The *Journal of Cotton Science* 3:160-170 (1999)
http://journal.cotton.org, © The Cotton Foundation 1999

ARTHROPOD MANAGEMENT

Remote Sensing, Line-intercept Sampling for Tarnished Plant Bugs (Heteroptera: Miridae) in Mid-south Cotton

Jeffrey L. Willers*, Michael R. Seal, and Randall G. Luttrell

INTERPRETIVE SUMMARY

Sampling for tarnished plant bug (*Lygus lineolaris*) at low population levels is important for developing better management tactics against this major cotton pest. The results of this study demonstrate a sampling technique that is efficient and easy to use and measures low population levels of plant bug nymphs and teneral adults. The method is based on the use of the drop cloth, a readily available and familiar scouting tool.

The sensitivity of the drop cloth can be improved by arranging a series of samples in a straight line at least eight rows long. Total numbers of plant bugs shaken onto the cloth along the line can be converted to numbers per hectare (or acre) using a simple formula applicable to any row spacing of solid or skip row cotton, except ultra-narrow row. This exception is stated because the method had not been tested for very narrow row spacings when this was written.

It was also demonstrated that spatial patterns of sample data can be detected if remotely sensed image maps are available. Using these image maps, differences in crop growth patterns throughout the field can be quickly identified. By sampling different areas of the field portrayed on the image map, we were able to demonstrate that plant bug densities differ by crop growth stage.

Used together, the potential exists for reducing the time and effort necessary to detect and monitor plant bug abundance in cotton, but still maintain the high integrity of sample data necessary for making appropriate management decisions for this pest.

Jeffrey L. Willers, USDA-ARS, Genetics and Precision Agriculture Research Unit, P. O. Box 5367, Mississippi State, MS 39762; Michael R. Seal, Space Remote Sensing, Bldg. 1103, Suite 118, Stennis Space Center, MS 39529; Randall G. Luttrell, Dale Bumpers College of Agricultural, Food and Life Sciences, 205 Agriculture, University of Arkansas, Fayetteville, AR 72701. Received 7 July 1999.
*Corresponding author (jwillers@ra.msstate.edu).

ABSTRACT

An accurate estimate of tarnished plant bug *(Lygus lineolaris* [P. de B.]) densities is necessary to achieve optimal pest control in cotton (*Gossypium hirsutum* L.) production. This research was conducted to create a sampling protocol for use in commercial cotton fields that would provide estimates of population abundance even at sparse densities. The protocol uses a modified line-intercept sample design, multispectral remote sensing imagery, and a drop cloth. Samples were collected from a belt transect line positioned at right angles to the row direction. Information was collected from drop cloth samples arranged as a series of at least eight adjacent units along the transect line. High-resolution multispectral remote sensing imagery assisted in the delineation of different sampling strata in a large cotton field. Various sample sites within these strata were selected and the plant bug density was estimated for each site. The novel sampling methodology detected a spatial distribution in tarnished plant bug abundance that corresponded to different phenological states (strata) of the crop as measured by remote sensing. Examples based on information collected from a large Mississippi Delta cotton field during 1997 illustrate major concepts and overall application of the integrated sampling scheme. The integrated sampling methodology can detect extremely sparse densities of tarnished plant bug nymphs and teneral adults. Remote sensing is an efficient technique that delineates sampling strata in large fields of cotton without excessive labor costs. The technique is best employed between the time of square initiation and canopy closure.

Many sampling techniques perform best whenever one can clearly define the boundaries of the area from which sample data are collected and to which management decisions will apply. Frequently, it is advantageous if a field can be subdivided, especially where field conditions vary (e.g., stage of plant growth or levels of fertility or moisture). When the field is divided (or stratified) into similar or homogenous blocks, each block can be sampled as if it were a unique field.

Each smaller sub-unit of a field is called a management unit and represents a specified area of land for which decisions are made and actions taken (Williams et al., 1995). The key concept that defines a management unit is that actions taken on this unit are carried out uniformly (See Williams et al., 1995, for further discussion). From the perspective of sampling, it is important that data are collected and kept distinct according to each management unit where soil type and fertility, water management, emergence date or other traits of the crop differ.

The identification of temporal and spatial patterns in pest distribution and abundance is difficult if stratification while sampling is not employed. Whenever spatial and temporal patterns in pest dynamics can be identified, the task of choosing appropriate pest management strategies and tactics becomes easier.

Defining uniform, or consistent, management units is not an easy task when large acreages are involved. Traditionally, discrete management units have been defined by roads, fence rows and waterways, with the consequence that these traditional units are often quite variable.

The problem has been that the cost of labor is too great to establish management units by using on-the-ground survey methods, especially when hundreds to thousands of acres are involved. Recently, spectral reflectance information collected by remote sensing methods was used to define homogenous management units to sample mirid populations in cotton. Results from these efforts strongly suggest that management units can be best defined by remote sensing. These management units may be irregular in size and shape and, at times, spatially discontinuous. Once these units have been delineated on a remotely sensed image map, though, it is a natural step to use these maps to select sample sites for insect pests.

Once a sample site has been identified, however, a field scout still must examine the crop at that site. During sampling, there is a conflict between the amount of time spent and the acquisition of an accurate sample. A goal of a sample design, or plan, is to provide guidance to the sampler on how to balance these tradeoffs and still obtain a dependable estimate (Thompson, 1992).

