FIELD AND FORAGE CROPS

Costs of *Lygus* Herbivory on Cotton Associated With Farmer Decision-Making: An Ecoinformatics Approach

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ABSTRACT Because the farmer is typically excluded from the experimental research setting, experimental research may face challenges in evaluating pest management tactics whose costs and benefits hinge on farmer decision-making. In these cases an ecoinformatics approach, in which observational data collected from the commercial farming setting are "mined" to quantify both biological variables and farmer behavior, can complement experimentation as a useful research tool. Here I analyze such an observational data set to characterize associations between early- (June) and mid-season (July) *Lygus hesperus* Knight populations and farmer decisions to apply plant growth regulators and defoliants. Previous experimental work suggested the hypothesis that *Lygus* herbivory, by inducing abscission of young flower buds, might generate increased use of plant growth regulators and defoliants. Cotton's ability to compensate for loss of flower buds may, however, increase as plants grow. On upland cotton, June *Lygus* populations were associated with increased use of plant growth regulators, as expected, but this relationship was not observed for July *Lygus* populations. June *Lygus* populations were not associated with the use of defoliants, whereas, surprisingly, July *Lygus* populations were associated with decreases in defoliant use. In contrast to these positive and negative associations observed on upland cotton, on Pima cotton *Lygus* populations exhibited no associations with use of either plant growth regulators or defoliants. These results suggest that cotton responses to *Lygus* herbivory, as demonstrated in previously published experimental studies, can translate into economically meaningful changes in farmer decisions to apply agricultural chemicals.

KEY WORDS ecoinformatics, observational studies, farmer decision-making, *Lygus*, cotton

Integrated pest management (IPM) research has traditionally relied on manipulative experiments performed by scientists, often on university farms (Rosenheim et al. 2011). This approach has many well-appreciated and important advantages, foremost of which is the ability to derive strong inferences regarding causal relationships between manipulated variables (e.g., pest densities) and response variables (e.g., aspects of crop performance). However, one difficulty of this approach emerges when farmer decision-making shapes the costs and benefits of different pest management practices (e.g., Bürger et al. 2012, Savary et al. 2012). Farmer behavior is typically excluded from the experimental research setting, and it is generally unclear if farmers' decisions can be anticipated accurately by researchers in the absence of direct observations. To cope with this problem, it may be useful to gather observational data from the commercial farming setting that include quantifications of not only biological variables (e.g., crop yield) but also descriptors of farmer decision-making (e.g., Breukers et al. 2012, Bürger et al. 2012). Such observational datasets will be subject to the usual interpretational challenges associated with correlational evidence (Diamond 1983, Paine 2010), but may nevertheless provide a useful complement to experimental research.

Here I present a case study of how observational data derived from commercial farms can be used to characterize costs (or benefits) of herbivory that flow from farmer decision-making, in this case farmer decisions to adjust their use of plant growth regulating chemicals. Such costs may contribute significantly to the overall economic damage generated by herbivores. The study is part of a broader attempt to develop a proof of concept for an 'ecoinformatics' approach to pest management research, wherein observational data gathered by farmers, consultants, and others are brought to bear on important questions in applied insect ecology (Rosenheim et al. 2011).

The case study involves the impact of *Lygus hesperus* Knight (Hemiptera: Miridae) herbivory on cotton in California's San Joaquin Valley. Two species of cotton are grown commercially in California: upland cotton, *Gossypium hirsutum* L., and Pima cotton, *Gossypium barbadense* L. Both are perennial plants grown as annual crops, and both show indeterminate growth, although upland cotton with a robust fruit set often

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expresses a more nearly complete cessation of growth by the end of the summer than does Pima cotton (Henneberry et al. 1998). To maximize yield of the harvested seeds and associated lint, farmers often make foliar applications of the plant growth regulator mepiquat chloride to shift plant resource allocations away from excessive vegetative growth and toward enhanced fruiting (Kerby et al. 1996). Farmers monitor plant growth and fruit set to adjust their applications of plant growth regulators: too much vegetative growth produces a large, vigorous plant, but little yield, whereas too little vegetative growth prevents the plant from building the photosynthetic capacity needed to mature a heavy fruit load.

