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Spatial Distributions of Thrips (Thysanoptera: Thripidae) in Cotton

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Abstract

A 4-yr study was conducted to determine the degree of aggregation of thrips and injury in cotton, *Gossypium hirsutum* L., and their spatial association with a multispectral vegetation index (normalized difference vegetation index [NDVI]) and soil apparent electrical conductivity (EC_a). Using the Spatial Analysis by Distance IndicEs analyses (SADIE), adult thrips were significantly ($P < 0.05$) aggregated in 4 out of 24 analyses for adult thrips (17%), 4 out of 24 analyses for immature thrips (17%), and 2 out of 15 analyses for injury (13%). The SADIE association tool showed that NDVI values were associated with adult thrips in 2 out of 20 paired datasets (10%), with immature thrips in 3 out of 20 paired datasets (15%), and with thrips injury in 1 out of 14 paired datasets (7.1%). Soil EC_a values were generally more associated with thrips variables than NDVI, with shallow EC_a positively associated with adult thrips in 6 out of 21 paired datasets (28.6%), with immature thrips in 8 out of 21 paired datasets (40.0%), and with thrips injury in 8 out of 14 paired datasets (57.1%). The greater frequency of positive associations between thrips variables and soil EC_a suggests a greater potential for site-specific management, particularly in the Coastal Plain of the southeastern United States, where soil types are highly variable.

Key words: SADIE, spatial aggregation, spatial association, NDVI, soil apparent electrical conductivity

Thrips (Thysanoptera: Thripidae) are frequent pests of seedling cotton, *Gossypium hirsutum* L., in the United States, and can reduce lint yield up to 50% (Cook et al. 2011). Epidermal cells are damaged by feeding of adults and immatures, which leads to malformation and tearing of leaves. Insecticides are commonly used as prophylactic applications at planting as a seed treatment or in the seed furrow, as thrips cause predictable and consistent damage in the southeastern and mid-southern United States (Cook et al. 2011). The main pest species of cotton, tobacco thrips, *Frankliniella fusca* Hinds, has developed resistance across the mid-southern and southeastern United States to the neonicotinoid insecticides thiamethoxam and imidacloprid, which are widely used for control of thrips in cotton (Huseth et al. 2016). Mid- to late-season pests such as the tarnished plant bug, *Lygus lineolaris* (Palisot de Beauvois) (Luttrell 1994), can also be managed by neonicotinoid insecticides, which can further increase section pressure on thrips that can be present in cotton throughout the season (Reay-Jones et al. 2017). Because alternative control options are lacking, methods to reduce selection pressure from neonicotinoid insecticides are needed.

Thrips are currently managed by decisions applied to entire fields, yet insects generally have aggregated distributions (e.g., Taylor et al. 1978, Wilson and Room 1983), including thrips in cotton (Deligeorgidis et al. 2002, Parajulee et al. 2006). Previously known as precision integrated pest management (Fleischer et al. 1999), site-specific management of insects involves managing insect pests using localized pest densities rather than uniform management across a field using average densities (Park et al. 2007). The resulting reduction in insecticide usage can slow the development of resistance, in addition to preserving beneficial insects by maintaining unsprayed refuges in fields (Midgarden et al. 1997, Karimzadeh et al. 2010). The availability of geographic information system tools has facilitated the development of spatially variable methods of sampling of insects in cotton and the application of insecticides (McKinion et al. 2009, Deleon et al. 2017). However, such methods have not yet been developed for thrips.

While thrips in cotton are known to be aggregated based on mean-variance relationships (Deligeorgidis et al. 2002, Parajulee et al. 2006), knowledge is lacking on within-field distributions of thrips, related

crop injury, and their spatial association. However, the high cost of sampling required to generate such distribution maps of insect pests can be offset with savings in control costs (Krell et al. 2003, Merrill et al. 2014). In addition, remote sensing, which involves collecting information about a subject from a distance, can be used to further save sampling costs by predicting spatial variability, often using multispectral vegetation indices (Riley 1989, Hatfield and Pinter 1993). Maps of cotton field habitats can be generated using remote sensing, and pest densities can be estimated within each habitat with reduced numbers of samples (Willers et al. 2005). A study in North Carolina examined the aggregation of stink bugs, boll injury, and the normalized difference vegetation index (NDVI) in cotton, with inconsistent spatial associations between boll injury and NDVI (Reisig et al. 2015). Stink bugs and stink bug injury were shown to be aggregated in field trials in South Carolina, with a stronger association between NDVI and stink bug injury than with stink bug densities (Reay-Jones et al. 2016). This 4-yr study aimed to 1) determine the aggregation of thrips densities, thrips injury, and NDVI in cotton; 2) determine the spatial association among sampling dates to quantify the stability of the spatial distributions; and 3) determine the spatial association between thrips densities, thrips injury, NDVI, and soil apparent electrical conductivity (EC_a). The ultimate goal is to use remote sensing to predict the risk of injury from thrips in cotton.

Materials and Methods

Field Trials

Eight field trials were conducted from 2013 to 2016 at the Clemson University Pee Dee Research and Education Center (REC) in Florence, SC, and at the Clemson University Edisto REC in Blackville, SC. In Florence, the same 5.5-ha field was used in 2013, 2014, and 2016 (field A), and a 6.5-ha field was used in 2015 (field B). In Blackville, a 4.8-ha field was used in 2013 (C) and the same 8.7 ha field (D) was used in 2014, 2015, and 2016. Fields were planted in Florence on 22 May 2013, 20 May 2014, 20 May 2015, and 17 May 2016, and in Blackville on 11 May 2013, 23 May 2014, 1 June 2015, and 17 May 2016. Conventional tillage was used in Florence and strip-tillage was used in Blackville. Second generation *Bt* cotton cultivars (Bollgard II [Deltapine, Memphis, TN]) producing *Cry1Ac* and *Cry2Ab2* proteins were planted in Florence (DP 1212 B2RF) in and in Blackville (DP 1137 B2RF) in all years. No soil-incorporated insecticide was used at planting other than insecticidal seed treatments of thiamethoxam (0.375 mg A.I. per seed). Foliar insecticides were not applied. Prior to planting in fields A and C in 2013 and field D in 2014, a Veris 3100 meter (Veris Technologies, Salina, KS) was used to measure apparent soil EC_a in the top 30 (shallow) and 90 (deep) cm of the soil profile. Soil EC_a was, therefore, measured once in 7 of the 8 field-year combinations. A one-time measurement of EC_a is common in agronomy studies (e.g., Kitchen et al. 2003), as it has been shown to be stable over time (Sudduth et al. 2005). Soil EC_a measurements from the tractor-mounted sensors were averaged within a 2.5-m radius circle of each sampling flag (see below) using ArcMap (ESRI 2014).

