Optimal Cotton Insecticide Application Termination Timing: A Meta-Analysis

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Selected Paper prepared for presentation at the Southern Agricultural Economics Association's 2015 Annual Meeting, Atlanta, Georgia, January 31-February 3, 2015

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ABSTRACT
The timing to terminate cotton insecticide applications are disputed among investigators. Nine publically available studies meeting selection criteria were synthesized to identify and develop a comprehensive optimal termination timing principle. The meta-database included 247 trial observations from 53 independent field experiments from the cotton belt between 1993 and 2007. Agronomic optimal timing to terminate insecticide applications when yield reached a plateau was estimated using an original econometric approach. Novel econometric methodology were developed to address multiple time points from multiple means comparison studies. Meta-analysis methodologies along with stochastic plateau theory were used to determine the shape of the functional form of both the optimal agronomic insecticide termination time and corresponding cotton yield potential. The proposed methodology can be extended to other crops and associated limiting factors of production, for further economic analyses. Results provided insights useful to improve production systems by applying inputs only when benefits were expected to be in excess of the respective costs. In addition to estimating the specific number of accumulated heat units needed to reach an overall cotton yield plateau, the developed meta-analysis framework evaluated whether field research results converged to an overall 'true' insecticide termination timing thereby addressing the question whether funding sources properly invested resources in later years.

Keywords: insecticide application termination, yield plateau, mixed effects model, multiple time points

JEL Codes: Q10, C10

INTRODUCTION

Agricultural scientists report on a plethora of topics and many times a large number of studies on any given topic with disparate conclusions. Farmers and their advisors make farm management decisions based on these research-based results that may not be consistent. For example, insecticide application termination timing (Bourland et al., 1992) has been studied extensively in cotton with respect to physiological cutout and last economic application of insecticide, and no overall conclusion have been achieved (Cochran et al., 1999; O'Leary et al., 1996).

Cotton farmers and researchers need to know the functional relationship relating cotton yield and timing of insecticide application termination such that they can identify when the cost of the next application is not offset by reduced cotton lint yield penalties. Thus, the need for a reliable and valid method to synthetize publically available research information. To this aim, meta-analysis techniques can be used to develop a comprehensive optimal termination timing principle.

Meta-analysis refers to a collection of rigorous and systematic statistical techniques geared towards providing a quantitative review of the literature, and an assessment of the "bottom line" of a series of previous empirical studies. Meta-analysis can be thought of as analysis of previous analyses (Hunter and Schmidt, 1990) or more specifically as a statistical approach to review and summarize quantitative empirical results of previous studies (Stanley, 2001).

Individual field experiments typically evaluate a set of discrete insecticide termination times and the results are reported as multiple treatment means comparisons. However, the analysis of multiple outcomes or time-points studies is an emergent subject of research in the meta-analysis literature, and little conceptual and empirical work has been conducted to analyze multiple treatment agricultural field experiments.

In this article we present a methodological framework that addresses the synthesis of publicly available research reporting on multiple time point treatments along with an econometric model for meta regression analysis (MRA). These techniques can easily be applied to other agricultural field studies such as irrigation initiation timing and nitrogen application rates. The specific objectives of this study were to 1) present our newly developed methodology that analyzes multiple time point data from previous multiple means comparison studies, 2) apply this methodology to insecticide termination timing decision rules for cotton production, and 3) use meta-analysis results to test for overall convergence of research results over time . The primary contribution of this paper is to provide a meta-regression methodology for the analysis of multiple time point studies in agronomy, livestock, or other sciences where timing is of concern to researchers and practitioners.

BACKGROUND AND LITERATURE REVIEW

Insecticide Termination Timing

Since 1993, at least 21 papers have been reported on optimal insecticide termination timing for cotton. Most have tested arbitrarily chosen heat units after some physiological growth stage. The heat units (HU) tested were loosely based on those proposed by O’Leary et al. (1996). Heat unit accumulation are measured after the bloom date of the highest first-position boll that is expected to contribute to yield, and assumed to occur at nodes above white flower equal to 5.0 (NAWF5) (O’Leary et al, 1996). Daily heat unit reported as growing degree days base 60 are calculated as

(1) $$GDD_{60} = \frac{T_{max}+T_{min}}{2} - 60$$

where T_{max} is the daily maximum temperature and T_{min} is the daily minimum temperature.

Accumulated HU are the summation of daily heat units after an event, such as NAWF5 physiological growth stage. Yields at the treatment levels are multiple outcomes or time-points within an experiment (Borenstein et al., 2009)

Insecticide application does not directly influence plant growth or yield but rather eliminates yield damaging insects such that yield penalty is avoided (Zhang et al. 1994), therefore the yield response to termination timing is expected to plateau at some time after physiological maturation (i.e., when cotton bolls are no longer susceptible to insect damage) (Figure 1). Thus, additional insecticide applications after the termination time associated with the occurrence of the yield plateau have no further economic or agronomic benefits.