L. hesperus prefers to feed on developing flower buds ("squares") of cotton. Cotton plants may respond to *Lygus* damage by abscising damaged flower buds. Loss of fruiting structures can translate eventually into reductions in yield, which are amenable to measurement in experimental settings. However, experimental studies using simulated and actual insect damage have established that the loss of fruiting structures may also disrupt the balance of resource allocations to vegetative versus reproductive structures, resulting in more vigorous vegetative growth (Jubb and Carruth 1971, Tugwell et al. 1976, Sadras 1995, Holman and Oosterhuis 1999, Stewart et al. 2001, Lei and Gaff 2003, Wilson et al. 2003). Whereas plant growth responses to loss of fruiting structures has thus been well established using experimentation, it is currently unknown if this translates into changes in farmer crop management practices. I hypothesize that farmers may respond to this increase in vegetative growth with increased applications of mepiquat chloride.

Too vigorous vegetative growth ("rank growth") may also create a problem for farmers at the end of the growing season, when cotton plants need to be defoliated to allow lint to dry before harvest. One or more foliar applications of chemical defoliants are applied at the end of the season to trigger the shedding of leaves, but the abscission response is less readily initiated when plants are still growing vigorously (Roberts et al. 1996). Thus, one might also hypothesize that *Lygus* herbivory may trigger additional use of defoliants.

Finally, if farmers do not increase their defoliant applications sufficiently, another possibility is that excessive vegetative growth could lead to incomplete defoliation. Incomplete defoliation in turn could cause a decrease in lint quality through (1) lint staining by green leaves; (2) inadequate lint drying and a consequent increase in the risk of lint-yellowing microbial activity in the harvested seed cotton during storage before ginning; or (3) an increased risk of leaf fragments remaining in harvested lint (Roberts et al. 1996). In summary, farmer decisions to increase the use of plant growth regulators and defoliants, in addition to possible effects on lint quality, are candidates for costs of *Lygus* herbivory that may be important in a commercial setting, but difficult to address in an experimental setting, where crop management decisions are made by research staff rather than by the farmers themselves.

The sensitivity of cotton to *Lygus*-induced loss of young flower buds may decrease during the ontogeny of the cotton plant. Young plants have a relatively high supply:demand ratio for photosynthate, and can potentially convert each flower bud that they initiate into a mature fruit; however, as plants grow, the supply:demand ratio decreases dramatically, such that many flower buds are abscised even if they remain undamaged (Gutierrez et al. 1991). Thus, older plants may have a greater capacity to absorb *Lygus* herbivory with little if any shifts in growth form (Sadras 1995). For this reason, in the analyses presented below I divide the fruiting season into two segments: early season (late May through June; this is roughly the preflowering period), when we expect greater sensitivity to *Lygus* herbivory, and mid-season (July), when we expect diminished sensitivity.

The goals of this study were therefore to explore the possibility that *Lygus* populations are producing economic damage through any of three possible effects: (1) by eliciting increased applications of the plant growth regulator mepiquat chloride; (2) by eliciting increased applications of defoliants; or (3) by impeding effective defoliation, and thence reducing cotton lint quality.

Materials and Methods

The data set was built exclusively by collecting preexisting data ("data mining") from commercial cotton farming operations in California's San Joaquin Valley. Data were obtained from four 'independent' pest control consulting firms; independent consultants are those who do not sell agricultural chemicals, but rather provide intensive pest sampling services and management recommendations. Consultant records describing agricultural chemical applications were supplemented with data obtained from the California Department of Pesticide Regulation's on-line Pesticide Use Reporting system (Epstein and Bassein 2003). The final data set for analyses of plant growth regulator and defoliant use included observations for 455 Pima cotton and 955 upland cotton crops that were produced by 38 farms between 1997 and 2008.