Sampling

A sampling grid used in each field consisted of one sampling location (marked with a 1.8-m fiber glass flag) for every 0.12 ha beginning at the field periphery, with each flag separated by 40 m. Fields were spatially mapped with ArcMap 10.4.1 (ESRI 2014), and then overlaid with a grid of sampling points starting from the field edge. The GPS coordinates of all sampling points were recorded using a Trimble GeoXM (Trimble, Sunnyvale, CA). Thrips were sampled once a week for up to five weeks after planting by submerging 5 (in Florence) or 10 (in Blackville) randomly selected seedling plants within 5 m of each flag in 0.95-liter jars half filled with 50% isopropyl alcohol to dislodge thrips before enumeration of adult and immature thrips under a microscope. While thrips were not identified to species, tobacco thrips, *Frankliniella fusca* (Hinds), is the dominant species found on cotton seedlings in the southeastern United States, comprising up to 93 and 94% of thrips in a trial in Blackville, SC, during 2009 (Reed et al. 2010) and in a series of trials in the region during 2016 (Wang et al. 2018). A recent study across five southeastern states showed that *F. fusca* represented 86.7% of all thrips on seedling cotton, including samples collected in the same fields used in this study (Reay-Jones et al. 2017). The effects of thrips injury to seedling cotton plants was visually rated once per week for up to five weeks after planting on a 0–5 scale, where '0' described no damage and '5' described severe damage/dead plants (Kerns et al. 2019).

Crop reflectance was measured using NDVI (Rouse et al. 1973) at each flag with either tractor-mounted (Florence in 2014; Crop Circle, Holland Scientific, Lincoln, NE) or handheld (all other fields and years; GreenSeeker, NTech Industries, Ukiah, CA) sensors. Tractor-mounted measurements were made at a height of ~1 m above the tallest plants with GPS coordinates over two rows immediately adjacent to sampling flags, with an average measurement recorded by the sensor every 2 s; prior to analysis, an average NDVI value was determined for each sampling flag and sampling date by averaging NDVI values across the two rows over a 5-m section centered on the sampling flag using ArcMap (ESRI 2014). Handheld sensors measured NDVI on ~6 m of one row centered at each flag (recording 30–50 individual measurements), at a height of ~1 m above the tallest plants; an average NDVI value across the 6-m section of row was used for analysis. This commonly used remote sensing index, with values ranging from –1 to +1, uses normalized red (R) and near-infrared (NIR) spectral bands: NDVI = (NIR – R)/(NIR + R). NDVI was measured on three dates in Florence in 2013 (from 10 June to 24 June), one date in Blackville in 2013 (30 July), four dates in Florence in 2014 (5–23 June), three dates in Blackville in 2014 (6–20 June), one date in Florence in 2015 (18 June), three dates in Blackville in 2015 (11–25 June), two dates in Florence in 2016 (9 and 21 June), and four dates in Blackville in 2016 (1–24 June). Fifteen of the 21 NDVI measurements reported in this study were also reported in Reay-Jones et al. (2016); a study that examined spatial aggregation of stink bugs and boll injury and the association with 48 NDVI measurements; the majority of which were made later in the season than those reported here.

Data Analysis

Spatial Analysis by Distance IndicEs (SADIE Version 1.22, Perry et al. 1999) analyses were used for thrips counts, injury, NDVI, biomass, and soil EC_a. Thrips densities and injury ratings were summed across the 5 (in Florence) or 10 (in Blackville) plants per flag prior to analysis. In order to transform data to counts suitable for SADIE analysis, NDVI and soil EC_a values were then expressed as the integer of 100 and 10 times the average at each flag, respectively.

Grid sampling locations expressed as absolute positions were used with the SADIE red-blue methodology. This method determines the minimum distance D required to attain regularity, which is the distance moved by counts in the observed sample to reach the most uniform distribution possible. A clustering index was given to every location, with either a positive cluster index ($\bar{v}_i$) for counts above the

average of each field-date combination or a negative gap index ($\bar{v}_j$) for counts below the average. A random spatial pattern has indices $\bar{v}_i = -\bar{v}_j = 1$. Non-randomness is quantified by comparing observed patterns with rearrangements in which the sample counts are randomly redistributed across the sampling locations. The overall index of dispersion (I_a) specifies either an aggregated (>1), random (=1), or uniform pattern (<1). The null hypothesis of spatial randomness is rejected when $P < 0.025$ (aggregation) or $P > 0.975$ (uniformity). Each test consisted of a total of ~6,000 randomizations.

The SADIE association tool (Perry and Dixon 2002) was used to assess spatial associations between thrips densities, injury, NDVI, biomass, and soil EC_a. Associations between NDVI and thrips or thrips injury were generally determined for datasets resulting from samples taken on the same date. Exceptions included NDVI in Blackville in 2013 and Florence in 2015, where the only measurements of NDVI were taken on 31 July and 17 June, respectively; these two NDVI datasets were used with the spatial association tool for all sampling dates with thrips densities and injury for the given year and location. An overall index of association (X) was determined between each of the paired datasets, with a positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.975$). The average X is computed from the local spatial associations (X_k) at each sampling location k. A positive association at the local scale between two variables specifies the presence of either a patch or a gap for both variables; a negative association specifies the presence of a patch for one variable and gap for the other variable at the same location. Using the inverse distance weighted spatial method (ArcMap 10.4.1, ESRI 2014), interpolation maps of local aggregation indices were created. Instead of using geostatistical methods such as semiovariograms and kriging, SADIE was selected to describe and illustrate local variability of spatial distribution and association among datasets sharing the same locations (Perry et al. 2002).

Results

Across the 4 yr of study, a total of 3,202 adults thrips (mean of 5.52 ± 0.38 [SEM] per 10 plants) and 4,491 immature thrips (7.74 ± 0.57) were sampled in Blackville; a total of 2,730 adults thrips (mean of 3.73 ± 0.24 [SEM] per 5 plants) and 9,611 immature thrips (13.13 ± 0.77) were sampled in Florence. Thrips injury averaged a rating of 1.68 ± 0.05 in Blackville and 1.84 ± 0.03 in Florence. Densities of thrips and injury fluctuated between sampling dates and fields (Fig. 1). The lowest average injury rating (1.4) occurred in Blackville in 2016, when immature thrips were also the lowest across all locations and years (6.4 per 10 plants). The greatest average injury (3.0) occurred in Florence in 2015, when immature thrips were also the greatest across all locations and years (24.5 per 5 plants).

