Modeling *Lygus hesperus* Injury to Cotton Yields

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ABSTRACT A model of the impact of a lygus, *Lygus hesperus* (Knight), population on cotton square development and subsequent impact on boll development is proposed. The model is specified as a multistage production process and parameters are estimated using data collected in Kern County, Calif. in 1974. Lygus cause significant injury to cotton during two disjoint periods. The first period occurs during the early squaring stage of the plant when squares are forming at a rate of ca. 100% a week. The second period occurs when the cumulative number of squares per unit area has peaked. The ultimate impact of lygus on cotton yields depends heavily on plants bearing fruit in the early period. Results of computations indicate that lygus can significantly injure the cotton yield in fields with subaverage square loads during the early period. The model can be used to determine economically optimal spraying strategies.

AN ANALYTICAL MODEL of the relationship between lygus, *Lygus hesperus* (Knight) and cotton in the San Joaquin Valley of California is developed and parameters of the model are estimated using field data. The approach taken in this paper is methodologically different from previous work done by Gutierrez et al. (1975, 1976, 1977, 1979) who used relatively complex computer simulation modeling to characterize cotton plant and lygus interaction. Their models examined interrelationships between variables such as main-stem node production, position of the first branch fruiting, fruit production, dry matter accumulations, individual boll weight, potential leaf, stem and root growth, water use, and lygus damage associated with crop consumption. In contrast, the model presented here abstracts much of the detail embedded in those microlevel models and concentrates simply on square and boll formation. The advantage of such simplicity is that it allows forecasts of yield losses with only a few data inputs that are readily available to growers; namely, initial status of the plant (e.g., squares per area) and pest population levels (e.g., lygus per 50 sweeps of a sweep net).

In the next section, the data set used in the estimates of the presented work is described. In later sections, the analytical models of lygus–square and square–boll interactions are described, followed by estimates of cotton damages. The last section contains concluding comments and a qualitative comparison of the results with those of the more complex microsimulation models.

Materials and Methods

The Data Set. The data used in this study were collected by a joint U.S. Department of Agriculture–University of California Cooperative Extension Cotton Pest Management Program involving 146 fields in Kern County during the 1974 season. Kern County accounted for 28% of California's cotton production in that year and consistently accounts for over 25% of California's cotton production. The fields in this data set are from two areas, the Kern Delta Gin and the Arvin Cooperative Gin.

Each field or group of small fields was divided into four equal areas. Plant growth analyses and complete insect and spider mite population evaluations were conducted in each quadrant. A field-inspection report, containing the date and time of visit and the identification of the county, field, producer, and checker, was submitted each time a field was visited. The report consists of the crop history, and pest and beneficial insect species counts. The crop history contains legal descriptions of the field, information on preplant fumigation, herbicide or systemic pesticides, records of cultural practices throughout the season, pesticide use and time of use, and plant damage from disease. Irrigation and cultivation practices were observed by the checkers on the day of the visit but weather, adjacent habitat (e.g., presence of alfalfa or safflower), and yields were not recorded.

Since the fields in the Kern Delta Gin are closest to the Maricopa, Calif. national climatic reporting station and the fields in the Arvin Coop Gin are closest to the Arvin, Calif., local temperature reporting station, degree day listings for the Maricopa and Arvin climatic reporting stations (for the 1974 season) were used in the analysis.

L. hesperus was one among several of the pest species recorded. Counts were made twice weekly at intervals of 3–4 days beginning with squaring in June and continuing into August. Each sample consisted of 25 sweeps down a single row of cotton; a minimum of four samples was taken at each inspection. When counts were in the range of 7–10 lygus per 50 sweeps, additional samples were taken.

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An area of 5.5 m^2 was also sampled in each field for plant-growth analysis. This area was divided into four equal sample areas, with one sample per field quadrant. Once the number of plants within the marked off area was counted, the number of mainstem nodes and the height of the tallest plant in each sample area were recorded. A record was also made of all squares, flowers, and small and large bolls on the plants within the sample area. A more detailed description of the field inspection and reporting procedures is given in appendix 3.A of Stefanou (1983).