The analyses focused on four variables: (1) *Lygus* densities, (2) applications of plant growth regulators, (3) applications of defoliants, and (4) cotton lint quality. *Lygus* density estimates were generated by consulting firm personnel. Integration of *Lygus* density estimates from different consultants into a single data set was straightforward, because a standardized sampling methodology has been adopted by nearly the entire industry in California: the sweep net. A single sweep sample is made by executing 50 swings of a sweep net across the top of the plant canopy; all *Lygus* collected, including nymphs and adults, are counted and recorded. Consultants typically sampled in 3–6 locations per field depending on field size, with 2–3 sweep samples per location, for a total of 6–12 samples per field. Fields were sampled approximately weekly, beginning with cotton squaring (late May to early June) and continuing until early August. Mean *Lygus* densities during two time periods, June (from the start of sampling until 30 June) and July (1–31 July) were calculated as the area under the curve of mean *Lygus* density versus time ("insect-days," where densities between successive samples were estimated with linear interpolation) divided by the number of days between the first and last sample. This was preferred over a simple averaging of density estimates, because sampling intervals were sometimes unequal. *Lygus* populations in California cotton are heavily dominated by *L. hesperus* Knight, but may occasionally include *Lygus elisus* Van Duzee (Mueller et al. 2005). As these congeners are not distinguished during commercial scouting, all observations refer to their combined density.

When plant growth regulators or defoliants were applied to the entire field on any given date during the growing season, the count of applications was incremented by 1.0. When applications were made to only part of the field, the count of applications was incremented by the proportion of the field's area that was treated. Tank mixes of multiple active ingredients are common in defoliation treatments, but were still recorded as a single application.

An opportunity to provide a preliminary examination of *Lygus* effects on lint quality, as recorded by automated lint color grading at the cotton gin for each bale of harvested cotton lint, was afforded by one large grower who provided cotton lint quality data for 39 Pima and 150 upland cotton crops grown between 2003–2008. Lint quality grading systems differ somewhat for Pima versus upland cotton. Pima cotton is placed into one of six color grade classes, whereas upland cotton is graded separately for two quality variables, reflectance and brightness/yellowness, creating a larger number of grade class combinations. I calculated mean color grade (for Pima cotton) and mean reflectance and brightness/yellowness grades (for upland cotton) measured across all bales harvested in a particular crop. I also calculated the total proportional loss of crop value by averaging the price discounts associated with the observed color grades, using the spot market data reported by the U.S. Department of Agriculture on 12 June 2012 (U.S. Dep. Agric. Agricultural Marketing Service 2012). All data were managed in a customized relational database ("*Cottonformatics*") designed by a private software developer (Ten2Eleven Business Solutions) and programmed in SQL Server.

Statistical Analyses. The number of applications of plant growth regulators or defoliants applied to a given cotton crop were not strictly integer value variables, because applications to portions of fields occurred in some cases. It was not possible, a priori, to specify the form of any relationship that might exist between *L. hesperus* densities and the use of plant growth regulators or defoliants. Therefore, I analyzed the data using a flexible, nonlinear regression method, Generalized Additive Models (GAM), which allow the data to "speak for themselves" in suggesting the form of the function. GAMs also provide an objective means of avoiding the over-fitting of the data by penalizing excessive 'wiggliness' of the fitted curve, as quantified by the second derivative of the function ("generalized cross validation"). GAMs were constructed using R version 1.7–6, program mgcv (Wood 2006). Standard model checking plots (quantile-quantile, distributions of residuals, residuals vs. linear predictors, and response vs. fitted values) were performed for all models. Linear analysis of covariance (ANCOVA) models were also fit to confirm the main underlying trends, with *Lygus* density included as a continuous covariate. The ANCOVA models were also used to explore the possibility that early and late *Lygus* densities might interact in their associations with plant growth regulator or defoliant use (generalized additive models assume additivity, and thus are not appropriate for testing interaction terms). As these interaction terms in all cases failed to approach significance ($P > 0.15$), they are not reported. ANCOVA results are also reported below in the analyses of lint quality and to project rough cost estimates for the observed changes in plant growth regulator and defoliant applications.