Meta-analysis Methodology

Meta-analysis can be thought of as a quantitative literature review aimed to analyze and summarize empirical results of previous studies (Stanley, 2001). See Cooper et al. (2009) and Borenstein et al. (2009) for a complete overview of meta-analysis. Meta-analysis had its origins in agriculture. Although not formally referred to as meta-analysis until the mid 1970's by Glass (1976), the general thought of combining estimates from several small sample studies was discussed in agricultural terms over 40 years earlier by Tippett (1931) and obtaining a single test for significance of the aggregated probability from observed probability by Fisher (1932). These pioneers in agricultural statistics presented the foundation for assimilating studies together and using the effect sizes to weight the influence of a given study by its precision. However, even though the idea of meta-analysis was born in the agricultural production sciences, meta-analysis has been circumvented almost entirely in agriculture with general agricultural discipline studies as exceptions until recently.

Meta-analysis methods have been used to synthesize research output from studies in areas such as medicine (Caldwell et al., 2006; Cipriani et al., 1999; DerSimonian and Laird, 1986), psychology (Barrick and Mount, 1991; Kluger, DeNisi, 1996), and agriculture. Agricultural examples include organic (Bengtsson et al., 2005), wetlands (Woodward and Wui, 2001), economic development (Alston et al., 2000; Thiam et al., 2005), forecasting (Armstrong, 1994), elasticities (Espey and Thilmany, 2000; Espey and Espey, 2004; Nijkamp and Pepping, 1998), production risk (Marra and Schurle, 1994), developmental economics (Phillips, 1994; Raitzer, 2003; Thiam et al. 2001), plant pathology (Rosenberg et al., 2004; Shah and Dillard, 2006), cover crops (Miguez and Bollero, 2005), carbon markets (Manley et al., 2005), impacts of agricultural policy (Oltmer and Florzx, 2001), and crop production (Burzaco et al., 2014; Tremblay et al., 2013; Treseder, 2004).

In terms of multiple time point studies, Caldwell (2005), Cipriani et al. (2009), Rosenberg et al. (2004), and Shah and Dillard (2006) used meta-analysis to evaluate multiple treatments; however, no meta-analytic methods were identified to evaluate multiple time point results from multiple comparison agricultural studies. Trikalinos and Olkin (2012) report multiple time points in a clinical trial although not for multiple means comparisons. Borenstein et al. (2009) address multiple time points with respect to inference on the response variable in their book; however, no literature evaluating categorical treatment levels were found.

The most common statistical technique for multiple means comparison (MMC) in agricultural field sciences is analysis of variance (ANOVA) using Fisher's Least Significant Difference (LSD). MRA techniques have been developed for pairwise comparisons reported as ANOVA but not for MMC and in particular multiple time points. Most agricultural field experiments compare multiple categorical treatments or multiple rates of a treatment, and our meta-database is no different. Multiple comparison studies have not been subjected to meta-analyses as readily as paired comparisons and little methodology exists regarding this idea (Caldwell et al., 2005; Rosenberg et al., 2004).

DATA

Research Literature Retrieval, Compilation and Coding

This study followed meta-analysis research protocols suggested by Stanley et al. (2013). Literature retrieval included studies known *a priori*, basic internet search using Google Scholar, direct solicitation to approximately 500 researchers known to conduct work in the relevant topics via email (February 2009) plus follow-up contact a month later, systematic library keyword searches, casual browsing of tables of contents and reviews, research summaries submitted to Cotton Incorporated as the funding agency, and snowballing. The study selection criteria included: 1) Conducted in the U.S. and written in English, 2) heat unit accumulation measured with respect to NAWF5, 3) primary study evaluated a range of at least three HU timings (i.e. was not a one-tailed test comparing against *status quo* farmer practices), 4) cotton lint yield per unit area could be calculated, 5) a measure of variability (i.e., LSD metric or enough information to estimate it), and 6) primary study results were based on biophysical factors rather than economic. Search terms included “COTMAN”, “cotton”, “insecticide termination”, “end of season decision rules”, “NAWF”, and “cutout”. The literature search ceased September 1, 2014.

Studies reporting cotton lint yield as per boll or per plant without sufficient data to calculate per acre yield did not meet the selection criteria. Data from primary studies based on biophysical factors rather than economic were chosen so that biophysical production functions can be estimated and economic analyses performed on the estimated functions. Primary studies reporting mean treatment effects only on economics were omitted from this meta-analysis since those are not directly comparable across studies and are pertinent only for a given point estimate from the profitability surface.

After an inclusive search for potential studies conducted by the senior author, a total of 135 primary field experiments from 41 individual papers related to end of season decision rules for cotton production were identified, reviewed and coded. However, only 53 primary field experiments fit the selection criteria of this meta-analysis from nine primary papers providing 247 usable observations. Parameters from the nine papers meeting minimal criteria were checked by double entry methodology.

The selected studies for this meta-analysis are summarized in Table 1. The nine studies were published in non-peer reviewed outlets from 1997 to 2008. Primary authors represented the disciplines of entomology, agronomy, and economics from Arkansas, Louisiana, Mississippi, and Texas. The minimum HU evaluated was typically 0, occurring at NAWF5, although some studies had later minimum HU. The maximum HU ranged from 426 to 744, well above the hypothesized 350 optimum HU (Cochran et al., 1999; O'Leary et al., 1996).

