0.1537	1.023	0.3866	**0.326**[†]	**0.0230**
Barnwell	2010	N. viridula	—	—	1.118	0.2306	—	—
Barnwell	2010	All	1.309	0.0754	0.958	0.5247	**0.324**[†]	**0.0187**
Barnwell	2011	E. servus	0.987	0.4597	—	—	—	—
Barnwell	2011	C. hilaris	0.887	0.6906	1.312	0.0618	**0.434**[†]	**0.0110**
Barnwell	2011	N. viridula	—	—	—	—	—	—
Barnwell	2011	All	1.054	0.3377	1.167	0.1798	0.090	0.3061
Lee	2009	E. servus	1.249	0.0984	1.427	0.0255	**0.569**[†]	**<0.0001**
Lee	2009	C. hilaris	0.885	0.7178	1.103	0.2423	0.293	0.0328
Lee	2009	N. viridula	1.310	0.0603	1.357	0.0402	**0.535**[†]	**<0.0001**
Lee	2009	All	1.361	0.0385	**1.472***	**0.0146**	**0.706**[†]	**<0.0001**
Lee	2010	E. servus	1.289	0.0670	**2.016***	**0.0002**	**0.579**[†]	**<0.0001**
Lee	2010	C. hilaris	**1.667***	**0.0017**	**1.477***	**0.0132**	**0.491**[†]	**0.0006**
Lee	2010	N. viridula	1.024	0.3752	1.151	0.1766	**0.439**[†]	**0.0046**
Lee	2010	All	1.389	0.0275	**2.058***	**0.0002**	**0.617**[†]	**<0.0001**
Lee	2011	E. servus	**1.852***	**0.0003**	1.041	0.3472	**0.360**[†]	**0.0141**
Lee	2011	C. hilaris	0.813	0.8966	1.115	0.2199	**0.413**[†]	**0.0020**
Lee	2011	N. viridula	—	—	—	—	—	—
Lee	2011	All	**1.835***	**0.0003**	1.070	0.2961	**0.384**[†]	**0.0061**
Tift	2009	E. servus	1.292	0.0771	1.259	0.0897	**0.291**[†]	**0.0069**
Tift	2009	C. hilaris	0.853	0.7783	—	—	—	—
Tift	2009	N. viridula	**1.524***	**0.0144**	1.368	0.0474	**0.582**[†]	**<0.0001**
Tift	2009	All	1.441	0.0258	1.435	0.0282	**0.398**[†]	**<0.0001**
Tift	2010	E. servus	1.119	0.2226	1.030	0.3617	0.118	0.1826
Tift	2010	C. hilaris	1.124	0.2041	0.899	0.6524	−0.028	0.5934
Tift	2010	N. viridula	1.008	0.4153	1.139	0.1966	0.123	0.1888
Tift	2010	All	1.207	0.1354	1.104	0.2517	0.165	0.0874
Tift	2011	E. servus	1.049	0.3270	**1.499***	**0.0188**	**0.359**[†]	**0.0031**
Tift	2011	C. hilaris	—	—	—	—	—	—
Tift	2011	N. viridula	—	—	—	—	—	—
Tift	2011	All	1.103	0.2422	1.425	0.0288	**0.407**[†]	**0.0009**

I_a = overall index of dispersion indicating aggregated (>1), random (1) or uniform (<1) pattern. P_a = P value for null hypothesis of spatial randomness. X = Overall index of aggregation between each paired dataset. Missing data represented by "—" indicate that insect counts were insufficient to generate aggregation indices.

*Significance in aggregation determined by α = 0.05 ($P < 0.025$ or $P > 0.975$; in bold).

[†]Significance (in bold) in association is positive for $X > 0$ ($P < 0.025$) or negative for $X < 0$ ($P > 0.975$).