Results

Farmers recorded regular use of both plant growth regulators and defoliants on their cotton crops. Pima cotton crops ($N = 455$) received an average of 1.05 ± 1.03 (mean ± SD; range: 0–4.22) applications of plant growth regulators and 1.76 ± 0.55 (range: 0–3.34) applications of defoliants. Equivalent numbers for upland cotton crops ($N = 955$) were 1.27 ± 1.05 (range: 0–5) and 1.66 ± 0.63 (range: 0–3.69). Because defoliants are absolutely required for harvest, crops for which zero defoliant use was reported ($n = 11$ out of 455, 2.4% of the total for Pima, and $n = 48$ out of 955, 5.0% of the total for upland) give some insight into the degree of underreporting. Records reporting zero defoliant use were excluded from analyses of *Lygus* associations with defoliant use.

Lygus densities during the early period of flower bud production (June) were positively correlated with densities observed during the mid-season (July) for both upland and Pima cotton ($P < 0.0001$). However, the correlations were of only intermediate strength for Pima cotton ($R^2 = 0.498$; $N = 444$) and were relatively weak for upland cotton ($R^2 = 0.189$; $N = 907$). Thus, whereas this multicolinearity might have made it difficult to disentangle effects of June versus July *Lygus* on Pima cotton, such effects were not found (see below), eliminating the possible problem. For upland cotton, there were ample opportunities to separate these effects of these two successive time periods.

On upland cotton, associations between *Lygus* densities and farmer decisions to apply plant growth regulators or defoliants varied with the time period of *Lygus* herbivory. *Lygus* populations present early during squaring (June) were associated with increased applications of plant growth regulators (Fig. 1A; Table 1). The GAM analysis revealed some modest nonlinearities in this association (Fig. 1A), but the generally positive association was also supported by the ANCOVA: for each integer increase of mean *Lygus* count