Combining the drop cloth with a line-transect sampling design and remote sensing images of a cotton field results in an efficient sampling technique for both the nymph and teneral adult life stages of tarnished plant bugs once squaring has begun and until just prior to canopy closure. Once the canopy has closed, though, one should use other sampling plans along with recently acquired imagery (if available).

The visually based, non-adjacent quadrat sampling method first mentioned for use with Heliothines (Willers et al., 1990a,b), expanded for use with other pests in Williams et al. (1991, 1995), and more recently described in Willers (1998) is one possibility for sampling after canopy closure.

Several excellent references describe the traditional line-intercept sampling technique (Kaiser, 1983; Lucas and Seber, 1977; McDonald, 1980, 1991; and Thompson, 1992). Line-intercept sampling applications in forestry and wildlife biology have existed for decades. For row crop applications, however, the approach has been rarely employed. The line-intercept design initially was modified by Willers et al. (1992) to help growers make replanting decisions. Extensions of the method to estimate the number of plants per acre, or stand, were described later in Williams et al. (1995), Willers (1998) and Willers et al. (1999).

In general, the traditional line-intercept design has tremendous utility when it is customized for row crop sampling problems. These advantages result from the presence of parallel and systematically spaced rows (Willers, unpublished). At present, the applicability of the line-intercept design for narrow row (row spacings <0.762 m [30 in]) planting patterns has not been explored, but research for use in narrow row spacings is planned. For the work reported herein, the described sampling methodology applies only in fields where the row spacing is wide enough (i.e., ≥0.762 m [30 in]) for a drop cloth to be easily used.

This article emphasizes adapting line-intercept concepts for use with both a drop cloth and remote sensing imagery for the purpose of estimating *L. lineolaris* abundance and dispersion in commercial cotton fields. Only key points and a brief statistical description of the integrated method will be mentioned. Further details or narrative, especially those of a statistical nature, can be found elsewhere (see reference list).

We will present an illustrative data set comprised of two dates and collected from a large commercial cotton field in July 1997 to demonstrate the main features and concepts of the sampling technique. Note that the number of sites selected and arrangement of sites within a strata during 1997 bear no relationship to a recommendation for use by commercial field scouts. The questions of sample size and optimal site selection are important, but require additional research with the use of imagery in additional years and locations.

MATERIALS AND METHODS

General Sampling Procedure

Samples were collected from a transect line of specified length and width positioned at right angles to the row direction. Sample information was collected from constant-size quadrats (small, rectangular units that corresponded to the size of a standard drop cloth) for each row of cotton along the length of the transect. A single drop cloth repeatedly was placed in different furrows to comprise a series of adjacent quadrats along the transect line.

At each furrow position, one row of plants was shaken with a stout wooden dowel and the number of plant bugs dislodged onto the cloth was recorded. Thus, a sampling design of improved sensitivity that easily detects low numbers of plant bug nymphs and teneral adults was created by a series of samples arranged along a straight line.

A typical transect line length corresponded to the number of rows planted by one pass of the planter (Willers, unpublished; Willers et al., 1992). For convenience and theoretical reasons (McDonald, 1991; Willers et al., 1992; Willers, unpublished) the transect length never exceeded four planter passes.

The use of a drop cloth (a readily available and familiar scouting tool) afforded several advantages. The series of drop cloth samples defined a belt transect (i.e., a transect line that also has width) so that a large number of plants could be examined easily and rapidly for the presence of plant bugs. Performing a visual examination for a similar number of plants one at a time would be too time-consuming. In addition, the awkwardness of using most vacuum type devices was avoided.

The data acquired with this sampling approach can be analyzed by several equations that are the classical line-intercept estimators (McDonald, 1980, 1991; Willers et al., 1992). However, several conceptual changes to the classical line-intercept notation were necessary for use in row crops (Willers, unpublished), yielding a simple expression (Eq. [1]), which readily estimated the number ($\hat{Y}$) of plant bugs per 0.405 ha (1 acre).

Here, the total number of bugs (either the number of adults or nymphs or the combined count of adults and nymphs) observed from the transect was divided by the total number meters (or feet) per row sampled (i.e., the drop cloth length, *l*, the side that lies parallel to the rows) multiplied by number of rows (*n*) sampled along a line. The quotient was multiplied by the number of linear meters per 0.405 ha (or linear row feet per acre [*R*]) applicable to the management unit that was sampled. These steps are summarized in Eq. [1] as follows:

$$\hat{Y} = [\sum_{i=1}^{n} y_i \ / \ (n \times l)] \times R \qquad [1]$$

The number of linear meters per 0.405 ha (or linear feet per acre) was determined by the row spacing and skip width (if any). The classical line-intercept estimator (McDonald, 1980, 1991; Willers et al., 1992) is algebraically equivalent to Eq. [1].

Acquisition of the Images

The study site was an 81 ha (200 acre) cotton field near the Mississippi River on the northern edge of Bolivar County, MS. In 1997, the NASA Commercial Remote Sensing Program (CRSP) acquired imagery throughout the growing season. A three-band digital camera system mounted in the belly of a fixed wing aircraft operated at an average speed 204 km h^{-1} (110 knots) obtained the multispectral imagery at an altitude of 1824 m (6000 ft) above ground level, which rendered a 1 m^2 spatial resolution per pixel.

The spectral resolution of the sensor was: Band 1 (green band, 540 ± 5 nm center wavelength), Band 2 (red band, 695 ± 5 nm center wavelength), and

Band 3 (near-infrared (nir) band, 840 ±5 nm center wavelength).