The planting dates in this sample vary between 18 March and 7 May. Since plant development depends upon degree days, a normalization procedure was used to place all fields in the sample on an equivalent plant development time scale. A lower cotton plant development temperature threshold of 15.5°C is widely applied in California and Arizona and was used in the empirical study presented here. To normalize all fields in the data set, a peak square date was used as the reference date. In the Sevacherian model available on the University of California Integrated Pest Management group computer system, peak square occurs at 1,200 degree-days above 15.5°C after planting. The normalization procedure involves identifying the week in which 1,200 degree-days was achieved for fields planted on a given date. The plant development data are then adjusted to place the field on a common development scale. An approximate conversion of calendar days to degree days for the Kern County data set in 1974 is given by Stefanou (1983).

Sizes of the 146 fields in this data set range from a minimum of 3.64 ha to a maximum of 69.6 ha. The grouped mean field size is just under 26 ha with a grouped coefficient of variation of 56%. Over 65% of the fields range between 10.5 and 30.4 ha.

Modeling the Lygus–Cotton Interaction

Specifying damage relationships empirically generally involves trade-offs due to limited data. For example, much of what has been done to date examines total season-end damages as a function of pest population level and spray applications at a few points in time. In the analysis reported here, a detailed single-season time series and cross-sectional data set (described above) on the status of the cotton plant and the lygus population is used in the model that estimates lygus injury to cotton yields. The estimated model identifies empirically when the plant is especially vulnerable to lygus during particular periods of the plant growth process without resorting to complicated microlevel modeling or detailed multivariate data sets.

Although the strategy taken in this paper differs from that traditionally employed in entomological literature, the aim is still one of usefulness, particularly to growers who may need simple decision aids and rules of thumb. Our approach effectively assumes that nature carries out the experiment that is observed by the analyst (Judge et al. 1982). Resulting data on actual cotton yields is empirically fit to some actual data on plant status and lygus populations using hypothesized functional relationships. This approach, of necessity, aggregates over many of the underlying processes involved but has as an advantage a simplicity that should be appealing to real-world decision makers. In the final analysis, a simple or complex approach must be judged according to its ultimate usefulness. Where forecasting (as opposed to explaining the underlying structure) is involved, simple models often perform better than their complicated counterparts (Tukey 1961).

The Lygus–Square Relationship. There are three state variables that summarize all of the necessary detail in this model. These are the numbers of squares and bolls, which measure the state of the plant at any point in time, and the number of lygus. Since these variables were measured weekly, the following notation is used in what follows.

$$\begin{aligned} S(i, t) &= \text{no. of medium and large squares on 5.5 m}^2 \text{ in field } i \text{ at the start of week } t \\ L(i, t) &= \text{no. of lygus adults plus nymphs per four sets of 25 sweeps in the middle of week } t. \end{aligned} \quad (1)$$

Midweek lygus counts are used to represent lygus population during the interval (i.e., a week) that additional squares are developing. We hypothesize that $S(i, t)$ satisfies the dynamics

$$\begin{aligned} S(i, t) = {} & \beta_1(t-1)S(i, t-1) \\ & + \beta_2(t-1)S(i, t-1)^2 \\ & + \beta_3(t-1)L(i, t-1) \\ & + \beta_4(t-1)L(i, t-1)^2 \\ & + \nu(i, t) \quad \text{for} \quad t = 3, \ldots, 8. \end{aligned} \quad (2)$$

In this equation, $\beta_i(t)$ are parameters to be estimated and $\nu(i, t)$ is assumed to be normally distributed error terms with mean zero and variance $\sigma^2_\nu(t)$. The first two terms in equation 2 characterize the square growth in the absence of lygus. Square growth assumes a logistic shape if $\beta_1 > 0$ and $\beta_2 < 0$. Since the intrinsic growth rate of squares is $\beta_1(t-1)$, one expects this quantity to be positive until peak squaring. The next two terms characterize the effect of lygus on the plant. One expects that $\beta_3(t) < 0$, so that lygus decrease the number of squares, but the sign of $\beta_4(t)$ may be positive or negative. The period of interest spans the time between the third week after square initiation and the eighth week.