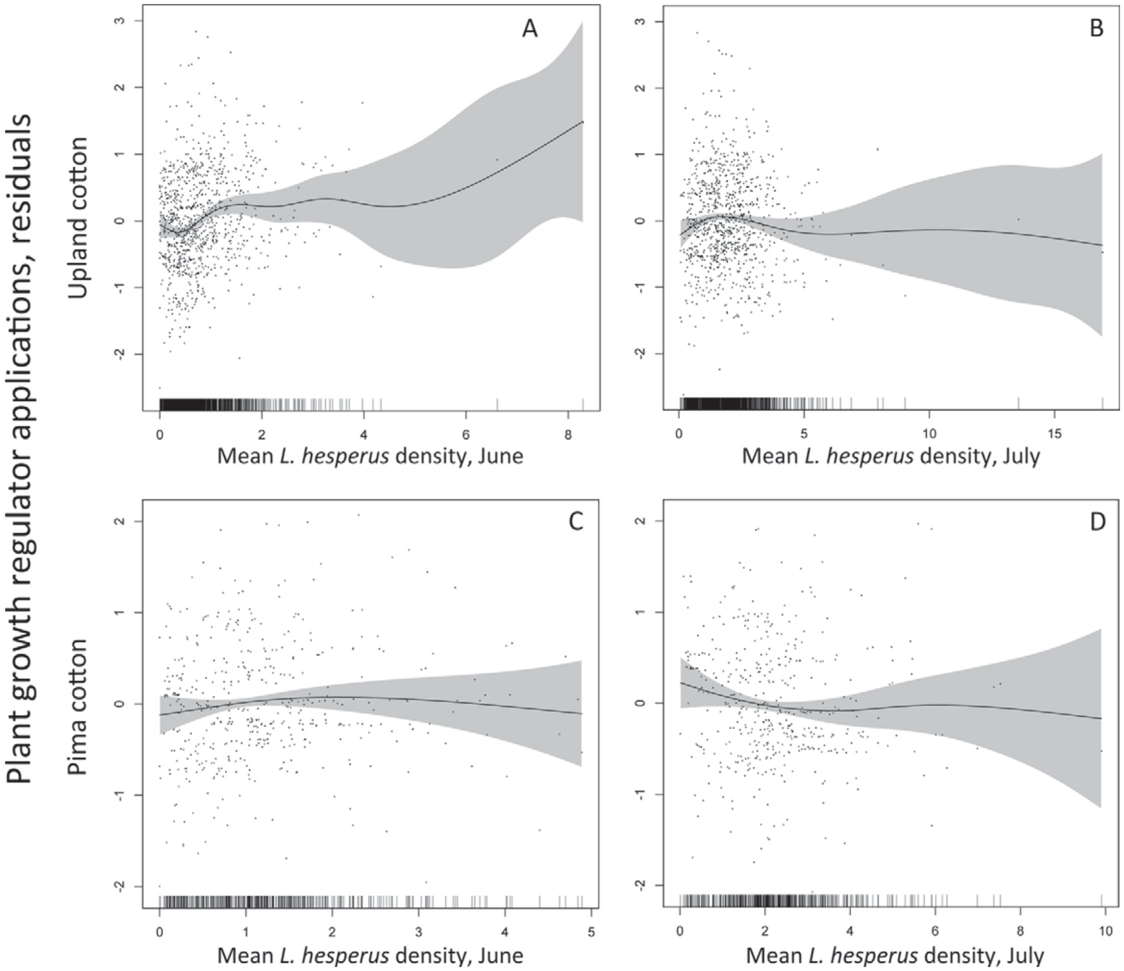

Fig. 1. Associations between *Lygus* population densities during the early- (June, panels A and C) and mid-fruiting (July, panels B and D) periods and the mean number of plant growth regulator applications made to upland cotton (panels A and B) and Pima cotton (panels C and D). Numbers of plant growth regulator applications are residuals after controlling statistically for effects of farm and year. The solid lines are the smooths from the GAM models, and the shaded regions are the 95% CIs.

during June, the mean number of plant growth regulator applications increased by 0.186 ± 0.047 ($F = 15.8$, $P < 0.0001$). This association disappeared, however, during July, when *Lygus* populations showed no association with plant growth regulator use (Fig. 1B; Table 1). *Lygus* densities showed a different temporal pattern of association with defoliant use. During June, *Lygus* densities exhibited a complex, highly nonlinear relationship with defoliant use (Fig. 2A; Table 2); ANCOVA suggested the absence of an underlying linear trend ($F = 2.27$; $P = 0.13$). In contrast, *Lygus* present during July were associated with *decreased* use of defoliants (Fig. 2B; Table 2), contrary to initial expectations. The GAM suggested only modest nonlinearities in this relationship, and the ANCOVA confirmed a significant negative relationship, with the mean number of defoliant applications dropping by 0.058 ± 0.018 with each integer increase in *Lygus* densities ($F = 9.87$; $P = 0.0017$).

Table 1. GAMs for factors associated with the no. of plant growth regulator applications made to upland cotton (full model: deviance explained = 54.7%; $N = 955$) and Pima cotton (full model: deviance explained = 58.9%; $N = 455$) during either the early (June) or middle (July) period of fruiting

Source	(Effective) df	*F* ratio	*P*
Upland cotton			
Farm	38	20.77	<0.0001
Year	10	5.95	<0.0001
June *Lygus*	6.4	3.52	0.0007
July *Lygus*	4.57	1.52	0.17
Pima cotton			
Farm	24	14.99	<0.0001
Year	9	16.32	<0.0001
June *Lygus*	1.90	0.78	0.48
July *Lygus*	2.58	0.83	0.49

On Pima cotton, *Lygus* densities present during either June or July were not significantly associated with farmer decisions to apply either plant growth regula-