The multispectral imagery was processed with Imagine software (ERDAS, Atlanta, GA) using the following steps: (i) band-to-band registration—alignment of all bands, (ii) layer stack—stack all three bands together to form one composite image, (iii) subset—subset all edges to eliminate any edge effects, and (iv) calculate the NDVI (Normalized Difference Vegetation Index) to provide the green, yellow, and red zones of Fig. 1.

The NDVI (Rouse et al., 1974) is an equation equal to (nir − red)/(nir + red). The result of this expression was a range grouped into a 16-category plant vigor legend. The categories with the most plant vigor were assigned the greenest range while categories with the least plant vigor were assigned the red range within the legend. The categories assigned to yellow were of intermediate plant vigor and are between the green and red levels. For scouting purposes, however, a color printout of the classified, multiband composite was apportioned subjectively into four strata by color: (1) dark green, (2) green, (3) yellow, and (4) red.

Data Collection and Analysis of Variance and Correlation

The spatial resolution of a color printout was more than adequate to select sample sites in each strata by navigation on the ground without the assistance of using global positioning systems (GPS) waypoints.

The image shown in Fig. 1 depicts the field used during the study and reflects the status of the crop during July 1997. A different portion of the field in each stratum was sampled on each date. Each color (or sample strata) was sampled at two locations on two dates: 17 and 22 July 1997 (Tables 1A, 1B).

At a location, three nonoverlapping eight-row-long transect lines were placed arbitrarily in a triangular pattern in the center of a large, contiguous area as indicated by the classified image and were about 46 m (150 ft) apart from one another. Along each line the plants on each individual row of cotton were shaken with a heavy wooden dowel onto the drop cloth and the number of mirids (adults or nymphs) found for each of the eight rows was recorded.

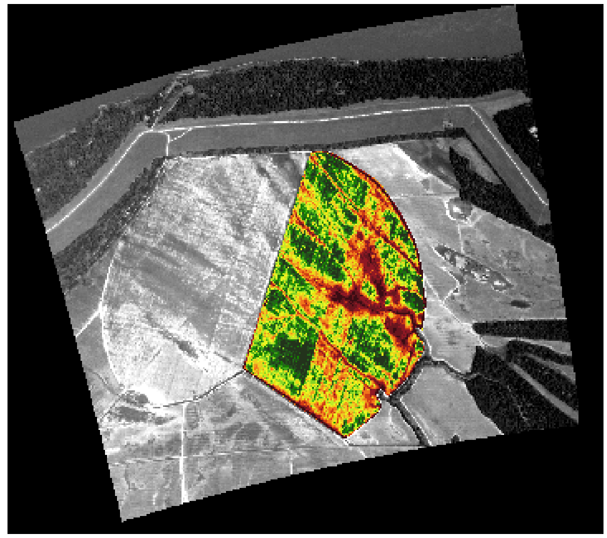

Fig. 1. Multispectral image of a 81 ha (200 acre) cotton field during July 1997. The cotton growing in the green zones was more rank, taller, and more heavily fruited than that in the yellow or red zones. The cotton was shorter and more open in its canopy and less heavily fruited in the red zones. The yellow zones were intermediate between these two extremes.

Table 1A. Original sample data obtained 17 July 1997 and reported by eight adjacent quadrats (units) along the transect line. Frequencies of adult and nymphal stages of the tarnished plant bug (TPB) are combined into a single total per quadrat. The last column provides the percent of the total (line-intercept only) that was the adult life stage.

Sample strata	TPB/ quadrat	TPB/ 25 sweeps	Density/ 0.405 ha	Adult TPB
	----------------no.----------------			%
Green	2 2 2 0 2 0 2 3	0	7085	1.5
	0 2 0 1 0 0 0 0		1635	3.3
	0 1 0 0 0 0 0 0		545	100
	0 0 0 0 0 0 1 0		545	100
	0 0 0 0 0 0 1 0		545	100
	0 0 0 0 0 2 0 0	0	1090	0.0
Green	1 0 0 0 2 2 1 0	0	3270	3.3
(Dark)	0 0 0 1 1 0 0 0		1090	50
	1 1 0 1 0 2 0 1	0	3270	1.7
	0 1 0 0 0 0 0 1		1090	0.0
	0 0 0 0 0 1 0 0	0	545	0.0
	0 0 0 0 0 0 0 0		0	
Yellow	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0	0	0	
	0 0 0 0 1 0 0 1		1090	50
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0	1	0	
Red	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 1 0 0		545	100
	0 0 0 0 0 0 0 0	0	0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0	0	0	
	0 0 0 0 0 0 0 0		0	

Table 1B. Original sample data obtained 22 July 1997 and reported by eight adjacent quadrats (units) along the transect line. Frequencies of adult and nymphal stages of the tarnished plant bug (TPB) are combined into a single total per quadrat. The last column provides the percent of the total (line-intercept only) that was the adult life stage.