Agricultural field experiments tend to be reported as multiple treatment levels of a factor. The *de facto* statistical analysis procedures for agronomic research is the analysis of variance (ANOVA) utilizing a means separation test such as Fisher's Least Significance Difference (LSD) typically evaluated at the $\alpha = 0.05$ level. Some primary studies provide a table (see Figure 2 as an example), others provide graphical representation (see Figure 3 as an example), and other studies provide data in narrative form. Reported LSD metrics were decomposed for each experiment to recover the corresponding mean squared error (MSE). Not all agricultural field studies report LSD metrics, in these cases the summary tables or graphs were used to estimate the upper bound for LSD by examining the difference in yields between statistically different means based on LSD.

The meta-database was constructed by entering the mean treatment effects (cotton lint yield), insecticide termination timing (heat unit accumulation after NAWF5), and the associated MSE for each experiment. Location and year of the considered experiments were also recorded along w ith the authors' stated optimal HU based on LSD. The main descriptive statistics for individual field studies of the meta-database are presented in Table 2.

METHODS AND PROCEDURES

The primary principal investigators conducted field experiments that were essentially multiple outcomes or time-points within a study (Borenstein et al, 2009). Each treatment factor level was a distinct time-point relative to heat unit accumulation after NAWF5. Typically, multiple time-point studies follow the same subjects across different points in time. Consequently, effect sizes based on the same subjects are expected to be correlated. In our context, primary studies evaluated the treatment levels of interest at individual plots within a uniform field, and reported treatment level means based on the same experimental fields. Given small plot experimental designs, time-points or treatment levels within an experimental field can be considered to come from the same subject, i.e. each plot is considered to be the same participant observed at different treatment levels. Therefore, experimental fields from each primary experiment could be considered independent. However, the output variable for primary field experiments, cotton lint yield, is not independent across treatment factor levels; therefore the dependence must be addressed in order to provide reliable estimates.

Based on the information reported on each study, it is possible to identify the 'best' time to cease insecticide applications. Particularly, within an experiment the agronomic optimal time to terminate insecticide application could be defined as the earliest termination time which associated yield is not statistically different from the maximum yield reported in the experiment. The studies considered on this meta-analysis used a LSD test to determine the best time to terminate insecticide applications (henceforth HU^{LSD}). One could be tempted to use the reported HU^{LSD} estimates as the effect size of interest. However, the HU^{LSD} estimates present some severe limitations for further meta-analysis. Namely, meta-analysis typically examines effect sizes derived from primary studies' estimates. In our case, the effect sizes of interest are the arbitrarily chosen treatment levels (HU) and not their corresponding mean yields. Consequently, no variability of the HU used is reported. In fact, the only precision reported on the different experiments was estimated from the original estimate (yield) evaluated for all treatment levels (HU). Specifically, the LSD metric was calculated for the system of multiple comparisons rather than for any individual yield estimate at a given treatment level.

Additionally, HU^{LSD} was reported by authors of primary studies to be the earliest HU that its associated yield is not statistically different from the maximum yield observed in the experiment. Consequently, HU^{LSD} is an undefined boundary measure of the agronomic optimal insecticide termination time (i.e., the true yield plateau could occurred just before or after HU^{LSD}) with no estimate of its own variance available. Given these disadvantages, we attempt to remedy this gap in meta-analysis methodology. Our proposed econometric model addresses the limitations of existing methodologies with respect to using HU^{LSD} or other categorical time point data as the effect size for when yield plateaus.

Meta Regression Analysis (MRA)

In this paper we developed a flexible econometric approach to model both the potential heterogeneity between studies and the distinctive yield plateau of cotton with respect to insecticide termination timing. The proposed model, Meta Plateau Model (MPM), is based on the well-known random effects model used in meta-analysis literature (Brockwell and Gordon, 2001) in combination with random plateau theory (Tembo et al., 2008). The MPM extends the traditional meta-analysis random effect model by defining the overall true effect size not as a single parameter, but as a plateau function. Compared to the random plateau functions suggested by Tembo et al. (2008), individual intercept random effects were estimated by each considered experiment, and the insecticide termination time at which the yield reaches a plateau is modeled in terms of experiment observable characteristics, thus a functional form for both yield potential and insecticide termination time was estimated.

Given a collection of N independent studies, each containing a set of experiments with a finite number of treatment levels, the MPM is specified by the random effects model

(2) $$Y_{ijk} = \mu + \varepsilon_{ijk} + e_{ij},$$

where Y_{ijk} is the observed average yield corresponding to the kth treatment level of the jth experiment in the ith study, μ is the overall mean of all true effects, $\varepsilon_{ijk} \sim N(0, \sigma_{\varepsilon}^2)$ is the between-experiment error, and $e_{ij} \sim N(0, \sigma_{e_{ij}}^2)$ is the within-experiment error. The model in equation (2) assumes that Y_{ijk} is sampled from a distribution with true effect equal to $\theta_{ij} = \mu + \varepsilon_{ijk}$ and variance $\sigma_{e_{ij}}^2$. In turn, the true effect θ_{ij} is sampled from a distribution with mean μ and variance σ_{ε}^2.