The Square–Boll Relationship. To model the square-to-boll transformation, it was necessary to specify three phases encompassing 1) the initial phase where boll counts were related to past square

Table 1. Parameter estimates of lygus/square interaction

	$\beta_1(t)$	$\beta_2(t)$	$\beta_3(t)$	$\beta_4(t)$	$\bar{R}^{2\,a}$	n^b
t = week 3	2.01	−0.002	0.973		0.53	131
	(16.5)[c]	(−4.1)	(0.9)			
	1.91	−0.002	4.51	−0.14	0.53	131
	(13.8)	(−3.7)	(1.8)	(−1.5)		
t = week 4	1.97	−0.0002	−5.72		0.92	128
	(16.5)	(−4.6)	(−1.9)			
	2.01	−0.0002	−11.1	0.21	0.92	128
	(15.7)	(−4.7)	(−1.7)	(0.9)		
t = week 5	1.56	−0.001	1.57		0.29	118
	(15.9)	(−5.9)	(0.9)			
	1.63	−0.001	−2.63	0.21	0.29	118
	(13.1)	(−5.8)	(−0.5)	(0.9)		
t = week 6	1.19	−0.0006	0.44		0.40	114
	(13.4)	(−3.6)	(0.3)			
	1.30	−0.0007	−0.79	0.46	0.41	114
	(11.6)	(−4.0)	(−1.5)	(1.6)		
t = week 7	1.15	−0.0006	−2.56		0.42	107
	(12.0)	(−3.6)	(−2.0)			
	1.25	−0.0007	−6.83	0.152	0.42	107
	(10.5)	(−3.9)	(−2.1)	(1.4)		
t = week 8	0.98	−0.0005	−2.12		0.46	58
	(8.2)	(−1.98)	(−1.45)			
	1.08	−0.0006	−6.30	0.19	0.46	58
	(6.5)	(−2.2)	(−1.3)	(0.9)		

[a] Adjusted R^2.
[b] Number of fields.
[c] t Values in parentheses.

counts; 2) the intermediate phase where nutrients are divided between squares and bolls; and 3) the final phase where boll conversion to yield has been completed.

Let $B(i, t)$ denote the number of large bolls in field i at week t per 5.5 m². In the empirical study, no large bolls were observed before the 5th week. Consequently, for the first phase, $B(i, 5)$ was modeled simply by

$$B(i, 5) = \gamma_1 S(i, 3) + \gamma_2 S(i, 3)^2. \quad (3)$$

The estimated coefficients for γ_1 and γ_2, respectively, were 0.013 and 0.0002 with 0.8 and 4.9 t values, respectively, and the value of the coefficient of determination adjusted for degrees of freedom is $\bar{R}^{-2} = 0.44$.

For weeks 6–10, in the intermediate phase, boll development was hypothesized to satisfy the following dynamics

$$\begin{aligned} B(i, t) = {} & \gamma_1(t-1)B(i, t-1) \\ & + \gamma_2(t-1)B(i, t-1)^2 \\ & + \gamma_3(t-1)S(i, t-2) \\ & + \gamma_4(t-1)S(i, t-2)^2 \\ & + u(i, t) \quad \text{for} \quad t = 6, \ldots, 10. \end{aligned} \quad (4)$$

In this equation, $\{\gamma_k(t)\}$ are parameters to be estimated and $u(i, t)$ is an error term, assumed to be normally distributed with mean 0 and variance $\sigma^2_u(t)$. The model (4) captures the resource competition between squares and bolls through the coefficients $\gamma_3(t)$ and $\gamma_4(t)$. The logistic function for the number of bolls captures the idea of limited plant resource. The maximum number of large bolls the plant can support in period t is $[-\gamma_1(t)/2\gamma_2(t)]$.

For the 11th and 12th weeks when boll formation has been completed, cumulative bolls were hypothesized to grow logistically according to

$$\begin{aligned} B(i, t) = {} & \delta_1(t-1)B(i, t-1) \\ & + \delta_2(t-1)B(i, t-1)^2 \\ & + \epsilon(i, t) \quad \text{for} \quad t = 11, 12. \end{aligned} \quad (5)$$

where $\delta_1(t)$ and $\delta_2(t)$ are parameters to be estimated and $\epsilon(i, t)$ is normally distributed with zero mean and with variance $\sigma^2_\epsilon(t)$.