According to SADIE aggregation indices (Table 1), adult thrips were significantly ($P < 0.05$) aggregated in four out of 24 analyses for both adult and immature thrips (17%), and two out of 15 analyses for injury (13%). Datasets in Florence were generally more aggregated than in Blackville, with three of four aggregated datasets for adult thrips, two of the four aggregated datasets for immature thrips, and both aggregated datasets for injury. Measurements of NDVI on seedling cotton were significantly ($P < 0.05$) aggregated in six out of 21 analyses (29%) (Table 2). Four of the six datasets with significant aggregations occurred in Florence. Soil EC_a was aggregated in field A in Florence in 2013 (shallow [range of 0.25–6.28 mS/m]: $I_a = 2.376$, $P = 0.0002$; deep [range of 0.2–8.4 mS/m]: $I_a = 2.996$, $P = 0.0002$) and in field C in Blackville in 2013 (shallow [range of 2.1–19.6 mS/m]: $I_a = 2.152$, $P = 0.002$; deep [range of 1.8–14.8]:

$I_a = 3.139$, $P = 0.0002$). In field D in Blackville in 2014, soil EC_a was not aggregated in the shallow sample (range of 0.7–6.9 mS/m: $I_a = 1.385$, $P = 0.0535$) and in the deeper sample (range of 0.6–10.6: $I_a = 1.472$, $P = 0.0293$).

SADIE association indices between adult thrips and NDVI, generally measured on the same sampling date, were significant in two out of 20 paired datasets (10%; Table 3). Associations between NDVI and immature thrips were significantly positive in three out of 20 paired datasets (15%) and significantly negative in one out of 20 paired datasets (5%). Thrips injury was positively associated with NDVI in 1 out of 14 paired datasets (7.1%) in Florence in 2013. Soil EC_a values were generally more associated with thrips variables than NDVI (Table 4). Shallow EC_a was positively associated with adults in 6 out of 21 paired datasets (28.6%), with immature thrips in 8 out of 21 paired datasets for (40.0%), and with injury in 8 out of 14 paired datasets (57.1%). Deep EC_a was positively associated with adult thrips in 5 out of 21 paired datasets (23.8%), with immature thrips in 8 out of 21 paired datasets (38.1%), and with thrips injury in 6 out of 14 paired datasets (42.9%). NDVI measurements were positively associated with shallow EC_a in 10 out of 20 paired datasets (50.0%) (Table 2). Deep EC_a was positively associated with NDVI in 9 out 20 paired datasets (45.0%) and negatively associated in 1 out of 20 paired datasets (5.0%).

Spatial stability in time as quantified by SADIE association indices between datasets collected in a given field at different sampling dates showed that adult datasets were positively associated in 3 out of 27 paired datasets and negatively associated in 1 paired dataset (3.7%). Immature datasets were positively associated in 7 out of 27 paired datasets (25.9%) and negatively associated in 1 paired dataset (3.7%). Injury datasets were positively associated in four out of 18 paired datasets (22.2%) and negatively associated in 2 paired datasets (11.1%).

Spatial association among thrips datasets showed that adults thrips were positively associated with immature thrips in 12 out of 24 paired datasets (50.0%) and negatively associated in one out of 24 (4.2%) paired datasets (Table 5). Adult thrips were positively associated with thrips injury in 7 out of 14 paired data sets (50.0%) and negatively associated in 1 out of 14 (7.1%) paired datasets. Immature thrips were positively associated with thrips injury in 7 out of 14 paired data sets (50.0%).

Selected interpolation maps are shown with clusters and gaps for thrips variables in fields in Florence and in Blackville in 2013–2014 (Fig. 2) and in 2015–2016 (Fig. 3). In Florence, where cotton was planted in the same field in 2013, 2014, and 2016, clusters of elevated levels of adult thrips, immature thrips, and injury were present in the north eastern side of the field (Fig. 2F, I, and J). Positive associations were apparent between adult and immature thrips on 16 June 2014 in Florence (Fig. 2I and J) and in Blackville on 6 June 2014 (Fig. 2L and M). Soil EC_a and NDVI on 17 July 2013 in Florence showed similar areas with clusters and gaps (Fig. 4A and D). Immature thrips were positively associated with EC_a shallow on 10 June (Fig. 4H), and NDVI and immature thrips were also positively associated on 23 June in 2013 (Fig. 4I).