Thomas et al. (2001) noted that SADIE is not a sensitive method using smaller datasets. Xu and Madden (2004) also suggested that the number of clusters and positions influence the index more than the cluster sizes. In our study, SADIE analyses sometimes used datasets with numbers as low as three stink bugs per field. Increased captures, either by increasing the size of the areas sampled or by increasing the number of points in a field sampled might have increased the aggregations and associations detected by SADIE. Despite these limitations, clusters of E. servus, often along soybean interfaces, could be clearly detected on 21 July 2009 by interpolation of SADIE indices in Lee County (Fig. 3). Weekly SADIE aggregation indices for E. servus in Lee County in 2009 and 2010 were significant in May and June and wheat, which coincides with peak densities. Similar results were found with E. servus in a recent study in wheat in South Carolina (Reay-Jones 2014). Significant aggregation indices were also noted in August and September as populations increased in soybeans.

E. servus is bivoltine in Arkansas, Georgia, Illinois, and Virginia (Woodside 1946, Rolston and Kendrick 1961, Munyaneza and McPherson 1994, Herbert and Toews 2011). Though well timed insecticide applications, applied for pest control in commercial fields, hindered our ability to detect clear generation peaks, our study supports bivoltinism in E. servus. Two distinct populations of nymphs were recorded for E. servus in Lee County in 2009 and 2010, with two also recorded in Barnwell County in 2010; the first generation of nymphs

occurred in wheat, and the last prediapause generation occurred in soybean. Low numbers of E. servus nymphs collected in Barnwell County might have been inadequate to determine peaks in 2009 and 2011 and in Lee County in 2011. Although data from Tift County demonstrated late-season peaks in all years, no early-season peak was observed. As no wheat was available for sampling in Tift County, sampling started in late June in 2009 and 2010, and sampling was delayed until mid-August in 2011 as a result of severe drought that delayed planting. Sampling in Tift County likely missed the early-season peak, which was recorded in other studies from the same area in early May (Herbert and Toews 2011).

Densities of C. hilaris in corn have often been recorded as low when found at all (Tillman 2010), consistent with our observations in Lee and Barnwell Counties in all 3 yr where none were detected in corn. Cotton and soybean both hosted adults later in the season, and the largest peaks of nymphs in Lee County in all years were in soybean in R6, likely the last generation before diapause. Early generations of C. hilaris were not found on major agronomic crops until July in a study in Georgia (Herbert and Toews 2012). The authors indicated that it is unknown if the late arrival in crops is due to development in noncrop hosts or immigration from another area. Several tree species have been recorded hosting the first generation in South Carolina (Jones and Sullivan 1981, 1982). C. hilaris might be bivoltine in South Carolina and Georgia, but early-season populations would have had to develop away from our sampling points (located in agronomic crops), remaining undetected until second-generation adults moved into the farmscape. More research remains to be done to clarify the overwintering behavior and life cycle of C. hilaris. For N. viridula, the irregular nymph stage peaks across multiple crops (Fig. 1D) suggested multivoltinism, a view supported by Jones and Sullivan (1981, 1982) and Herbert and Toews (2012), but the low densities and use of insecticide hindered our ability to accurately determine multivoltinism for this species.

Stink bugs disperse following the fruiting cycle of crops, with densities decreasing in other crops as plant senescence begins (Jones and Sullivan 1982). The diversity of crops and relatively small size of fields in the Southeast leads to colonization of patches within a farmscape. Our results confirm peak populations occurring sequentially in order of crop fruiting (Figs. 1 and 2). The predictable sequence of host usage in our study and others could allow for insecticide applications timed to target aggregations of stink bugs, possibly in the nondispersing nymph stage in soybean and cotton, resulting in lower costs of application. Stink bugs are not considered economic pests of wheat, but a reproductive peak can occur on wheat before moving to corn (Reay-Jones 2010). Insecticide treatments are sometimes warranted in corn adjacent to wheat (Reisig 2011). The predictable peak populations of stink bugs during squaring and the first WOB in cotton might permit more efficient usage of insecticides by timing an application to occur early in egg hatching or during the early instars, as suggested by Herbert and Toews (2012), preventing the peak populations of nymphs from developing. Including all species of stink bugs, reproductive stage soybean hosted the largest numbers of stink bugs, with cotton fields adjacent to soybean fields often hosting peak populations on the same day (Fig. 3). More research is needed on the dispersion of stink bugs within and among fields. At present, stink bug movements are inferred through repeated sampling over time and cannot be directly observed. Harmonic radar tracking, which uses radio signals to locate and follow small animals and insects, is being investigated as a means to further elucidate the ecology and dispersal of stink bugs in the farmscape (Pilkay et al. 2013a).