Sample strata	TPB/ quadrat	TPB/ 25 sweeps	Density/ 0.405 ha	Adult TPB
	--------------no.--------------			%
Green	0 0 1 0 0 0 0 0		545	100
	0 2 1 1 1 0 0 1		3270	80
	0 1 0 1 0 1 0 0	1	1635	67
	0 1 1 0 0 1 0 0		1635	100
	1 1 0 0 0 1 0 0		1635	100
	0 1 1 0 0 0 1 0	0	1635	100
Green (dark)	0 0 0 0 0 0 0 1		545	100
	0 0 1 0 0 0 1 1		1635	100
	1 0 1 0 0 0 0 0	0	1090	50
	1 0 0 1 1 0 1 1		2725	100
	1 0 0 0 0 0 0 0		545	100
	0 0 1 1 0 0 1 0	1	1635	100
Yellow	0 0 0 0 1 0 0 0		545	100
	0 0 0 0 0 0 0 1		545	100
	0 0 0 0 0 0 0 0	0	0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 1 0 0 0 0		545	100
	0 0 0 0 0 0 0 0	0	0	
Red	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0	0	0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0		0	
	0 0 0 0 0 0 0 0	1	0	

The two sample dates corresponded to the time window when an image was available and the canopy of the crop remained suitable for use with a drop cloth. The canopy closed the week after the 22 July sample date. It is difficult to use a drop cloth in closed cotton canopy, so sampling by this method was discontinued at that time.

Additionally, several transect lines were paired randomly with a standard, 38 cm (15 in.) sweep net by using 25 sweeps near the line (the set of sweeps began or ended within a few steps of the origin of the line). Correlation coefficients were calculated for both of these sample techniques.

The counts of the number of plant bug adults and nymphs at each sampling strata were analyzed as a completely random design on each sample date. The strata, coded by color, comprised the treatment structure and each sample line in a particular stratum was considered as a replicate (r = 6). For the ANOVA, the sample strata were considered as fixed treatment effects. The SAS system (SAS Institute, 1990) was used to complete the necessary analyses.

The density estimates (Tables 1A, 1B) among the strata were nonnormal. To facilitate a statistical analysis, the entire set of observations by date was first ranked in ascending order (using the TIES = LOW option in Proc Rank). Performing an ANOVA on the rank values, instead of the original data values, is known as a rank-transformation procedure (Conover and Iman, 1981).

The Proc Mixed (Littell et al., 1996) procedure completed the ANOVA that compared density estimates (obtained by Eq. [1]) across strata (management units) on each sample date. The least significant difference (PDIFF) option was selected to perform pairwise comparisons among the treatments. The procedure, Proc Corr, computed the correlation coefficients between the sweep net data and data from the closest transect line (SAS Institute, 1990).

RESULTS

Imagery and Crop Status

The NDVI is one of many indices used to determine relative plant vigor (Rouse et al., 1974; Elvidge and Chen, 1995). The most vigorous plants depicted in the enhanced vegetation stress map (Fig. 1) of the crop are displayed in green while the least vigorous plants are displayed in red. The yellow strata represent plants that are intermediate in vigor between these two extremes.

Field observations suggested several relationships between the NDVI and several phenological attributes. In general, plant height was strongly correlated with these different plant vigor classes coded by color; plants in green areas were the tallest and in the red areas plants were the shortest (Willers, unpublished). The different plant vigor zones are irregular in size, shape, and continuity. Each different color defined a distinct management unit, or sampling strata.

One-Way ANOVA

On both dates, the yellow and red strata predominantly had a high frequency of zero or low plant bug density estimates (Tables 1A, 1B). Of the dark green, or green, strata only one transect line of 24 showed a density estimate of zero.

Often with insect data, large occurrences of zeros and small estimates for means involve skewed distributions that compromise some of the assumptions of classical ANOVA. For this reason, the rank transformation procedure (Conover and Iman, 1981) was used rather than the use of a transformation (Mead, 1988) to normalize the density estimates. A one-way ANOVA on the rank values, rather than the density estimates, indicated that the null hypothesis of equality among the four strata was rejected for 17 July ($P = 0.0009$) and 22 July ($P = 0.0001$).

The estimates of the numbers of plant bugs 0.405 ha^{-1} were slightly higher on 17 July than on 22 July (Tables 1A, 1B). Nymphs were more common on 17 July, whereas on 22 July the population was predominantly adults, many of which had just molted to the adult life stage. The presence of teneral adults was indicated by the extreme pale color. The detection of this type of transition in the age structure of the population was an additional benefit of the sampling technique.

The ANOVA results indicated that density of tarnished plant bugs during these two weeks of 1997 corresponded to different strata delineated on the image. It is unlikely that this type of spatial association between crop vigor and tarnished plant bug abundance would have been detected if another sample design had been used and the image map was unavailable (Willers, in preparation).

To guard against observer bias and to confirm independently these findings, the services of a private consultant not working in the vicinity of the study field were enlisted. This consultant, using traditional procedures (i.e., did not use the imagery or the line-intercept sample plan), intensively scouted the field for an entire day, and strongly agreed that the plant bug density was clearly higher in the rank areas (i.e., the greener zones) of the field.

The density estimates for the dark green, or green, strata were highly significant when compared with density estimates ($P < 0.002$) from the yellow or red color strata. Examination of the original sample data and ANOVA results indicated that mirid abundance in the dark green class was similar to the green class ($P = 0.747$ [17 July] and $P = 0.563$ [22 July]). Therefore, the dark green and green sample data were pooled.

Similarly, a multiple comparison of the ANOVA results indicated that the plant bug density estimates between the yellow and red strata was nonsignificant on 17 July ($P = 0.82$) and marginally significant on 22 July ($P = 0.074$). These two groups were pooled also.