A common correlation is introduced to account for the expected dependence among observations from the same experiment. Namely, the variance-covariance matrix of the model described in equation (2) is specified as a block diagonal matrix with block corresponding to the experiments and with each block having a compound-symmetry structure (i.e., diagonal elements equal to $\sigma_{\varepsilon}^2 + \sigma_{e_{ij}}^2$and off-diagonal elements equal to σ_{ε}^2). Therefore, all pairs of observations within the same experiment have a common correlation equal to $\sigma_{\varepsilon}^2 / (\sigma_{\varepsilon}^2 + \sigma_{e_{ij}}^2)$.

The main objective of all considered studies was to determine the best time to terminate insecticide applications, thus different termination times measured as accumulated heat units after NAWF5 were tested in each original experiment. Experiments also differ in terms of the year and location they were conducted. With the aim to incorporate these intrinsic differences between experiments into the analysis, it was assumed that the general mean μ is a function of several explanatory variables including insecticide termination time (HU), time trend beginning at year 1992 (T) and state (S) of each experiment.

The relationship between cotton yield and insecticide applications was further assumed to have a linear response until yield reaches a plateau, where additional insecticide applications have no effect on yield. By specifying the mean of true effects μ as a plateau function, the model in (2) can be rewritten as:

(3)
$$Y_{ijk} = \beta_0 + \beta_1 HU_{ijk} + \beta_3 T_{ij} + \beta_4 S_{ij} + e_i + \varepsilon_{ijk} \qquad \text{if } HU_{ijk} < HU^*$$
$$Y_{ijk} = Y^* + e_i + \varepsilon_{ijk} \qquad \text{if } HU_{ijk} \geq HU^*,$$

where the β's are yield response parameters, HU_{ijk} is the treatment level associated to Y_{ijk}, HU^* are the accumulated heat units (or the agronomic optimal insecticide termination time) required to reach the plateau, Y^* is the expected yield plateau, and independence is assumed across the two random components. It can be shown that for a continuous yield function, when $HU_{ijk} \geq HU^*$ the yield plateau parameter (Y^*) is equal to $Y^* = \beta_0 + \beta_1 HU^* + \beta_3 T_{ij} + \beta_4 S_{ij_i}$.

Additional flexibility is added to the model by allowing HU^* to be a function of the year and location of each experiment. Namely, the agronomic optimal insecticide termination time of the jth experiment from the ith study is given by

(4) $$HU_{ij}^* = \alpha_0 + \alpha_1 T_{ij} + \alpha_2 S_{ij},$$

where the α's are parameters to be estimated. Therefore, different critical values of HU^* are estimated for each observed combination of year and location.

The MPM model was estimated by maximizing its restricted maximum likelihood (REML) function using the statistical software R (R Core Team, 2014). As suggested by Rosenberg et al. (2004) and Brockwell and Gordon (2001), the variance of the within-experiment errors ($\sigma_{e_{ij}}^2$) were substituted by the corresponding experiment MSE metrics and treated as known constants during the optimization.

Overall Insecticide Termination Time and Convergence

Estimates from the Meta Plateau Model can be further used to create a general estimate for the agronomic optimal insecticide termination time. Specifically, the estimated optimal termination time of each experiment (HU_{ij}^*) can be aggregated using the standard meta-analysis fixed effect model (Brockwell and Gordon, 2001; Rosenberg et al., 2004), where the overall optimal insecticide termination time is estimated as a weighted average of the individual HU_{ij}^* with a weight assigned to each experiment proportional to $w_{ij} = 1/v_{ij}$; where v_{ij} is the estimated variance of HU_{ij}^*. Thus, the overall insecticide termination time ($\overline{HU^*}$) is calculated as

(5) $$\overline{HU^*} = \boldsymbol{w}`\boldsymbol{HU},$$

where $\boldsymbol{w}$ is a vector of weights and $\boldsymbol{HU}$ is the corresponding vector of HU_{ij}^*. The standard error of $\overline{HU^*}$ is given by

(6) $$SE(\overline{HU^*}) = (\boldsymbol{w}`\boldsymbol{V}\boldsymbol{w})^{1/2},$$

where $\boldsymbol{V}$ is the estimated variance-covariance matrix of $\boldsymbol{HU}$.

Convergence over time of the mean insecticide termination time ($\overline{HU^*}$) was tested by comparing $\overline{HU^*}$ estimates at different periods. Namely, given P periods, $\overline{HU^*}$ at period p ($\overline{HU^*}_p$) is calculated by including the n_p experiments conducted at and before period p, such that the estimate of the last period ($\overline{HU^*}_P$) includes all the experiments in the meta-database. Then, the $P-1$ different $\overline{HU^*}$ estimates are compared to the overall mean $\overline{HU^*}_P$ using the following hypotheses

(7) $$H_0^p: \ \overline{HU^*}_p = \overline{HU^*}_P \qquad \text{for } p = 1,2, \ldots . P-1,$$

where the corresponding *t*-statistics are given by $t_p = (\overline{HU^*}_p - \overline{HU^*}_P)/SE(\overline{HU^*}_p)$, and t_p under the null hypothesis has a *t*-distribution with $n_p - 1$ degrees of freedom. Converge of $\overline{HU^*}$ is declared at period p, where current and subsequent $\overline{HU^*}_p$ are not statistically different from the overall insecticide termination time $\overline{HU^*}_P$.