Discussion

Thrips were positively associated with NDVI on only two occasions for adults, three for immatures, and one for injury. Temporal variations in NDVI in cotton are closely related to leaf area index (Li et al. 2001), and thrips injury can lead to reductions in leaf area measured with a leaf area meter (Sadras and Wilson 1998).
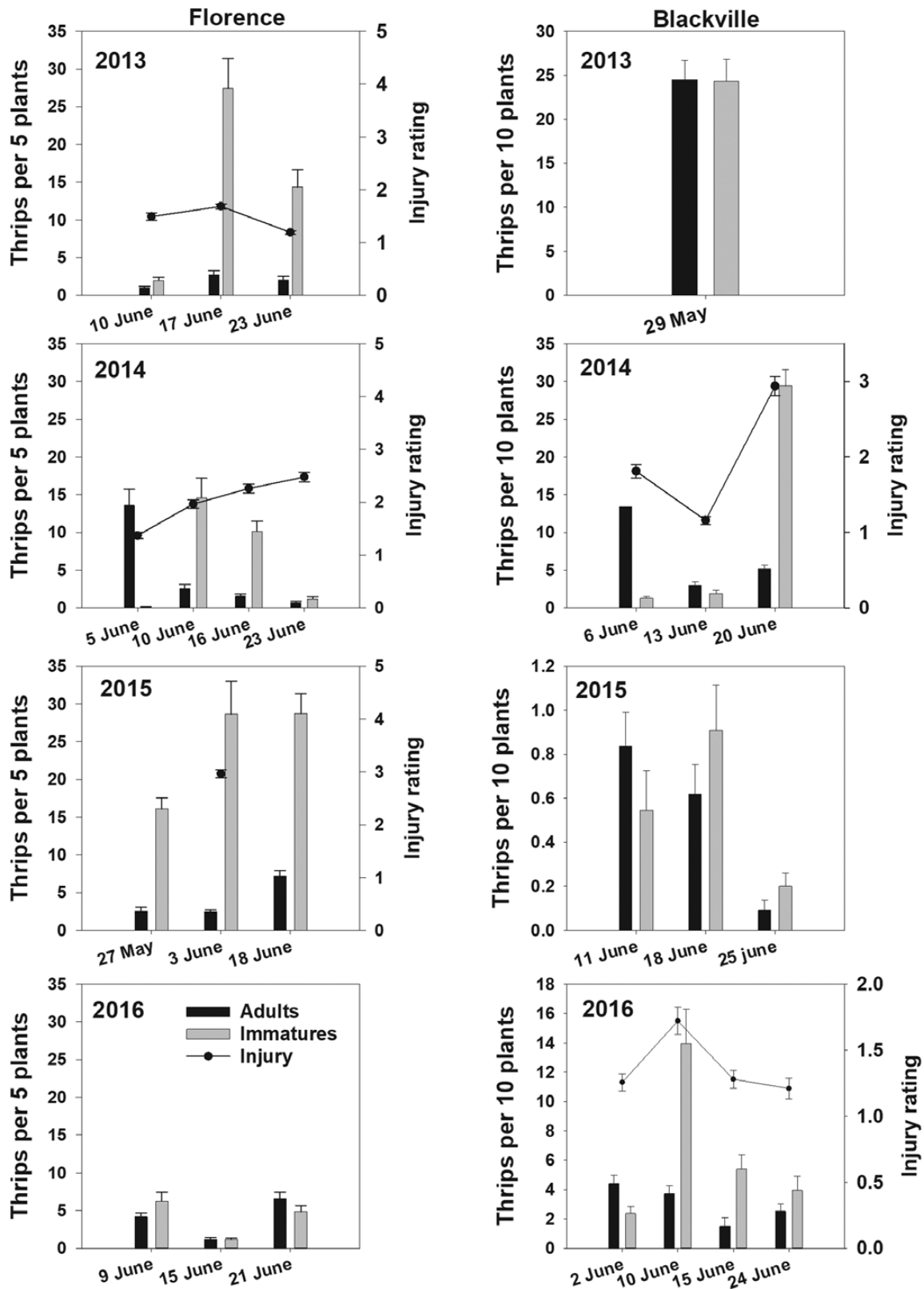
Fig. 1. Densities of thrips and injury (±SEM) in cotton trials in Florence and Blackville, South Carolina (2013–2016).

However, a study showed that detection of seedling cotton up to 15 d after emergence using NDVI is challenging because the high variability in spectral characteristics of the bare soil surrounding the small plants can hinder the use of spectral data (Wanjura

et al. 2003). Measurements of NDVI may therefore not sufficiently correlate with seedling cotton growth or a reduction in seedling growth caused by thrips injury, which may explain the limited number of significant SADIE association indices among

Table 1. Characterization of spatial distributions of thrips and thrips injury with SADIE index of dispersion (*Ia*) in cotton fields in Florence and Blackville, SC, 2013–2016.

Year	Location	Date	Adults	Immatures	Injury
2013	Florence	10 June	1.019	0.988	1.387
		17 June	0.801	1.128	1.409
		23 June	1.325	0.5834	0.897
	Blackville	29 May	1.652	0.890	–
2014	Florence	5 June	1.639*	1.017	1.782**
		10 June	1.199	0.813	0.940
		16 June	1.706*	2.237**	1.355
		23 June	0.834	0.827	1.991**
	Blackville	6 June	1.327	1.770**	1.338
		13 June	1.887**	1.616*	1.446
		20 June	0.847	1.344	1.457
2015	Florence	27 May	1.668**	2.192***	–
		3 June	1.217	1.234	–
		10 June	–	–	0.995
		18 June	0.999	1.270	–
	Blackville	11 June	0.949	0.206	–
		18 June	1.450	0.929	–
		25 June	1.304	0.969	–
2016	Florence	9 June	1.384	1.287	–
		15 June	0.949	0.862	–
		21 June	0.853	1.048	–
	Blackville	2 June	0.925	0.999	0.788
		10 June	0.988	1.174	1.293
		15 June	1.008	1.195	1.186
		24 June	1.113	0.925	0.861

Overall index of dispersion indicates aggregated pattern for I_a > 1: ***P < 0.001; **P < 0.01; *P < 0.025.

Table 2. Characterization of spatial distribution of NDVI in cotton fields in South Carolina with the SADIE index of dispersion (*Ia*), and indices of spatial association (X) between NDVI and soil EC_a using the SADIE spatial association tool

Year	Location	Date	I_a	X	
				Shallow	Deep
2013	Florence	10 June[a]	1.139	0.161	−0.093
		17 June[a]	1.369	0.606***	0.321*
		23 June[a]	1.262	0.297*	−0.043
	Blackville	31 July[a]	1.005	−0.335	−0.325
2014	Florence	5 June[a]	3.310***	0.581***	0.711***
		12 June[a]	3.054***	0.515***	0.711***
		19 June[a]	1.673*	0.291	0.382**
		26 June[a]	1.160	−0.025	−0.140
	Blackville	6 June[a]	1.259	−0.039	−0.054
		13 June[a]	1.374	0.239	0.340**
		20 June[a]	0.966	0.135	0.150
2015	Florence	18 June[a]	1.424	–	–
	Blackville	11 June[a]	1.527*	0.496**	0.589***
		18 June[a]	1.534*	0.281	0.416**
		25 June[a]	0.946	0.367*	0.281
2016	Florence	9 June	2.321***	0.715***	0.652***
		21 June	0.969	0.659***	0.385**
	Blackville	1 June	0.788	0.322	−0.128
		8 June	1.008	0.436*	0.161
		16 June	1.091	0.479**	0.216
		24 June	0.946	−0.220	−0.981*

[a]Indicates NDVI data and SADIE aggregation indices previously published in Reay-Jones et al. (2016).

Overall index of dispersion indicates aggregated pattern for I_a > 1: ***P < 0.001; **P < 0.01; *P < 0.025.

Overall index of association between each of the paired data sets, with a positive association for X > 0 (P < 0.025) and a negative association for X < 0 (P > 0.975). ***P < 0.001; **P < 0.01; *P < 0.025.