Results and Discussion

The set of coefficients $\{\beta_i(t)]$ was estimated using ordinary least squares regression. To do this, it was assumed that there was no autocorrelation between variables at different times. Table 1 shows the results of the estimation procedure. Using t values, tests of the significance of $\beta_4(t)$ indicated that it was not significantly different from zero at the 10% level, and, hence, estimates were also made with $\beta_4(t)$ set equal to zero. Based on Table 1, the intrinsic growth rate of squares $\{\beta_1(t)\}$ decreases during the squaring period and becomes negative

Table 2. Parameter estimates of square boll relationship

	$\gamma_1(t)$	$\gamma_2(t)$	$\gamma_3(t)$	$\gamma_4(t)$	$\bar{R}^{2\,a}$	n^b
$t = 6$	1.69	−0.0095	0.078		0.57	109
	(5.9)[c]	(−3.0)	(7.3)			
	1.73	−0.010	0.054	0.0001	0.57	109
	(6.0)	(−3.2)	(2.2)	(1.1)		
$t = 7$	1.33	−0.002	0.073		0.67	114
	(5.6)	(−1.0)	(4.5)			
	1.39	−0.002	0.056	0.00003	0.67	114
	(5.2)	(−1.1)	(1.5)	(0.5)		
$t = 8$	1.05	−0.001	0.098		0.63	113
	(6.5)	(−1.2)	(4.8)			
	1.29	−0.002	−0.00002	0.0002	0.64	113
	(6.3)	(−2.1)	(0.0)	(1.9)		
$t = 9$	1.43	−0.002	0.053		0.61	104
	(8.7)	(−2.8)	(1.9)			
	1.31	−0.002	0.112	−0.0001	0.60	104
	(5.0)	(−1.6)	(1.1)	(−0.6)		
$t = 10$	1.13	−0.0006	−0.011		0.63	61
	(6.8)	(−0.9)	(−0.2)			
	1.35	−0.001	−0.19	0.0003	0.63	61
	(4.5)	(1.28)	(−1.0)	(0.9)		

[a] Adjusted R^2.
[b] Number of fields.
[c] t Values in parentheses.

at the start of the eighth week. Thus, on the average, peak squaring occurs in the seventh week. Observe also from Table 1 that $\beta_3(t)$ varies considerably over time, with apparently insignificant damage in some weeks. In view of the results of one-tailed significance tests on β_3, lygus significantly impact the cotton only in weeks 4, 7, and 8. The observation that lygus do significant damage in some weeks and not others can be interpreted in terms of a resource allocation model for the plant (e.g., see Mirmirani and Oster 1979 for a different use of such a model). During periods in which the rate of formation of squares is high, most of the plants' resources are allocated to square production, and, hence, the ability to retain squares under pest population pressure is reduced. During the 7th and 8th weeks, the lygus also do significant damage to the square load. At this point, the plant is setting bolls. According to the resource allocation model, the plant is dividing nutrients between bolls and squares during this early stage of boll development. This decreases the rate of square

Table 3. Parameter estimates of last-season boll growth relationship

	δ_1	δ_2	$\bar{R}^{2\,a}$	n^b
$t = 11$	1.41	−0.002	0.50	117
	(18.1)[c]	(−5.4)		
$t = 12$	1.67	−0.003	0.69	58
	(21.9)	(−8.4)		

[a] Adjusted R^2.
[b] Number of fields.
[c] t Values in parentheses.

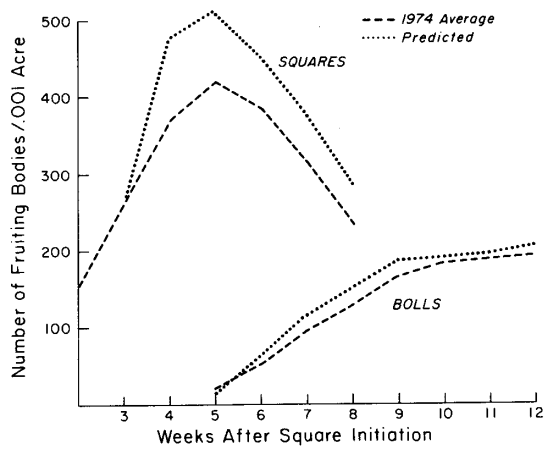

Fig. 1. Comparison of the solution of equation 6 and the averages of the observed squares and bolls.

production and may lessen the plant's ability to retain squares.

Tables 2 and 3 show the results of the estimation procedures for the coefficients in equations 4 and 5. Two-tailed t tests of significance on $\gamma_4(t)$ show that this set of coefficients is not significantly different from zero, so that it is possible to use a linear relationship between squares and bolls.

The results of the estimation procedure imply that there are two periods within the season when lygus can adversely affect cotton yields. Although the plant growth and development depends upon heat accumulation, the phenology of the plant can be used to identify these two periods. These two periods can be identified by the intrinsic rates of growth of squares. The first period involves the early part of the squaring stage when squares are forming at a rapid rate (100% intrinsic rate of growth in squares per week); the second period occurs during the peak squaring stage.