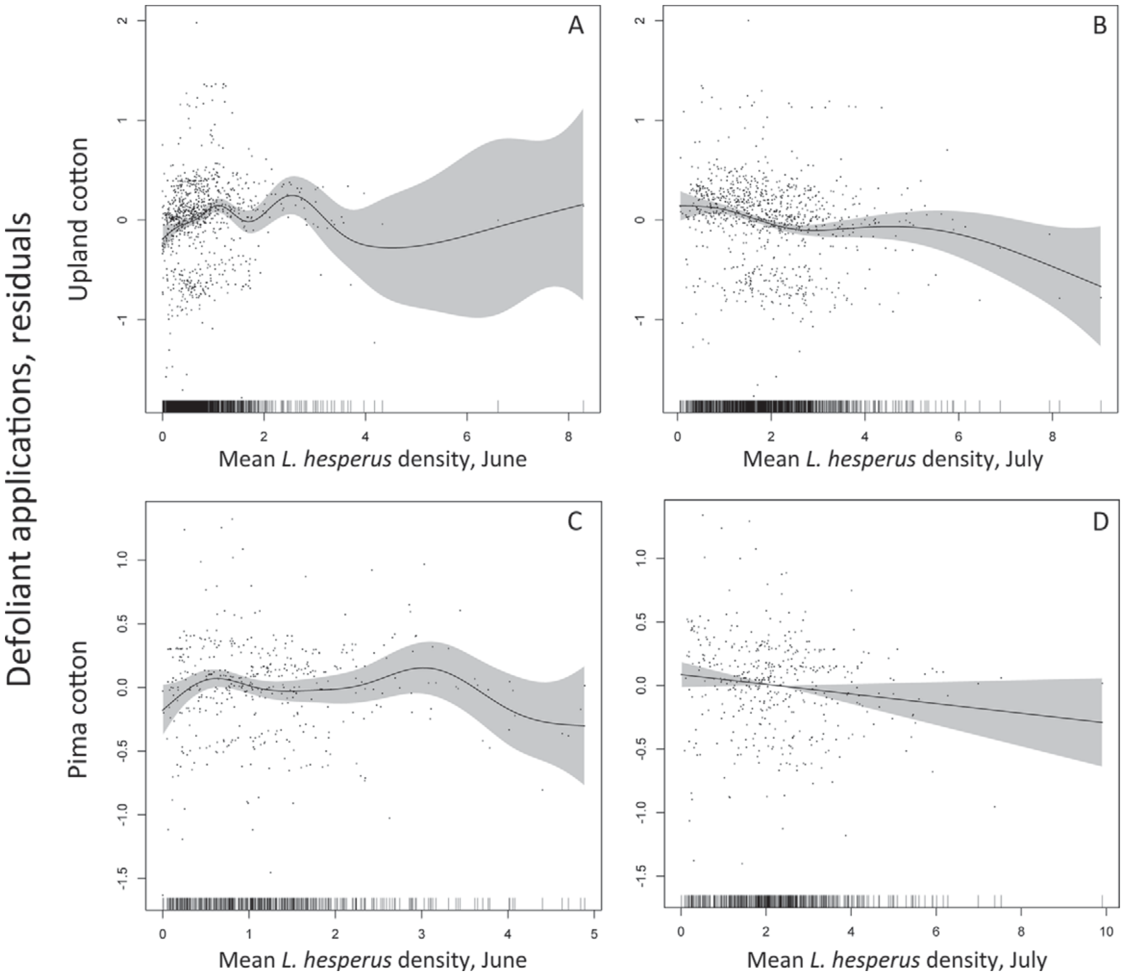

Fig. 2. Associations between *Lygus* population densities during the early- (June, panels A and C) and mid-fruiting (July, panels B and D) periods and the mean number of defoliant applications made at the end of the growing season, before harvest for upland cotton (panels A and B) and Pima cotton (panels C and D). Numbers of defoliant applications are residuals after controlling statistically for effects of farm and year. The solid lines are the smooths from the GAM models, and the shaded regions are the 95% CIs. Note that because the GAM penalizes the second derivative of the fitted curve, the model collapses to linearity when evidence for nonlinearity is sufficiently weak, as is seen in panel (D).

tors or defoliants (Figs. 1C and D, 2C and D). All GAM analyses were nonsignificant (Tables 1 and 2), and ANCOVA failed to reveal any significant linear trends ($P > 0.3$ in all cases). Thus, Pima cotton, with its highly indeterminant growth, did not appear to shift its growth in a way that elicited changes in farmer management of plant growth.