The lack of impact of distance from field edge on stink bug densities in our study likely results from the low densities of stink bugs. Despite this, higher densities in fields adjacent to full-season soybean or woods compared with any crop adjacent to corn or double-crop soybean fields were clear in Lee County, possibly due to woods providing stink bugs with nonagricultural hosts for overwintering. Full-season soybean had the maximum stink bug densities out of all sampled crops in our study.
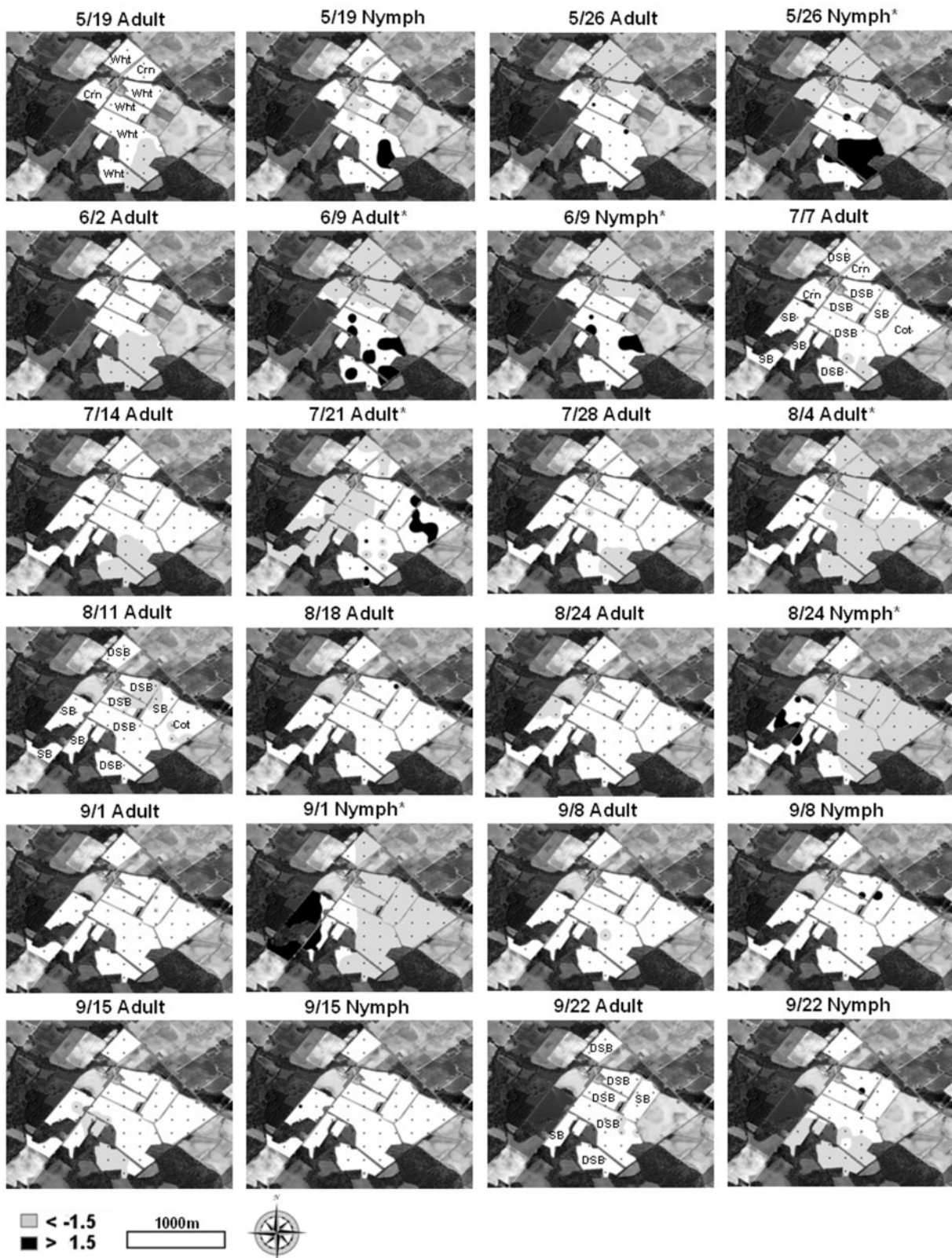
Fig. 3. Spatial interpolations of SADIE local aggregation indices for *E. servus* adults and nymphs in mixed crop farmscapes in Lee County, SC in 2009. Missing dates indicate insect counts were insufficient to generate local aggregation indices. Asterisks next to dates indicate significant ($P < 0.025$) aggregations. "Wht," "Crn," "Cot," "SB," and "DSB" indicate wheat, corn, cotton, soybean, and double-crop soybean, respectively. *Beta*-cyfluthrin was applied (0.017 kg [AI]/ha) to cotton on 15 July, to full-season soybean on 27 July, and to double-crop soybean on 24 August.