Table 3. Indices of spatial association (X) from SADIE analyses between NDVI and adult thrips, immature thrips and injury datasets in cotton in South Carolina, 2013–2016

Year	Location	Date (NDVI)	Date (Thrips)	Association index		
				Adult thrips	Immature thrips	Injury
2013	Florence	10 June	10 June	−0.009	0.028	0.040
		17 June	17 June	0.005	0.176	0.410**
		23 June	23 June	0.120	0.566***	0.098
2014	Florence	5 June	5 June	0.034	0.274*	−0.230
		12 June	10 June	−0.172	−0.049	0.212
		19 June	16 June	0.250	0.106	0.045
		26 June	23 June	−0.202	0.258	0.074
	Blackville	6 June	6 June	−0.091	−0.240	−0.259
		13 June	13 June	−0.149	0.170	0.152
		20 June	20 June	−0.105	−0.050	−0.132
2015	Florence	18 June	18 June	−0.126	0.028	–
	Blackville	11 June	11 June	−0.147	−0.182	–
		18 June	18 June	−0.085	0.227	–
		25 June	25 June	0.115	0.020	–
2016	Florence	9 June	9 June	0.256	0.159	–
		21 June	21 June	0.139	0.541***	–
	Blackville	1 June	2 June	0.369*	−0.109	0.202
		8 June	10 June	0.377*	0.166	0.357
		16 June	15 June	0.158	−0.053	0.032
		24 June	24 June	−0.101	−0.298*	−0.158

Overall index of association between each of the paired data sets, with a positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.975$). ***$P < 0.001$; **$P < 0.01$; *$P < 0.025$.

Table 4. Indices of spatial association (X) from SADIE analyses between soil EC_a and adult thrips, immature thrips and injury datasets in cotton in South Carolina, 2013–2016.

Year	Location	Date	Association index with shallow EC_a			Association index with deep EC_a		
			Adult thrips	Immature thrips	Injury	Adult thrips	Immature thrips	Injury
2013	Florence	10 June	0.210	0.375**	0.375**	0.081	0.352*	0.348**
		17 June	−0.060	0.038	0.397**	−0.036	−0.186	0.384**
		23 June	−0.027	0.430**	−0.115	−0.124	0.262	0.860
	Blackville	29 May	0.456**	0.328*	–	0.358*	0.108	–
2014	Florence	5 June	0.130	0.238	−0.335*	0.006	0.345*	−0.251
		10 June	−0.199	0.135	0.308*	−0.181	0.115	0.177
		16 June	0.189	0.432**	0.598***	0.311*	0.524***	0.302*
		23 June	0.403**	0.363*	0.444**	0.324*	0.401**	0.227
	Blackville	6 June	0.344**	0.008	0.309	0.598***	0.459***	0.451***
		13 June	−0.115	0.087	0.015	0.143	0.036	0.234
		20 June	0.024	0.215	0.186	0.046	0.464**	0.358**
2015	Florence	18 June	–	–	–	–	–	–
	Blackville	11 June	0.338	0.075	–	0.256	−0.017	–
		18 June	0.385*	0.288	–	0.434**	0.278	–
		25 June	0.164	−0.237	–	0.267	−0.266	–
2016	Florence	9 June	0.136	0.171	–	0.030	0.027	–
		15 June	−0.006	0.410**	–	−0.192	0.225	–
		21 June	0.109	0.350**	–	0.041	0.143	–
	Blackville	2 June	0.395**	0.271	0.315*	0.242	0.155	0.294
		10 June	0.340	0.252	0.214	0.003	0.404**	0.276
		15 June	0.270	0.181	0.114	0.117	0.068	0.115
		24 June	0.548**	0.470**	0.538**	0.313	0.494**	0.377*

Overall index of association between each of the paired data sets, with a positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.975$). ***$P < 0.001$; **$P < 0.01$; *$P < 0.025$.

thrips variables with NDVI in our study. Previous work in cotton showed a closer spatial association between stink bugs, stink bug boll injury, and NDVI (Reay-Jones et al. 2016), possibly due to the greater variability in NDVI measured later in the season during the weeks of bloom when the canopy was closed and stink bugs were sampled.

Table 5. Indices of spatial association (X) from SADIE analyses between adult thrips, immature thrips and injury datasets in cotton in South Carolina, 2013–2016.

Year	Location	Date	Association index		
			Adult-immature	Adult-injury	Immature-injury
2013	Florence	10 June	0.006	−0.043	0.051
		17 June	0.542***	0.154	0.027
		23 June	0.154	0.157	0.007
	Blackville	29 May	0.506***	–	–
2014	Florence	5 June	−0.417**	−0.495**	0.240
		10 June	0.098	0.029	−0.150
		16 June	0.523***	−0.071	0.123
		23 June	0.585***	0.347*	0.300
	Blackville	6 June	0.541***	0.647***	0.409**
		13 June	0.551***	0.568***	0.721***
		20 June	0.301**	0.394**	0.809***
2015	Florence	27 May	−0.036	–	–
		3 June	0.390**	–	–
		18 June	0.171	–	–
	Blackville	11 June	0.337*	–	–
		18 June	0.068	–	–
		25 June	0.088	–	–
2016	Florence	9 June	0.347*	–	–
		15 June	0.247	–	–
		21 June	0.362*	–	–
	Blackville	2 June	0.060	0.707***	0.324*
		10 June	−0.053	0.292	0.721***
		15 June	0.305	0.517**	0.721***
		24 June	0.452**	0.604***	0.540***

Overall index of association between each of the paired data sets, with a positive association for $X > 0$ ($P < 0.025$) and a negative association for $X < 0$ ($P > 0.975$). ***$P < 0.001$; **$P < 0.01$; *$P < 0.025$.

Positive spatial associations with thrips were, however, more frequent with soil EC_a, which in nonsaline soils correlates with soil properties including soil texture, soil moisture, and soil pore size (Sudduth et al. 2005). Soil EC_a is often positively correlated with clay content (Corwin et al. 2003) and soil brightness (Guo et al. 2012). In our study, cotton plants in darker soils with higher clay content often had greater densities of thrips than plants in lighter soils with higher sand content. Cotton in soils with high sand content can be more prone to water stress (DeTar 2008), which can lead to reduced plant heights (Ball et al. 1994). Increased numbers of thrips on larger plants may be caused by 1) increased production of volatiles on larger plants leading to higher densities of adults (Beyaert and Hilker 2014) and 2) females laying more eggs on larger plants that have more sites for oviposition (Courtney 1982), leading to increased numbers of immature thrips. In addition to variability in plant size being a potential driver of variability in thrips densities, visual cues and/or behavioral response to UV light can also interfere with host plant selection by thrips (Costa et al. 2002). The color of sticky traps is also known to strongly impact the number of thrips caught (Teulon et al. 1999). To our knowledge, no study has investigated the impact of soil color or soil texture on thrips infestation of field crops. However, because visual cues can play a major role in host selection, the color of the soil and the contrast of the soil relative to cotton seedlings may impact thrips densities. Our study suggests that monitoring and management efforts may need to focus more in areas of the field with higher clay content.