Table 2. GAMs for factors associated with the no. of defoliant applications made to upland cotton (full model: deviance explained = 33.4%; $N = 907$) and Pima cotton (full model: deviance explained = 41.5%; $N = 444$) during either the early (June) or middle (July) period of fruiting

Source	(Effective) df	*F* ratio	*P*
Upland cotton			
Farm	38	7.39	<0.0001
Year	10	2.81	0.0020
June *Lygus*	7.97	2.97	0.0020
July *Lygus*	4.36	4.14	0.0007
Pima cotton			
Farm	23	6.93	<0.0001
Year	9	10.61	<0.0001
June *Lygus*	6.09	1.89	0.068
July *Lygus*	1	2.76	0.098

No associations between June or July *Lygus* population densities and cotton lint quality or expected price discounts were observed for either upland or Pima cotton (ANCOVA, $P > 0.3$ in all cases; analyses performed with the subset of records for which lint quality measurements were available; data not shown), suggesting that crop defoliation was sufficient to avoid problems at harvest.

Discussion

I analyzed an observational data set gathered from the commercial farming setting as a case study of a research problem whose solution demands knowledge of farmer decision-making. The study focused on the possibility that *Lygus* herbivory on cotton might impose economic damage by eliciting increased use of plant growth regulators or defoliants. Such a response would not have been easy to address with traditional experimentation, because farmer behavior is typically excluded from experimental research settings. The analyses revealed changes in farmer crop management decisions associated with *Lygus* herbivory, at least for upland cotton. When *Lygus* populations are present in upland cotton during June, they were associated with increased applications of the plant growth regulator mepiquat chloride, but not with increased applications of defoliants at the end of the growing season (Figs. 1 and 2). This result suggests an early season period of crop sensitivity to *Lygus* herbivory. This result was not, however, observed for Pima cotton: early herbivory did not appear to be associated with increased use of either plant growth regulators or defoliants. Applications of plant growth regulators and defoliants are moderately expensive (approximately US$42 and US$95 per ha per application, respectively, including the costs of materials and aerial application; Hutmatcher et al. 2012). Because only a small fractional increase in application number was associated with each integer increase in *Lygus* density, the costs from June *Lygus* herbivory on upland cotton because of increased use of plant growth regulators will be modest (using the linear ANCOVA model, costs are projected to increase by US$11.90 per ha for every integer increase in June *Lygus* density), but not negligible. This cost appears to be roughly comparable to the cost of using insecticides to suppress June *Lygus* populations generated by the increased risk of secondary pest outbreaks (ca. US$15/ha; Gross and Rosenheim 2011).

The most important result, however, was the contrast between the *Lygus* effects observed during June versus those observed during July. I found no evidence for any change in farmer use of plant growth regulators on upland or Pima cotton in association with July *Lygus* populations. Defoliant use on Pima cotton similarly showed no association with July *Lygus.* However, on upland cotton, July *Lygus* populations were unexpectedly found to be associated with decreasing use of defoliants (Fig. 2B); a significantly negative slope was confirmed with the linear ANCOVA model ($F = 0.87$; $P = 0.0017$). This implies that July *Lygus* may actually save growers from some of the expense of defoliating their cotton crop (the linear ANCOVA model suggests a saving of US$6.03 for each integer increase of mean July *Lygus* densities). This result, in combination with ongoing work suggesting minimal effects of July *Lygus* herbivory on cotton yield (unpublished data), will be critical in encouraging farmers to recalibrate their management approach to *Lygus* during July, when most applications are currently made.

Because farmers currently respond to mid-season *Lygus* with aggressive applications of insecticides, often using a treatment threshold of 4–5 *Lygus* per sweep sample, higher *Lygus* densities are largely excluded from the commercial setting. The data set analyzed here includes many observations for July *Lygus* densities ranging up to a mean of 6.0 *Lygus* per sweep sample, but then only scattered observations up to a maximum of ≈10.0 *Lygus* per sweep sample. In the absence of insecticide use, still larger populations of *Lygus* would be likely to develop on occasion. It is important to note that an ecoinformatics approach like the one used here cannot ask what would happen under such a hypothetical scenario of relaxed control, although experimental studies suggest that yield losses should eventually be expected (Ellsworth and Barkley 2001). Observational studies like the one reported here are constrained to the analysis of existing variation. What the current data do suggest, however, is that cotton responds to mid-season herbivory by low to moderate densities of *Lygus* (≤10 *Lygus* per sweep sample) without the shifts in plant growth form that trigger extra applications of plant growth regulators or defoliants by farmers.