Calculating Lygus Impact on Yield. The model developed in equations 2–4 can be employed, as follows, to develop yield losses. Once an initializing square load $S(i, 3)$ is given, then

$$S(i, t) = \beta_1(t-1)S(i, t-1) + \beta_2(t-1)S(i, t-1)^2 \quad \text{for} \quad t = 5, 6$$

$$S(i, t) = \beta_1(t-1)S(i, t-1) + \beta_2(t-1)S(i, t-1) + \beta_3(t-1)L(i, t-1) \quad \text{for} \quad t = 4, 7, 8 \qquad (6a)$$

yields the number of squares in subsequent periods. To determine initializing boll levels we use

$$B(i, 5) = 0.013S(i, 3) + 0.0002S(i, 3)^2, \qquad (6b)$$

and subsequent boll levels are generated by;

Table 4. Net value of cotton production per acre (in dollars) with 3rd-week square load = 150[a]

		Second-period lygus population[b]		
		L	*M*	*H*
No spray in either period				
First period	*L*	566.22	563.13	557.18
Lygus population	*M*	548.80	544.71	536.86
	H	487.44	479.93	465.61
No spray in first period, spray in second period				
First period	*L*	560.83	560.55	560.05
Lygus population	*M*	544.25	543.87	543.21
	H	485.80	485.11	483.90
Spray in first period, no spray in second period				
First period	*L*	568.59	566.10	561.30
Lygus population	*M*	567.62	565.07	560.16
	H	565.82	563.17	558.06
Spray in both periods				
First period	*L*	562.70	562.47	562.07
Lygus population	*M*	561.77	561.54	561.13
	H	560.06	559.82	559.39

[a] Price of lint, $0.70 per pound; cost of spray, $8.00 per acre; and kill rate, 0.9.
[b] *L*, 4 lygus per 50 sweeps; *M*, 8 lygus per 50 sweeps; *H*, 15 lygus per 50 sweeps.

$$B(i, t) = \gamma_1(t-1)B(i, t-1) + \gamma_2(t-1)B(i, t-1)^2 + \gamma_3(t-1)S(i, t-2) \quad \text{for} \quad t = 6, \ldots, 10 \tag{6c}$$

and

$$B(i, t) = \delta_1(t-1)B(i, t-1) + \delta_2(t-1)B(i, t-1)^2 \quad \text{for} \quad t = 11, 12. \tag{6d}$$

Finally, yields are calculated by assuming a conversion based on 125,000 bolls per 480 pounds (217.73 kg) of Arcala cotton (T. A. Kerby, personal communication)—i.e., for observation i

$$[\text{Yield/acre}]_i = (B(i, 12)/125) \times 480. \tag{6e}$$

In addition to the initializing value of $S(i, 3)$, the values of $L(i, 3)$, $L(i, 6)$ and $L(i, 7)$ must be provided. When this is done, the system described above may be recursively solved to provide a predictive relationship between initial square load, lygus counts, and yield. In Fig. 1 we present the results of calculations using equations 6a–e.

To assess the net economic damage that the lygus may do to the cotton, one must include the cost of spraying under various strategies. In what follows, we will simplify by calling the critical week-4 period the first period and weeks 7 and 8 the second period. In each period, one can choose to spray or not and, thus, there are four cases to consider. Tables 4–6 show the results of some calculations using the system as estimated above. The state of the plant is measured by the square load per 5.5 m² during the rapid squaring period, $S(i, 3)$, and three different values of $S(i, 3)$ are considered: poor (150 squares), below average (200 squares), and average (250 squares). (The results of measurement of lygus injury to cotton yields indicate that lygus does not significantly injure cotton yields for above-average third-week plant performance.) A kill rate of 90% is assumed and three different lygus population level categories in each period are considered.