The correlation between 25 sweeps with a sweep net and a nearby eight-row sample (Tables 1A, 1B) was low and ranged between −0.26 to 0.34. Often, when the sweep net collected no plant bugs, the line-intercept/drop cloth technique discovered plant bugs. This occurred 76% of the time for 17 paired comparisons; otherwise, the sweep net detected at least one plant bug 12% of the time when line-intercept/drop cloth method found zero, and both found zero bugs 12% of the time. The evidence suggested that the line-intercept/drop cloth technique more often detected low populations of teneral plant bug adults and nymphs than did the sweep net.

Pattern Without and With Remote Sensing

The advantages of the line-intercept design and remote sensing imagery were seen most clearly by supposing that the sample data were unstratified. The results of the sample data, if a simple random sampling design had been employed, were illustrated in the frequency distribution of estimated densities combined from 17 and 22 July (Fig 2). This histogram of results with an assumed simple random

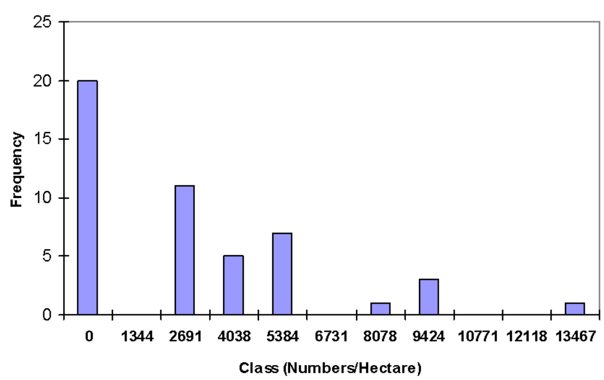

Fig. 2. Histogram of sample results for both sample dates assuming a simple random sampling design. This view of the data assumes that the observer enlisted no aids to select sample sites or define the data into unique strata. Density estimates greater than 13,467 plant bugs per hectare have been pooled into that particular class.

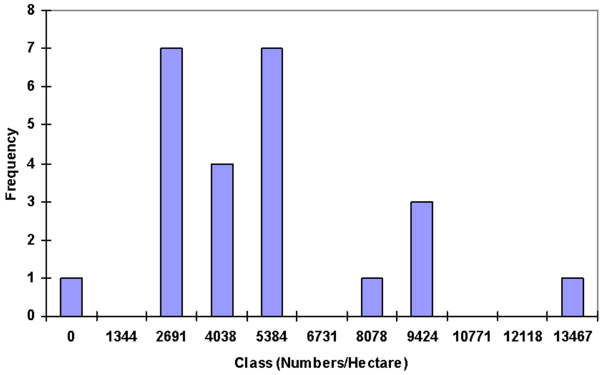

Fig. 3. Histogram of estimated plant bug densities obtained from 8-row long transect samples and the drop cloth for regions of the study field with most vigorous plants (dark green and green zones in Fig. 1). Data were combined for both sample dates (17 and 22 July 1997). Density estimates greater than 13,467 plant bugs per hectare have been pooled into that particular class.

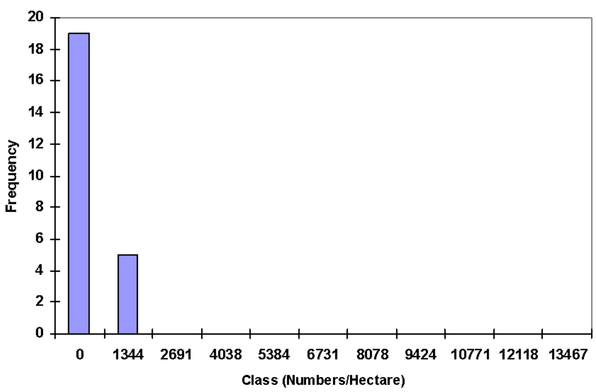

Fig. 4. Histogram of estimated plant bug densities obtained from 8-row long transect samples and the drop cloth for regions of the study field with least vigorous plants (yellow and red zones in Fig. 1). Data were combined for both sample dates (17 and 22 July 1997).

sampling design portrayed a high frequency of zero counts and high variability among the non-zero samples. This common pattern often has been observed in insect sampling data and has been assumed to be a consequence of natural variation or sampling error or a combination of both.

To illustrate the benefits that remote sensing brings to plant bug sampling problems, consider the analyses of the same data with stratification accomplished. A multispectral image identified different levels of plant vigor within the field (Fig 1). This map defined the management units for a stratified sampling scheme that yielded improvements in understanding these sample data. The high NDVI areas of the crop (i.e., dark green and green zones) had a broad range of estimates from low to high values, but the zero class was almost nonexistent (Fig. 3). Meanwhile, both the yellow and red zones (Fig. 4) had high frequencies of zero counts, with the yellow zone having slightly more occurrences of low counts (Tables 1A, 1B). Also, both the yellow and red strata did not exhibit occurrences of high counts (>2691 plant bugs ha^{-1} [1090 plant bugs/acre]). There was a clear apportionment of the density estimates into distinct groups that corresponded to the NDVI vigor classes.

DISCUSSION

The purpose of any sampling effort for pests of agricultural crops is to determine the relationship between the abundance of the pest and the potential for excessive crop loss (Pedigo and Buntin, 1993). Among cotton sampling efforts (Riley, 1989; Wilson et al., 1989; Wilson, 1993), the modified line-intercept design simultaneously used with a drop cloth and remote sensing imagery stands unique.