Upland versus Pima Cotton. Early season *Lygus* herbivory was found in this study to be associated with increased use of plant growth regulators only for upland cotton, and not for Pima cotton. Why might this difference emerge? One possible explanation flows from an underlying difference in the degree to which fruit production is indeterminate in these two closely related *Gossypium* spp. The weight of each fruit is substantially smaller for Pima cotton than for upland cotton (Gutierrez et al. 1991). Because the rate of fruit initiation by upland and Pima cotton are relatively similar during the early- and mid-fruiting period, Pima cotton is slower to reach a point where demand for photosynthate by developing fruits exceeds supply (Gutierrez et al. 1991). For this reason, Pima cotton produces fruit for longer and demands a longer growing season than does upland cotton. Pima cotton may, therefore, be almost universally in a state of strong vegetative growth through June and July, regardless of whether or not it sustains increased square abscission because of *Lygus* herbivory. Thus, grower management of Pima growth may be largely insensitive to *Lygus* population densities. In contrast, upland cotton with a heavy early fruit set may rapidly decelerate its vegetative growth as demand by large fruit for photosynthate outstrips plant supply, reducing the need for applications of mepiquat chloride. This natural brake on vegetative growth may be more readily disrupted by *Lygus*-induced abscission of young squares.

Inferences of Causality. Ecoinformatics studies that use strictly observational data sets must be very cautious about drawing causal inferences. It is for this reason that I have talked about ‘associations’ between *Lygus* densities and changes in farmer decision-making in this manuscript, rather than asserting that fluctuations in *Lygus* densities are an ultimate cause. How likely is it that this association is, in fact, an expression of an underlying causal link? As noted in the introduction, experimental studies have consistently demonstrated a causal relationship between *Lygus* herbivory, altered source-sink relationships for plant resources because of loss of squares, and resulting increases in plant vigor, often reflected in increased plant height (Jubb and Carruth 1971, Tugwell et al. 1976, Sadras 1995, Mann et al. 1997, Holman and Oosterhuis 1999, Stewart et al. 2001, Lei and Gaff 2003, Wilson et al. 2003). These plant responses to *Lygus* herbivory are clearly expected to increase the need for mepiquat chloride (Kerby et al. 1996, Roberts et al. 1996). It is for this reason that I hypothesized, a priori, that farmers would respond to *Lygus* with increased use of mepiquat chloride. Of course, just because this causal pathway was readily anticipated does not prove that it is, in fact, responsible for the associations observed in this study. However, the predictable appearance of this association is at least consistent with a causal link. In contrast, the observed association of July *Lygus* populations with decreased use of defoliants was entirely unexpected, and its basis remains unknown; both causal and noncausal explanations probably warrant further exploration.

If the association between *Lygus* densities and farmer use of plant growth regulators does reflect an underlying causal relationship, then the timing of *Lygus* damage and farmer decision-making is consistent with only one plausible direction of causality. Mepiquat chloride applications are generally made during July. Thus, it is plausible that mepiquat chloride use could be influenced by June *Lygus* herbivory, but not the reverse.

In conclusion, farmer decision-making can play a key role in modulating the costs and benefits of different pest management programs (Savary et al. 2012). Anticipating farmer behavior may, however, be difficult in the absence of direct observations. A weakness of the traditional experimental paradigm in agricultural entomology is that the farmer is excluded from the research setting, leaving us without the direct observations that we need. Observational data sets from the commercial farming setting can be useful in this regard as a tool that complements experimentation. Here I present a case study of the analysis of such a farmer-derived observational dataset. Decisions by farmers to apply more plant growth regulators were found to be associated with June, but not July, *Lygus* populations in upland cotton. Ecoinformatics studies may be useful in addressing a broad range of questions in pest management research (Rochester et al. 2002, de Valpine et al. 2010, Steinmann et al. 2011, Breukers et al. 2012, Bürger et al. 2012) and agricultural research more broadly (Jiménez et al. 2009), and may have a special role in including the human element of the agroecosystem.

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