SADIE was used in this study for the analysis of counts of thrips and several variables expressed as integers (thrips injury soil EC_a and NDVI). Even though SADIE was originally presented for analysis of insect and plant data expressed as counts (Perry 1995, Perry et al. 1999), SADIE can also be used for binary and continuous data that have been converted to integer format (Perry et al. 1999). As examples of this approach, SADIE has been used to quantify spatial patterns of environmental and plant variables including surface soil properties (biological crusts, physical crusts, mosses, rock fragments, earthworm casts, fine root accumulation, and below-ground stones [Maestre and Cortina 2002]), soil carbon and nitrogen content (Blackshaw et al. 2007), temperature (Cocu et al. 2005), cotton boll injury from stink bug feeding (Reay-Jones et al. 2010b, 2016; Reisig et al. 2015), and NDVI in cotton (Reisig et al. 2015, Reay-Jones et al. 2016). SADIE has also been used previously to spatially associate soil EC_a with emergence of predatory beetles in wheat and barley fields (Holland et al. 2007). However, NDVI and soil EC_a have not been used to explain spatial variability in thrips and thrips injury in cotton.

In our study, SADIE aggregation indices indicated that adult (17%) and immature thrips (17%) were slightly more aggregated than thrips injury (13%). While the majority of arthropods are spatially aggregated (Taylor et al. 1978, Wilson and Room 1983), the extent of spatial aggregation can vary substantially between species and often between life stages. For