Any sampling effort has limitations. One limitation may be small plot settings commonly associated with research experiments. The chief concern is that these plots could be over-sampled and cause an artificial downward bias, especially if the time interval between sampling episodes is short. Other limitations are that the drop cloth can be difficult to manage on brisk, windy days or with excessively muddy field conditions.

Some hindrances in timeliness of scouting may result when certain pesticides are applied that have long re-entry intervals according to the pesticide label. Finally, for mature adult insects, especially those that have strong flight capabilities, the use of the drop cloth along a transect line may not work well (Willers, unpublished). For sampling immigrant adults at first square the use of a sweep net is recommended. More research efforts comparing different sampling tools with the use of image maps are necessary during the early season prior to peak squaring.

The sampling method described offers several advantages. The method is not excessively time consuming and supplies data with high reliability. While we cannot report detailed time and motion data, several years of experience have shown that one eight-row sample can be completed in less than 10 min with two people (one to observe and the other to record the data) or less than 20 min with only one person.

These sample durations include the recording of plant stand, numbers of plant bug adults and nymphs, life stage, numbers of beneficial arthropods (by species), other pests, numbers of shed fruiting forms, and travel time to and from a vehicle at each selected location. However, these time spans can be considerably shortened if plant stand and plant bugs are the only items of interest.

Travel time between sampling sites can be better managed by using the remotely sensed image to select locations prior to going to the field. The allocation of samples to different management units is made more efficient with the use of imagery. Remote sensing techniques identify these uniform sampling strata and more clearly delineate the spatial relationships, including the discontinuities, among these units.

In the near future, remote sensing images will be easily and widely available at an economical price. For sampling programs at present, however, if images are not available, one can be practical and use available information on-site to apportion samples by strata. For example, stand density along with plant height (or differences in growth rate) as related to the slope and aspect of the terrain, soil type, or drainage can be used to define sample strata.

Sorting plant bug samples into similar groups using obvious differences in crop growth patterns gives similar results to that achieved with remote sensing image maps. The only information lacking is a clear sense of the extent and interrelationships of the different strata that the imagery so readily portrays.

For the sample technique described here, one important assumption is that the field (or more specifically, the management unit) has been gridded into quadrats of sizes defined by segments of row bisected by a transect line of known length and width. The random sample is obtained by drawing sample units arranged along a randomly placed transect line in a particular strata of the field, with the result that the sample unit size dynamically increases as additional, adjoining rows are sampled. This is a different tack from most other sampling plans that employ nonadjacent random samples of a constant size, whether the unit is comprised of a single plant or collections of several plants.

Therefore, it is possible to have the feature of expressing sample counts as numbers per area because the belt transect line provides a reference that scales the estimates for a line into numbers per 0.405 ha (1 acre) (refer to Eq. [1]; Kaiser, 1983; McDonald, 1980, 1991; Williams et al., 1995). This is the primary reason why the transect line lies at right angles to the row direction. Counting rows is a convenient method of knowing the exact length of the transect line.

Another assumption of this sampling method is that the spatial pattern of the population is best described by a random, fine-grained dispersion pattern (Pielou, 1977); that is, the individuals are not distributed patchily throughout the management unit. If several sample lines exist for each of several distinct management units from the same field, similarity in the magnitude of the quadrat values for similar strata is evidence that the assumption of a fine-grained dispersion pattern for each one is plausible. Therefore, it is best to have a few sample lines allocated to several distinct management units (strata) and to avoid intensively sampling only one.

For any characteristic density, there exists an optimal line length (or total linear feet of row, r) that maximizes the probability that the belt transect will encounter *at least* one insect (McDonald, 1991; Willers et al., 1990b; Willers, unpublished). It is instructive to see how this typical length varies at different population levels. A simple expression derived from Eq. [1] can be used. The characteristic length of row (r) necessary to find at least one plant bug in a sample at different densities ($\hat{\mathbf{Y}}$) can be found as follows:

$$r = (R / \hat{Y}) \qquad [2]$$

A practical minimal distance on the row length, r (for example, with 0.965 m (38 in) row spacings), is to sample no less than two adjacent rows with a drop cloth, especially when populations are greater than 7413 insects ha^{-1} (3000 insects/acre). A trace of the variable, r, for different population values parallels the results portrayed in Fig. 5.

The only strong assumption that influences the result of Eq. [2] is the relationship between density and the dispersion pattern of the insect population of

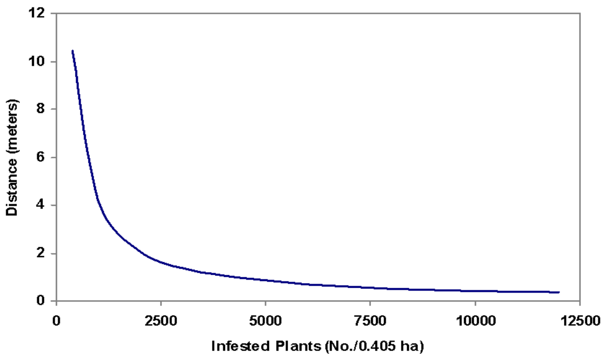

Fig. 5. Diagram representing the expected relationship of the mean distance (m) between individual insects and numbers of individuals per 0.405 ha assuming a random, fine-grained dispersion pattern and a stand density of 40,000 cotton plants per 0.405 ha (1 acre). Note that as the population of insects increases, there is a trend that the average distance between individuals decreases.

interest. For example, if the transect line crosses a boundary between two areas that differ in both density and pattern of dispersion, then Eq. [2] cannot apply. This limitation indicates the benefit of remote imagery to best apportion sample sites into strata that are as similar as possible.