RESULTS

Exploratory Data Analysis

Main statistics of the meta-database are presented in Table 2, including year and state of the field experiment, primary authors' suggested optimum heat unit timing (HU^{LSD}), MSE, and the minimum and maximum values of both yield and HU. All 4 states conducted field experiments in the earlier years while the most recent studies were only in Arkansas. The annual frequency of primary studies peaked in the mid-1990's; the earliest studies meeting criteria of this study were in 1993 and continued through 2007 (Figure 4) with a noticeable void from 2000-2006. Given that research funding continued after the peak number of field studies in 1995, no indication of whether the 'true' relationship between cotton lint yield and insecticide application termination were ever achieved. It is suspected that if interest waned but no consensus was achieved that the histogram would appear to be normal or bell-shaped. It is also suspected that if a consensus were achieved, then no further research funding would have supported additional studies thus a sharp decrease in number of studies and a truncated histogram distribution would be observed. In our dataset, the histogram appears roughly normally distributed (Figure 4) so we assume no consensus of field researchers and funding agency were drawn.

Exploratory analysis was also conducted on the reported insecticide termination timings (HU^{LSD}). In the absent of a specific measure of the variability of HU^{LSD}, we decided to use the variability of the whole field experiment (i.e., MSE) as a proxy of the precision measure of HU^{LSD}. This measure of variability was considered to be the estimated precision of each experiment. The last agronomic insecticide application timing suggested by each field experiment relative to the estimated precision with which the timing was chosen is graphed in Figure 5. It should be noted that the majority of principal investigators chose the discrete time-points tested as per O'Leary et al. (1996), which are 0, 200, 350, 500, and 650 HU after NAWF5. Time-points were not identically the same in every primary field experiment. In addition, the chosen optimal time-point (HU^{LSD}) does not indicate a 'true' timing for that primary experiment given that it represents a range between the next earlier time-point and the next later time-point.

Publication bias is a concern in meta-analysis. Sutton et al. (2000) state that "the simplest and most commonly used method to detect publication bias is an informal examination of a funnel plot" (Stanley, 2005 p. 1574). The traditional funnel plot is a scatter diagram of precision versus the non-standardized regression coefficient effect size (Egger et al., 1997). Rather than a traditional 'funnel' shaped plot, Figure 5 indicates that HU^{LSD} increased as precision of the primary experiment increased. The general trend is for inverse normalized root mean squared error (NRMSE) to increase as HU^{LSD} increases especially when ignoring HU^{LSD} equal to zero. The most precise measure of HU^{LSD} occurred at nearly 300 HU. The year that primary field experiments were conducted are also presented in Figure 5. No clear pattern in progression of primary results were visually apparent, however, higher termination times are observed in more recent year without an evident change in the HU tested in the field experiments.

State-level differences in HU^{LSD} were expected. It was hypothesized that lower latitudes would have lower optimal HU with which to terminate insecticide application. The highest HU^{LSD} in Texas occurred at less than 250 HU while Louisiana and Mississippi both had HU^{LSD} above 350 HU after NAWF5. Arkansas had only one observation that was strictly positive at 200 HU after NAWF5.

Several primary field experiments reported optimal HU as earliest HU tested. Thirty-eight of the 53 primary studies reported that yields at the earliest termination timing tested were not statistically significantly different from the maximum yield, i.e. there was no benefit to continued application of insecticide in 72% of the studies. No HU^{LSD} were reported less than 200 HU when considering only field experiments reporting HU^{LSD} not as earliest HU tested (Table 2). The distribution of HU^{LSD} values are presented as a histogram in Figure 6. The majority of HU^{LSD} occur before 200 HU; providing indication that the estimated optimal insecticide termination time may occur sooner than the hypothesized 350 heat units after NAWF5 (O'leary et al., 1996). Although a range of heat unit timings were tested, the literature revealed that the implicit hypothesis of less than 350 heat units after NAWF5 were being tested.

Given the large proportion of field experiments exhibiting no yield response to when insecticide applications ceased, either insect pressure was not sufficient to impact yields or time-points chosen were not sufficient to determine optimal timing. Cotton yield often has no response to applied inputs. Griffin et al. (2014) and Main et al. (2013) reported that more than half of nitrogen rate field experiments evaluated across multiple states had no significant yield response. It is also possible that the range of tested timings were correct and that there was truly no yield response for the site-years.