With $\beta_3(4) = -5.72$ and $\beta_3(7) = -2.56$, one may infer that feeding lygus can induce over twice as

Table 5. Net value of cotton production per acre (in dollars) with 3rd-week square load = 200[a]

		Second-period lygus population[b]		
		L	*M*	*H*
No spray in either period				
First period	*L*	588.59	586.78	583.29
Lygus population	*M*	582.12	579.93	575.70
	H	562.34	558.98	552.53
No spray in first period, spray in second period				
First period	*L*	582.12	581.95	581.66
Lygus population	*M*	575.97	575.77	575.42
	H	557.17	556.86	556.32
Spray in first period, no spray in second period				
First period	*L*	584.76	583.19	580.17
Lygus population	*M*	584.35	582.77	579.70
	H	583.62	581.98	578.83
Spray in both periods				
First period	*L*	578.07	577.93	577.68
Lygus population	*M*	577.69	577.54	577.29
	H	576.99	576.84	576.58

[a] Price of lint, $0.70 per pound; cost of spray, $8.00 per acre; and kill rate, 0.9.
[b] *L*, 4 lygus per 50 sweeps; *M*, 8 lygus per 50 sweeps; *H*, 15 lygus per 50 sweeps.

Table 6. Net value of cotton production per acre (in dollars) with 3rd-week square load = 250[a]

		Second-period lygus population[b]		
		L	*M*	*H*
No spray in either period				
First period	*L*	598.40	597.17	594.77
Lygus population	*M*	595.59	594.18	591.46
	H	587.81	585.93	582.31
No spray in first period, spray in second period				
First period	*L*	591.44	591.33	591.13
Lygus population	*M*	588.77	588.64	588.42
	H	581.39	581.22	580.92
Spray in first period, no spray in second period				
First period	*L*	592.31	591.19	589.02
Lygus population	*M*	592.12	590.99	588.80
	H	591.78	590.63	588.40
Spray in both periods				
First period	*L*	585.25	585.15	584.97
Lygus population	*M*	585.07	584.97	584.79
	H	584.75	584.64	584.46

[a] Price of lint, $0.70 per pound; cost of spray, $8.00 per acre; and kill rate, 0.9.
[b] *L*, 4 lygus per 50 sweeps; *M*, 8 lygus per 50 sweeps; *H*, 15 lygus per 50 sweeps.

many squares to shed during the first period when compared to the second period. However, whether or not it pays to spray depends also upon the fruiting condition of the plant in the first critical period and the levels of infestation expected. For example, for a poor square load of 150 squares per 5.5 m^2 (see Table 4), the best decision is to spray in both periods if high lygus populations are expected in both critical periods. This strategy results in a gain of about $94, $74, and $1 over the no-spray, spray in second period only, and spray in first period only strategies, respectively. In contrast, with an average square load (Table 6) under the same expected infestation levels, the best decision is to spray in the first period only, yielding smaller gains of $4, $8, and $6 over the spray in both periods, spray second period only, and don't-spray decisions, respectively. The net value of cotton production per acre does not include the damage the pink bollworm (PBW), *Pectinophora gossypiella* (Saunders), can inflict on cotton yields as a result of the second-period spray for lygus.

Generally speaking, the gains from spraying in the second period are low compared with gains from first-period spraying. In addition, the second-period spray for lygus invariably kills the predators of PBW, enhancing the PBW population level during the boll-setting stage of plant development and contributing to further yield loss due to PBW feeding. If the total costs of spraying for lygus in the second period included the spray cost *and* the potential PBW damage due to this period's spray, spraying for lygus in both periods would not generally be profitable.

Perhaps the most interesting comparison from these tables is the case of no spray in either period with spray in the first or both periods. The results of the calculations show that, depending upon the initial square load, spraying for lygus can increase economic yield considerably (almost $100/acre in some cases). However, a general result is that the largest gains are achieved if early plant performance is poor. With poor fruiting, for example, the maximum gains are $94, whereas with average fruiting the most that can be saved with spraying is about $6 per acre.

In summary, the model described by the system in equations 6a–e is the result of an empirical examination of cotton–lygus interaction using single-season time series and cross-sectional data. This effort is complementary to the computer simulation approach, and, in fact, verifies experimentally some of the conclusions from more sophisticated plant growth models. In addition, there is some new insight added to the understanding of the cotton–lygus relationship. For example, the empirical results reveal that there is a relatively straightforward predictable impact of lygus populations on cotton yield damage, depending upon the phase of the plant growth process. Of particular usefulness is the simplicity provided by focusing on a few critical variables and their values during critical plant growth phases.

Equations 6a–e, thus, provide a potential decision tool for the grower. It would be possible, for example, for the grower to use this model to predict yields, given initializing conditions and lygus counts, and then to optimally initiate a spray decision strategy. (See Stefanou [1983] for a presentation and implementation of the decision process.)

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