Therefore, with 0.965 m (38 in.) and other wide row spacings, scouting for tarnished plant bugs with an eight-row sample is adequate for most occasions; rarely would a user opt for 16-row sample lengths. The guiding factor determining the choice between an 8- or 16-row sample is clarity. If a series of well-placed eight-row samples does not build the confidence of the sampler about the status of plant bugs in the crop, a series of 16-row transect lines could be more informative.

Frequently, three lines of eight rows in length per management unit (strata) will be sufficient, provided the field is strongly stratified into homogeneous areas. Additionally, whenever plant bug densities dramatically increase above a treatment threshold, the line length can be shortened. With experience and judgment, the sampler will learn how to balance the length of the sample line against the value of the information needed to make a management decision as the row spacing and planting pattern vary.

More details of the relationships among sample unit size, density and dispersion pattern, along with graphical displays, can be found in Willers et al. (1990b). This simulation study, along with details from McDonald (1991), can be used to develop a detailed proof (Willers, unpublished) that a single belt transect eight rows long is more efficient at detecting low populations of tarnished plant bugs compared with four widely separated samples of two rows each.

In this study, a visual inspection of the data (Tables 1A, 1B) for different random draws of any two adjacent quadrats from a transect whether the sampling is unstratified or stratified, suffices to illustrate the efficiency of the belt transect compared with smaller sized sample units.

The plant health zones reflected in the imagery relate to the biology of plant bugs in two important ways. First, the more lush areas of the field have a higher squaring (flower bud production) rate than the yellow or red zones. Cotton squares, at times, are a preferred feeding site for both adult and immature tarnished plant bugs. Second, the canopy structure is the most developed in the green zones, possibly providing some protection against pesticides, particularly for plant bug nymphs that often reside inside square bracts for several days at a time.

SUMMARY

The accuracy of the modified line-intercept estimate of plant bug density depends on the variability of the stand, past spray history and efficacy, and most importantly, the skill of the observer. The precision of the line-intercept method depends on the length and number of transect lines used to collect the data and the correct placement of sample lines in homogenous strata (management units) of the field. When incorporated with line-intercept concepts, the drop cloth is the key tool that permits the scout to examine large size sample units for nymphs and teneral adults with greater efficiency and without excessive costs in time. It is probable that the sweep net also can be used with imagery, but the targeted life stage will be mature adults that exhibit an ability to easily take flight during any disturbance of the plant canopy. At times, all these tools could be employed to best determine plant bug abundance in large cotton fields.

Plant bugs were more common in the areas with more vigorous plants. The data suggested that the insects preferentially selected the better areas of the crop. Interestingly, this result is predicted by the Fretwell-Lucas model of habitat selection (Fretwell

and Lucas, 1970; Fretwell, 1972). Applying this model from the perspective of agricultural pests would be another reasonable next step of study. Another influence that could help explain the observed spatial pattern of density may be protection from pesticides of immature stages and some adults afforded by the more vigorous canopy structure in the green strata. Several years of experience in this location suggest that plant bugs are resistant to certain chemical classes of pesticides (Snodgrass, 1996; Snodgrass and Willers, unpublished). Probably both influences are at work to result in the higher number of plant bugs observed in the green zone.

Learning how to use these images on a practical scale will be an interesting area of study. Better pest management procedures and better decisions for the control of tarnished plant bugs are expected in the future. Also, based on the experiences from this study, it is necessary to use objective, rather than subjective, methods to apportion an image into strata. Therefore, the supervised or unsupervised classification (Schrader and Pouncy, 1997) of an image, using remote sensing software and analysis techniques for cotton insect scouting, is a current area of research. Work also needs to be devoted to learning how irrigation history and other agronomic practices impinge on these spatial patterns.

ACKNOWLEDGMENT

Supported by USDA-CSREES Special Grants 97-34374-3990. Mississippi Agricultural and Forestry Experiment Station Publication No. J9411. We thank Kenneth Hood of Perthshire Farms, Gunnison, MS. Thanks also to Dr. George May, Tim Gress, Richard Campanella, Jim Johnson, Ken Copenhaver, and Kelly Dupont of ITD, Spectral Visions for acquiring and processing the remotely sensed imagery and to Bob Shelton and Daniel Lee of Geotek Management Services for obtaining the images by aircraft. We also greatly appreciate the technical assistance of Shane Minor and Robert Turner in collecting the field data, and Martha Barnes for assistance with the preparation of several graphics. Thanks also to Dr. Patrick Gerard, Experimental Statistics, Mississippi State Univ., who suggested the use of the rank transformation procedure. Drs. Wes Burger, Dep. of Wildlife and Fisheries, and Mike Williams, Dep. of Entomology and Plant Pathology, Mississippi State Univ. and several anonymous reviewers contributed suggestions that improved the manuscript.

REFERENCES

Conover, W.J., and R.L. Iman. 1981. Rank transformations as a bridge between parametric and nonparametric statistics. Am. Stat. 35:124–129.

Elvidge, C.D., and Z. Chen. 1995. Comparison of broad-band and narrow-band red and near-infared vegetation indices. Remote Sens. Environ. 54:38–48.