Meta Plateau Model Results

The functional form of both agronomic optimal insecticide termination time (HU^*) and cotton yield were jointly estimated and are presented in Table 3. Experiment observable characteristics were found to have a significant effect on the agronomic optimal time to cease insecticide applications. Namely, the optimal time for the last insecticide application in cotton has been increasing by 37 HU every year. Although it is plausible that each year differs, no phenotypic changes were expected during the time of these experiments that impacted physiological development. However, a similar result is suggested by the reported HU^{LSD}, where higher termination times were observed in recent years.

Empirical results suggest that insecticide termination timing differs across states. No statistical difference was found between the insecticide termination times in Arkansas and Mississippi. However, cotton growers in Louisiana and Texas need to cease insecticide applications 214 HU and 113 HU earlier than their counterparts in Arkansas, respectively. These results are consistent with the literature that earlier termination timings are appropriate at lower latitudes (Harris et al., 1997).

The agronomic optimal insecticide termination time (HU^*) of each considered experiment was calculated using the MPM parameter estimates as described in equation (4). Individual HU^* for each field experiment are presented in Table 2 and their corresponding distribution is depicted in Figure 7. The majority of both the primary studies and this study is for insecticide termination times around 200 HU after NAWF5, much earlier than the hypothesized 350 HU. The discrepancy between 200 and 350 HU may be an artefact of university researchers making recommendations based on empirical evidence plus some intuitive factor to reflect uncertainty in future response. Given that yield is not impacted from applying insecticides after it is no longer needed, some risk averse field scientists may have opted to make conservative recommendations.

Regarding the functional form of cotton yield, MPM results suggest that before cotton yield reaches a plateau, yield increases at a rate of 0.24 lb/ac with respect to a unit increase in extending insecticide termination timing. For instance, extending the insecticide application timeframe by 100 HU (equivalent to approximately 4-5 days) it is expected to generate 24 additional lb/ac of cotton lint up to the timing where the plateau begins. Thus, this information can be used to assist cotton producers to decide if additional applications of insecticides are offset by the additional revenue generated by the expected increase on cotton yield production[1].

Based on the non-statistical significance of time trend on cotton yield, empirical results suggest that cotton yields have remained constant over the period considered in this study. At the very least, reported cotton yields across states and yields were similar to those reported by USDA NASS (USDA NASS, 2014). In terms of the effect of location on cotton yield, MPM results indicate that cotton yield varies across states. Namely, compared to Arkansas average yield, the cotton lint yield in Louisiana and Texas is expected to be 265 lb/ac and 257 lb/ac lower, respectively. Also, the expected yields in Arkansas and Mississippi were found to be non-statistically different. Given majority of Mississippi cotton production occurs at similar latitudes as Arkansas, it was expected that Arkansas and Mississippi cotton yields and insecticide

[1] Estimation of the economic optimal insecticide termination is beyond the scope of this study. However, the methods proposed by Tembo et al. (2008) could be easily adapted to the context and specifications of the MPM to conduct further economic analyses.

termination times to be similar. On the other hand, since Louisiana and Texas cotton production areas are at relatively lower latitudes than Arkansas, there were expected to have different and lower yields. These findings are consistent with state-level yields as reported by USDA NASS (USDA NASS). Finally, the standard deviation of the between-study errors (ε_{ijk}) was estimated at 256 lb/ac (i.e., squared root of the estimated σ_{ε}^2).

For illustrational purposes, the output of the Harris_Y1997_3 experiment in Harris et al. (1997) and shown in Figure 3 is used to exemplify both the agronomic optimal insecticide termination time and cotton yield functional form suggested by the MPM. The plateau response function along with its corresponding standard error (SE) bands are shown in Figure 8. The standard error bands represent the predicted plateau response function ± estimated standard error. The standard errors of the fitted function and HU^* were obtained using the delta rule. Cotton yield for this experiment is expected to reach a plateau when insecticide applications are terminated at 258 HU, compared to 296 HU suggested by the LSD test.

Overall Insecticide Termination Time and Convergence

Meta Plateau Model estimates in conjunction with the formulas described in equations (5) and (6) were used to calculate the aggregated agronomic optimal insecticide terminations time ($\overline{HU^*}$) and its corresponding standard error, respectively. The overall agronomic optimal insecticide termination time (using all experiments in the meta-database) was estimated at 286 HU with and standard error of 13.36 HU. A *t*-test was conducted to compare the overall agronomic optimal insecticide termination time estimate to the hypothesized 350 HU termination rule. The overall estimate (i.e., 286 HU) is statistically different than 350 HU with a *t*-statistic of -4.77 which is well beyond the critical value of -2.67 ($t_{52,0.01}$).

The estimated overall agronomic optimal insecticide termination time was compared to the year estimates ($\overline{HU^*}_p$) with the aim to identify the convergence year based on the results of the tests described in equation (7). Convergence results are presented in Table 4. At a 99 percent confidence level, test results suggest a lack of true convergence over the observed years. This is likely to be partially due to relatively few studies, suggesting than additional field studies are needed to have more robust estimates. Additionally, the year based $\overline{HU^*}_p$ estimates suggest a rising time trend in the insecticide termination timing.