Table 5. Statistical comparisons of stink bug densities at different distances from field borders and adjacent crop combinations in Lee and Barnwell County, SC, and Tift County, GA

Location	Effect	E. servus						N. viridula					
		Adult			Nymph			Adult			Nymph		
		df	F	P	df	F	P	df	F	P	df	F	P
Lee	Crop/adjacent	8, 11.45	0.62	0.7495	8, 11.42	3.84	0.0198	8, 11.41	2.84	0.0538	8, 11.45	0.62	0.7495
	Distance	3, 5.10	0.14	0.9305	3, 5.28	0.2	0.8898	3, 4.52	1.10	0.4364	3, 5.10	0.14	0.9305
	Interaction	24, 155.70	2.14	0.0030	24, 161.90	0.82	0.7090	24, 115.90	1.69	0.0358	24, 155.70	2.14	0.0030
Barnwell	Crop/adjacent	10, 18.37	0.87	0.5719	10, 7.98	1.5	0.2895	10, 19.38	0.62	0.7767	10, 164.00	1.08	0.3809
	Distance	3, 123.00	0.15	0.9317	3, 3.54	0.11	0.9514	3, 123.00	0.48	0.6990	3, 164.00	1.24	0.2971
	Interaction	3, 123.00	0.45	0.9930	30, 67.40	0.71	0.8532	30, 123.00	0.70	0.8742	30, 164.00	1.08	0.3676
Tift	Crop/adjacent	11,1.56	0.17	0.9967	11, 17.33	0.11	0.9996	11, 16.41	0.58	0.8195	11, 12.82	0.75	0.6813
	Distance	2, 3.27	0.51	0.6410	2, 74.59	1.59	0.2102	2, 2.30	0.62	0.6098	2, 3.27	0.04	0.9589
	Interaction	22, 147.30	0.39	0.9939	22, 74. 59	0.69	0.8372	22, 64.30	1.14	0.3294	22, 106.00	0.44	0.9856

Location	Effect	C. hilaris						All species					
		Adult			Nymph			Adult			Nymph		
		df	F	P	df	F	P	df	F	P	df	F	P
Lee	Crop/adjacent	8, 11.54	2.24	0.1037	8, 11.27	9.78	0.0004	8, 13.14	4.29	0.0098	8, 11.43	7.88	0.0011
	Distance	3, 5.55	0.93	0.4865	3, 5.57	0.41	0.7508	3, 6.26	1.60	0.2811	3, 5.56	0.03	0.9937
	Interaction	24, 162.60	0.82	0.7124	24, 166.40	2.65	0.0002	24, 161.60	1.50	0.0733	24, 164.20	2.39	0.0007
Barnwell	Crop/adjacent	10, 41.00	15.56	<0.0001	10, 20.48	1.11	0.4004	10, 19.11	4.40	0.0027	10, 164.00	2.89	0.0024
	Distance	3, 123.00	0.32	0.8122	3, 153.10	0.56	0.6455	3, 123.00	0.21	0.8923	3, 164.00	1.18	0.3178
	Interaction	30, 123.00	0.91	0.6026	30, 153.10	0.54	0.9751	30, 123.00	0.51	0.9826	30, 164.00	1.11	0.3327
Tift	Crop/adjacent	11, 14.95	0.74	0.6919	11, 5.31	0.05	1.0000	11, 11.50	0.18	0.9956	11, 16.96	0.13	0.9994
	Distance	2, 7.70	1.24	0.3401	2, 1.00	0	1.0000	2, 3.94	0.75	0.5288	2, 54.50	1.30	0.2809
	Interaction	22, 178.10	1.43	0.1044	22, 1.00	0	1.0000	22, 150.20	0.54	0.9544	22, 54.50	0.50	0.9602