Fretwell, S.D. 1972. Populations in a seasonal environment. Princeton Univ. Press, Princeton, NJ.

Fretwell, S.D., and H.L. Lucas. 1970. On territorial behavior and other factors influencing habitat distribution in birds. I. Theoretical development. Acta Biotheoretica. 19:16–36.

Kaiser, L. 1983. Unbiased estimation in line-intercept sampling. Biometrics 39:965–976.

Littell, R.C., G A. Milliken, W.W. Stroup, and R.D. Wolfinger. 1996. SAS System for mixed models. SAS Inst., Cary, NC.

Lucas, H.A., and G.A.F. Seber. 1977. Estimating coverage and particle density using the line-intercept method. Biometrika 64:618–622.

McDonald, L. 1980. Line-intercept sampling for attributes other than coverage and density. J. Wildl. Manage. 44:530–533.

McDonald, L. 1991. Line-intercept sampling for two-dimensional particles. p. viii.1–viii.9. *In* Sampling of biological populations and resource selection studies, Workshop Notes. Univ. of Wyoming, Laramie.

Mead, R. 1988. The design of experiments: Statistical principles for practical application. Cambridge Univ. Press, Cambridge, England.

Pedigo, L.P., and G.D. Buntin (ed.) 1993. Handbook of sampling methods for arthropods in agriculture, CRC Press, Boca Raton, FL.

Pielou, E.C. 1977. Mathematical ecology. Wiley Inter-Science, New York.

Riley, J.R. 1989. Remote sensing in entomology. Annu. Rev. Entomol. 34:247–271.

Rouse, J.W., Jr, R.H. Haas, D.W. Deering, J.A. Schell, and J.C. Harlan. 1974. Monitoring the vernal advancement and retrogradation (greenwave effect) of natural vegetation. NASA/GSFC Type III Final Rpt., Greenbelt, MD.

SAS Institute. 1990. SAS Procedures Guide, Version 6. 3rd ed. SAS Inst., Cary, NC.

Schrader, S. and R. Pouncy (ed.) 1997. ERDAS Field Guide. 4th ed. ERDAS, Inc. Atlanta, GA.

Snodgrass, G. L. 1996. Insecticide resistance in field populations of the tarnished plant bug (Heteroptera: Miridae) in cotton in the Mississippi Delta. J. Econ. Entomol. 89:783–790.

Thompson, S.K. 1992. Sampling. Wiley-Interscience, New York.

Willers, J.L. 1998. Perspectives on sampling for *Lygus* in cotton: Applications of quadrat-based sampling schemes. p. 928–933. *In* Proc. Beltwide Cotton Conf., San Diego, CA. 5–9 Jan. 1998. Natl. Cotton Counc. Am., Memphis, TN.

Willers, J.L., R.L. Olson, M.R. Williams, and T.L. Wagner. 1990a. Developing a Bayesian approach for estimating the proportion of cotton plants at risk to insect attack. p. 246–247. *In* Proc. Beltwide Cotton Prod. Res. Conf., Las Vegas, NV. 9–14 Jan. 1990. Natl. Cotton Counc. Am., Memphis, TN.

Willers, J.L., D.L. Boykin, J.M. Hardin, T.L. Wagner, R.L. Olson, and M.R. Williams. 1990b. A simulation study on the relationship between the abundance and spatial distribution of insects and selected sampling schemes. p. 33–45. *In* G. Milliken and J. Schwenke (ed.) Proc. Appl. Stat. Agric., 2nd, Kansas State Univ., Manhattan, KS. 29 Apr.–1 May 1990. Kansas State Univ., Manhattan, KS.

Willers, J.L., S.R. Yatham, M.R. Williams, and D.C. Akins. 1992. Utilization of the line-intercept method to estimate the coverage, density, and average length of row skips in cotton and other row crops. p. 48–59. *In* G. Milliken and J. Schwenke (ed.) Proc. Appl. Stat. Agric., 4th, Kansas State Univ., Manhattan, KS. 26–28 Apr. 1992. Kansas State Univ., Manhattan, KS.

Willers, J.L., G.W Hergert, and P.D. Gerard. 1999. Sampling tips and analytical techniques for soybean production. p. 311–353. *In* L.G. Heatherly and H.F. Hodges (ed.) Soybean production in the Midsouth. CRC Press, Boca Raton, FL.

Williams, M.R., T.L. Wagner, and J.L. Willers. 1995. Revised protocol for scouting arthropod pests of cotton in the Midsouth. Tech. Bull. 206. Mississippi. Agric. For. Exp. Stn., Mississippi State, MS.

Williams, M.R., T.L. Wagner, J.L. Willers, and R.L. Olson. 1991. Scouting protocol for arthropod pests of cotton in the Midsouth. Bull. 977. Mississippi. Agric. For. Exp. Stn., Mississippi State, MS.

Wilson, L.T. 1993. Estimating abundance, impact, and interactions among arthropods in cotton agroecosystems. p. 475–514. *In* L.P. Pedigo and G.D. Buntin (ed.) Handbook of sampling methods for arthropods in agriculture. CRC Press, Boca Raton, FL.

Wilson, L.T., W.L. Sterling, D.R. Rummel, and J.E. DeVay. 1989. Quantitative sampling principles in cotton IPM. p. 85–120. *In* R.E. Frisbie et al. (ed.) Integrated pest management systems and cotton production. Wiley & Sons, New York.