SUMMARY AND CONCLUSIONS

Despite the growing interest of meta-analysis in agriculture, limited attention has been given to analyze and combine research output from multiple time point studies. The main objective of this study was to develop a flexible meta-analysis regression methodology to evaluate multiple time point data from the agronomic literature. The proposed model is based on the random effects model used in meta-analysis literature in combination with random plateau theory. The techniques were useful to evaluate insecticide termination timing in cotton production; specifically to estimate the proper time and whether field studies had convergence before final field experiments were funded. The meta-database included 247 trial observations from 53 independent field experiments from the cotton belt between 1993 and 2007.

The overall insecticide termination timing was estimated at 286 HU. This estimate was found to be statistically different than the 350 HU termination time suggested in the literature. This finding indicates that insecticide applied after 286 HU may have been applied in excess, resulting in additional and unnecessary economic and environmental costs. Convergence over time of the overall termination time was further evaluated with no clear convergence over the observed years. Although, the aggregated estimate has been increasing over time.

Understanding the functional relationship between insecticide termination timing and yield penalty is fundamental to ensure the efficient allocation of production resources. The functional form of both the optimal agronomic insecticide termination time and corresponding cotton yield potential were simultaneously estimated. Empirical results suggest earlier termination timings as latitude decreased. Namely, no statistical difference was found between the insecticide termination times in Arkansas and Mississippi, and earlier termination timings were suggested for Louisiana and Texas. Additionally, a time trend in the insecticide application time was identified over the period of time considered in this study, although no time trend is expected over the long-term. It is possible that varietal differences may impact the optimal timing to terminate insecticide application, however, no empirical data were available to evaluate this possibility.

Empirical results also suggest that extending the insecticide termination time by one unit results in a cotton lint yield increase of 0.24 lb/ac up to the timing where the plateau begins. Thus, this result provided insights useful to improve production systems by applying insecticide only when benefits were expected to be in excess of the respective costs. In terms of the effect of location on cotton yield, results indicate that cotton yield varies across states. Specifically, higher yields are expected at higher latitudes (e.g., Arkansas and Mississippi) and lower yields as we move south (e.g., Louisiana and Texas). Lastly, no time trend was identified in the cotton lint yields of the considered experiments.

The proposed methodology can be extended to other crops and associated limiting factors of production. The most similar example is timing of irrigation initiation and termination in cotton (McConnell et al., 1999) and defoliation (O'Leary et al., 1996). Meta-analyses of other multiple time point studies in agriculture are now feasible including timing of fungicides (Harveson et al., 2011), herbicides (Lati et al., 2012) and planting dates (Hossain, et al., 2003).

Given the small pool of field researchers replicating research protocols across locations and years, publication bias and dependence were expected. In addition, principal investigators of primary studies may have established viewpoints that possibly influenced their results. Our inclusion criteria would allow additional studies if it were relaxed. Given that primary studies were not peer-reviewed and were published as either research bulletins or conference proceedings within the researchers' leading subject matter conference, the propensity of principal investigators self-censoring by reporting only statistically significant results could not be readily discerned.

Acknowledgements

The senior author express gratitude to Cotton Incorporated, in particular Dr. Patricia O'Leary, for data support. The senior author expresses gratitude to Diana M. Danforth, University of AR – Division of Agriculture for suggestions on identifying relevant literature. The senior author expresses gratitude to the participants of the MAER-NET colloquia at the 2009 MAER-Net Colloquium for constructive suggestions and questions, especially Drs. Raymond Florax, Henri DeGroot, and Tom Stanley.

Table 1. Description of Primary Studies

Lead Author	Publication Year	Discipline[a]	Number experiments	Location	Source Type
Benedict	1997	Ento	2	TX	proceedings
Torrey	1997	Ento	7	LA	Bulletin
Harris	1997	Ento	6	MS	Bulletin
Cochran	1996	Econ	7	AR, LA, MS	proceedings
Torrey	1997	Ento	4	LA	proceedings
Cochran	1999	Econ	18	AR, LA, MS, TX	bulletin
Cochran	1998	Econ	6	AR, LA, TX	proceedings
Oosterhuis	2000	Agron	2	AR	bulletin
Teague	2008	Ento	1	AR	proceedings