Barnwell County exhibited greater stink bug densities in cotton fields adjacent to soybean or peanut and soybean fields adjacent cotton or peanut fields compared with any other crop and adjacent combination. Our results support past studies in Georgia and South Carolina where stink bug densities were greater in cotton adjacent to peanut and soybean fields than in cotton adjacent to corn or other cotton fields (Toews and Shurley 2009, Reeves et al 2010). In Tift County, where fields were separated by grass borders that were regularly treated with insecticides and mowed, contrast statements found no difference in densities between fields adjacent to soybean and fields bordering other crops for any species (Table 5). The treatment of borders separating crops with insecticide undoubtedly influenced stink bug dispersion between fields in the farmscape. Potential strategies to minimize stink bug densities at cotton-soybean interfaces with grass borders may include reducing host suitability by mowing reproductive staged grass and applying insecticides between fields, provided that care is taken to use a product labeled for both adjacent crops and the interface area.

Among cultural practices used to manage stink bugs, early-maturing soybean cultivars have been used as a trap crop to attract large numbers of stink bugs of multiple species in Arkansas, which were then treated with insecticides (Smith et al. 2009). Although this offered a decrease in stink bug densities in the short term in the main soybean crop, densities rebounded to damaging levels later in the season. Stink bugs were believed to have not come from the trap crop but, instead, had originated from other soybean crops in the surrounding area (Smith et al. 2009). Another study found soybean trap cropping to be effective if insecticides were used, while the stink bugs were still immature (McPherson and Newsom 1984). If applications of insecticide were delayed, or if the stink bugs reached adulthood, the trap crop increased the populations of stink bugs in the surrounding areas. Combining trap crop practices with biological control of *N. viridula* has been attempted by growing sorghum along the interface of a corn-cotton farmscape, similar to the concept of a disruptive border. In cotton with adjoining sorghum trap crops, *N. viridula* densities never reached economic thresholds (Tillman 2006). When this system was used adjacent to a peanut-cotton farmscape, *N. viridula* dispersed to the sorghum. Parasitism by the adult parasitoid *Trichopoda pennipes* (F.)

(Diptera: Tachinidae) was higher in sorghum trap crop plots than surrounding cotton (Tillman 2006), underlining the potential of trap crops as a control method. Stink bug infestations that are a mix of *N. viridula, E. servus, and C. hilaris* would require multiple parasitoid species to reduce all species.

The application of integrated pest management relies on an understanding of pest ecology. This study confirms the patterns of spatial and temporal variation in seasonal dispersion and host usage by multiple pest species of stink bugs across multiple locations over time in the southeastern United States. In a farmscape with grass borders between crops, no crop and adjacent effects were found, despite the crops being within flying range. Prior studies have suggested altering crop planting dates to avoid damage from bivoltine species (Herbert and Toews 2012), though such strategies were noted to be ineffective against multivoltine species. The stink bug complex must be examined with the varying life cycles of multiple species in mind. Further investigations into increasing the influence of natural enemies must take our stink bug species complex into account, as not all native parasitoids in farmscapes target all species of stink bugs equally (Worthley 1924; Jones et al. 1996; Pilkay et al. 2013b, 2014). A focus on stink bug ecology could help to mitigate the impact of the stink bug complex in multiple crops in the southeastern United States.

Acknowledgments

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