example, stink bugs in cotton were less frequently aggregated for nymphs (4%) than for adults (17%) (Reay-Jones et al. 2016). Adult and immature *Thrips palmi* Karny were both similarly aggregated in potato, *Solanum tuberosum* L., based on Taylor's power law (Cho et al. 2000). Another study in mango (*Mangifera indica* L.) orchards showed that immature thrips (*Thrips hawaiiensis* [Morgan], *Scirtothrips dorsalis* [Hood], *Franklieniella schultzei* [Trybom], and *Meglurothrips usitatus* [Bagnall]) were more aggregated than adult thrips (Aliakbarpour and Salmah 2011). The main pest species of seedling cotton, *F. fusca*,
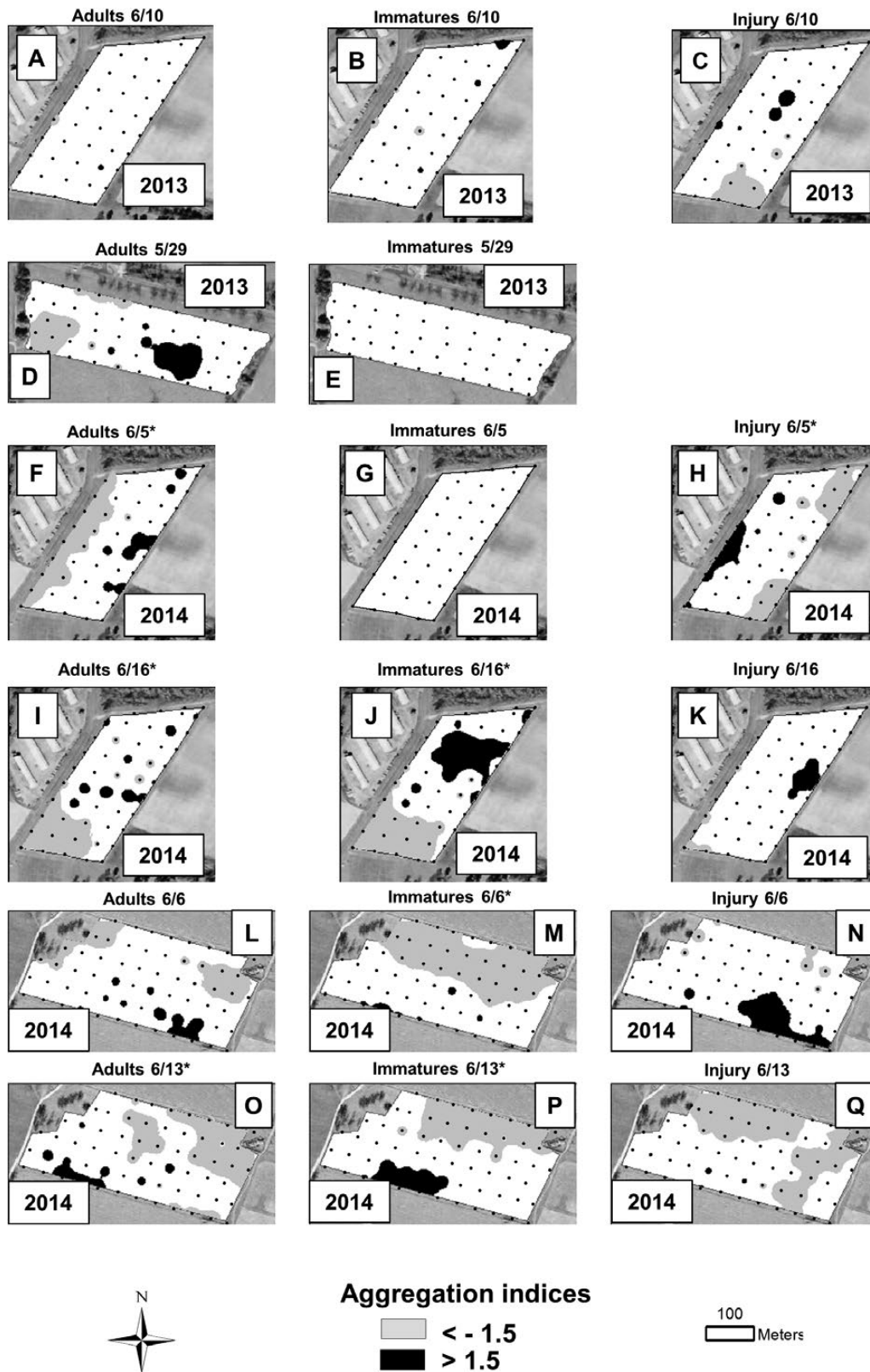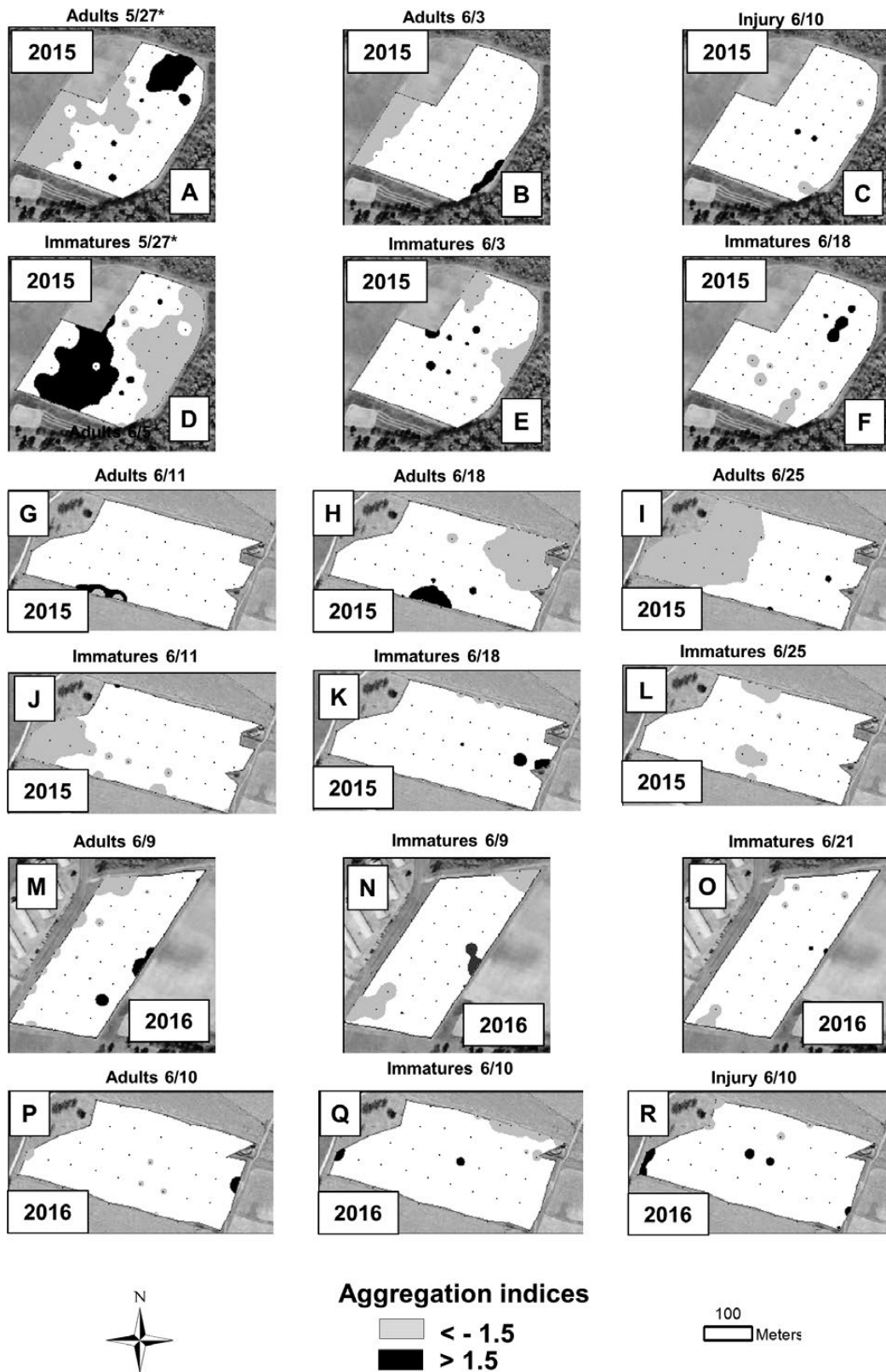
Fig. 2. Spatial interpolation of SADIE local aggregation indices for adult thrips, immature thrips, and thrips injury in datasets in Florence and Blackville, South Carolina (2013–2014). Asterisks indicate significant ($P < 0.025$) aggregations. Clusters are indicated by excluding aggregation indices between −1.5 and 1.5, with patches indicated in black ($\bar{v}_i > 1.5$) and gaps indicated in gray ($\bar{v}_j < -1.5$).
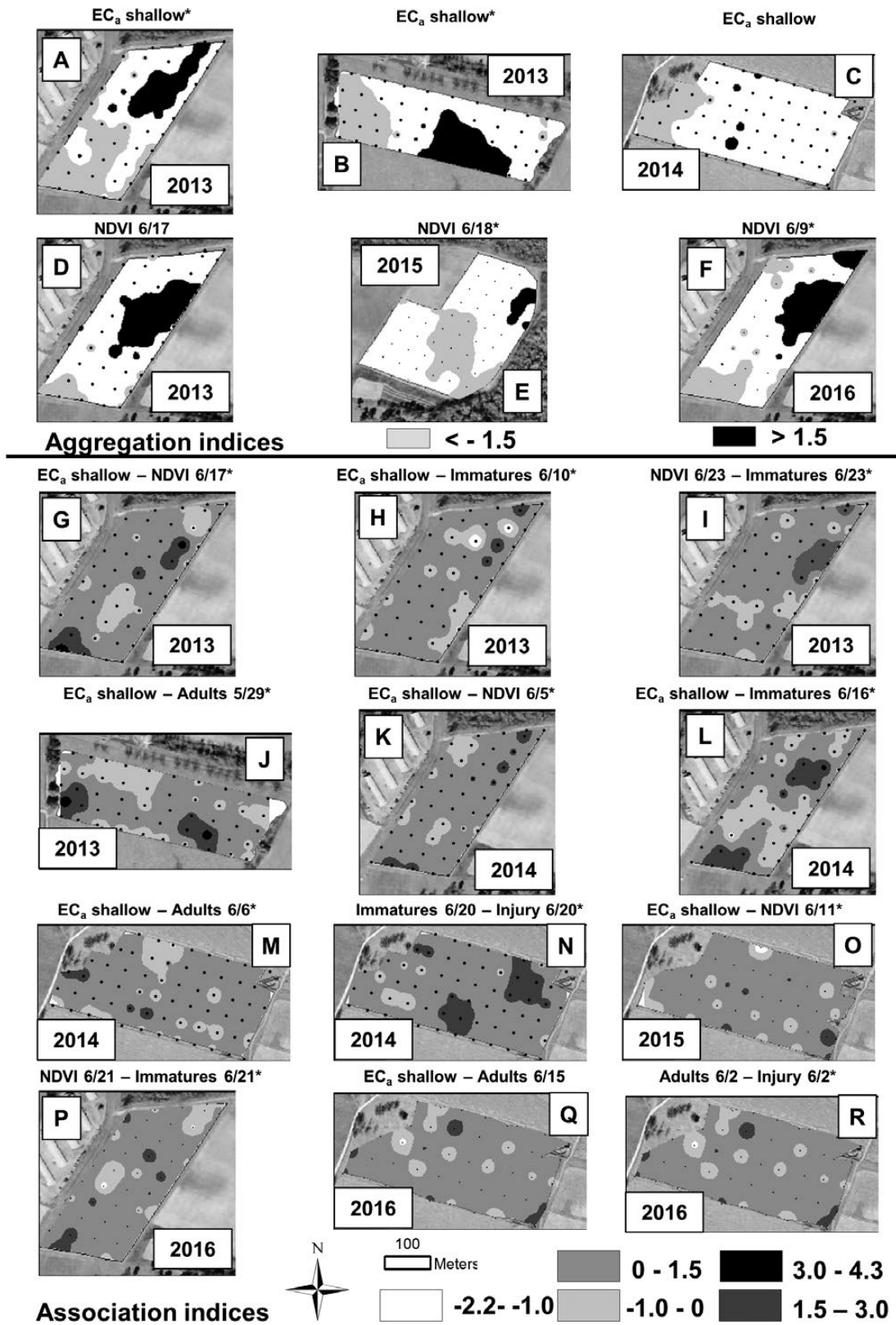
Fig. 3. Spatial interpolation of SADIE local aggregation indices for adult thrips, immature thrips, and thrips injury in datasets in Florence and Blackville, South Carolina (2015–2016). Asterisks indicate significant ($P < 0.025$) aggregations. Clusters are indicated by excluding aggregation indices between −1.5 and 1.5, with patches indicated in black ($\bar{v}_i > 1.5$) and gaps indicated in gray ($\bar{v}_j < -1.5$).

Fig. 4. Spatial interpolation of SADIE local aggregation indices (A–F) for soil EC_a and NDVI in datasets in Florence and Blackville, South Carolina (2013–2016). Clusters are indicated by excluding aggregation indices between –1.5 and 1.5, with patches indicated in black ($\bar{v}_i > 1.5$) and gaps indicated in gray ($\bar{v}_j < -1.5$). Indices of spatial association (X) from SADIE analyses (G–R) among soil EC_a, NDVI, adult thrips, immature thrips, and thrips injury in datasets in cotton in South Carolina. Asterisks indicate significant aggregations or associations ($P < 0.025$).

has been shown to lay 15–33 eggs per cotyledon leaf at the second to fourth true leaf growth stage (D' Ambrosio et al. 2019). Because of the limited mobility of immature thrips and the numbers of eggs laid per plant, we were surprised to not see greater aggregation with immature thrips. While other studies have shown that thrips can be aggregated in cotton based on mean-variance relationships (Deligeorgidis et al. 2002, Parajulee et al. 2006), we are not aware of any study in cotton comparing spatial distributions between adult and immature thrips.

Spatial distributions of immature thrips (25.9% positive associations among paired SADIE datasets) and thrips injury (22.2%) were more stable than for adults thrips (0%). Locations of patches and gaps within fields of adult thrips, therefore, varied more frequently from week to week than for immature thrips and thrips injury. Another study in cotton on stink bugs showed positive associations among sampling dates ranging from 12.5 to 25%, depending on species, compared with 37% for stink bug injury (Reay-Jones et al. 2016). Spatial stability of injury distributions for both thrips and stink bugs was therefore sometimes greater in cotton compared with the stability of distributions of thrips and stink bugs. Highly mobile insects such as stink bugs and thrips can be difficult to sample with sweep nets and whole-plant sampling, respectively. For stink bugs in cotton, the semipermanent presence of boll injury relative to the temporal presence of stink bugs on a plant, combined with the partial portion of a cotton plant being sampled with a sweep net, underlines the added value of using injury for making management decisions (Reay-Jones et al. 2010a). For thrips, recommended thresholds for applying insecticides in each state in the southeastern and mid-southern United States include the use of plant injury, with more variability among states in the use of actual thrips counts in addition to plant injury (Cook et al. 2011).

For a number of years, cotton growers used aldicarb at-planting to manage both thrips and nematodes; however, the availability of aldicarb has been limited in recent years in the southeastern United States (Marshall et al. 2016). With widespread resistance to neonicotinoid insecticides (Huseth et al. 2016), supplemental foliar applications of insecticide such as acephate can be needed up to the fourth true leaf stage (Cook et al. 2011). As a promising new control tactic, a transgenic cotton trait expressing Cry51Aa2.834_16 reduced thrips damage (Graham and Stewart 2018); however, this trait is not yet commercialized, and large-scale field studies have yet to be published. The current practice of an application of a broad-spectrum insecticide such as acephate would benefit from a site-specific approach; our study is the first effort into establishing spatial associations between thrips, injury, and soil/plant measurements that could potentially be used to target applications of insecticides to portions of cotton fields at higher risks of yield loss.

This study showed significant variability in thrips densities, thrips injury, and NDVI within cotton fields. The degree of aggregation varied among thrips variables, with more datasets showing a significant aggregation for adults and immature thrips (17%) than for thrips injury (13%). Distributions that were significantly aggregated indicated that thrips were more abundant in some parts of fields, which were, therefore, at a greater risk of thrips injury (clusters); conversely, other parts of the same fields had lower densities of thrips (gaps), which were, therefore, less likely to suffer from thrips injury. The majority of datasets were characterized by random distributions, suggesting that control tactics applied to entire fields may often be more suitable than site-specific management tactics. Because NDVI was rarely associated with adult and immature thrips, and thrips injury, it may not be suitable as a remote sensing tool for sampling and site-specific management of thrips in cotton. The greater frequency of positive associations between thrips variables and soil

EC_a (e.g., 57% for thrips injury and shallow soil EC_a) suggests a greater potential for site-specific management using soil characteristics, particularly as soils are highly variable in the southeastern coastal plains in the United States (Duffera et al. 2007). Because cotton yield and quality are highly sensitive to variability in soil properties (Johnson et al. 2002), future studies should further characterize the spatial associations between cotton yield and quality, thrips injury, and soil quality. Developing our understanding of the interactions between the environment and the dynamics of insect pests in crop systems is needed to optimize management practices with reduced use of insecticides. The value of remote sensing for insect management in cotton needs further study, with an aim to develop tools such as risk assessment maps that will help growers to reduce insecticide inputs.

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