[a] Discipline of lead author

Table 2. Descriptive statistics of primary field experiment

Field Exp. ID	Year	State	n	min HU	max HU	min Yield	max Yield	MSE	HU^{LSD}	HU^{*}
Benedict_Y1997_1	1995	TX	5	0	740.5	696	815	3577	219.5a	200
Benedict_Y1997_2	1995	TX	5	117.5	744	737	782	4923	117.5	200
Cochran_Y1998_1	1995	LA	5	0	650	564	640	5793	0	98
Cochran_Y1998_2	1995	LA	4	0	500	496	520	473	0	98
Cochran_Y1998_3	1995	AR	4	0	650	859	974	3693	0	313
Cochran_Y1998_4	1995	TX	5	0	650	698	815	3489	200a	200
Cochran_Y1998_5	1995	LA	4	0	500	531	587	2061	0	98
Cochran_Y1998_6	1995	TX	5	0	650	741	771	3098	0	200
Cochran_Y1996_1	1996	AR	5	0	650	931	1153	6414	200a	350
Cochran_Y1996_2	1996	LA	5	32	655	1143	1420	13164	396a	136
Cochran_Y1996_3	1996	LA	5	25	652	1288	1361	6144	25	136
Cochran_Y1996_4	1996	LA	5	32	655	349	397	2912	32	136
Cochran_Y1996_5	1996	MS	5	98	500	1271	1442	13690	98	371
Cochran_Y1996_6	1996	MS	3	230	450	1106	1256	6926	230	371
Cochran_Y1996_7	1996	LA	5	0	622	750	801	1363	0	136
Cochran_Y1999_1	1995	LA	5	0	650	564	640	5793	0	98
Cochran_Y1999_2	1995	LA	5	0	650	685	719	713	0	98
Cochran_Y1999_3	1995	AR	5	0	650	1288	1361	6144	0	313
Cochran_Y1999_4	1995	TX	5	0	650	698	815	3489	200a	200
Cochran_Y1999_5	1995	TX	5	0	650	741	773	3098	0	200
Cochran_Y1999_6	1995	AR	4	0	650	859	974	3626	0	313
Cochran_Y1999_7	1995	LA	5	0	650	656	725	2442	0	98
Cochran_Y1999_8	1996	AR	5	0	650	931	1153	6414	200a	350
Cochran_Y1999_9	1996	LA	5	0	650	750	801	1363	0	136
Cochran_Y1999_10	1996	LA	5	0	650	1143	1420	13164	350a	136
Cochran_Y1999_11	1996	LA	5	0	650	1288	1361	6144	0	136
Cochran_Y1999_12	1996	LA	5	0	650	349	397	2912	0	136
Cochran_Y1999_13	1996	MS	5	0	650	1271	1442	13690	0	371
Cochran_Y1999_14	1996	MS	3	200	500	1106	1256	6926	200	371
Cochran_Y1999_15	1997	LA	5	0	650	676	786	3975	0	173
Cochran_Y1999_16	1997	LA	5	0	650	421	459	218	200a	173
Cochran_Y1999_17	1997	LA	4	0	500	445	545	923	350a	173
Cochran_Y1999_18	1997	LA	4	0	500	164	229	1538	0	173
Harris_Y1997_1	1993	MS	4	0	426	987	1075	3692	217a	259
Harris_Y1997_2	1993	MS	4	0	608	892	945	5316	0	259
Harris_Y1997_3	1993	MS	4	0	426	926	1048	901	296a	259
Harris_Y1997_4	1994	MS	5	0	790	1531	1591	2229	0	296
Harris_Y1997_5	1995	MS	5	137	631	884	1204	9719	386a	333
Harris_Y1997_6	1996	MS	4	98	712	1161	1315	5726	98	371
Oosterhuis_Y2000_1	1998	AR	4	0	450	870	1008	3806	0	425
Oosterhuis_Y2000_2	1999	AR	4	0	450	1019	1089	981	0	462
Teague_Y2008_1	2007	AR	4	0	450	1100	1210	8821	0	762
Torrey_Y1997(1)_1	1993	LA	5	0	809	836	919	2905	0	24
Torrey_Y1997(1)_2	1994	LA	5	0	804	873	960	575	418a	61
Torrey_Y1997(1)_3	1995	LA	5	0	650	528	567	1429	0	98
Torrey_Y1997(1)_4	1996	LA	5	0	653	581	658	1930	0	136
Torrey_Y1997(1)_5	1996	LA	5	0	642	637	680	617	0	136
Torrey_Y1997(1)_6	1996	LA	5	0	655	926	1190	22587	0	136
Torrey_Y1997(1)_7	1996	LA	5	0	651.5	1058	1118	1156	0	136
Torrey_Y1997(2)_1	1997	LA	5	0	654	717	833	4409	0	173
Torrey_Y1997(2)_2	1997	LA	4	0	591.5	635	669	267	199.5	173
Torrey_Y1997(2)_3	1997	LA	5	0	591.5	472	578	1633	479a	173
Torrey_Y1997(2)_4	1997	LA	5	0	722	174	243	1412	0	173

HU^{LSD} = optimal time-point suggested by principal investigator of primary study based on LSD metric. Earliest time-point tested with yield not statistically significantly different from maximum yield. HU* = estimated optimal heat units after NAWF=5.
a = denotes HU^{LSD} that was not the earliest time-point tested

Table 3.Agronomic Optimal Insecticide Termination Time and Yield Functional Forms

Parameter	HU* Functional Form			Yield Functional Form		
	Value	Std.Error		Value	Std.Error	
Intercept	200.338	8.999	***[a]	962.735	147.018	***
HU				0.237	0.043	***
Time Trend	37.416	2.014	***	4.817	20.456	
Location[b]: LA	-214.253	55.558	***	-264.942	109.695	**
MS	20.775	92.412		153.871	136.049	
TX	-112.594	12.889	***	-257.222	149.356	*
σ_ε^2				65508.880	13222.540	***

[a] Significance levels of 0.01, 0.05 and 0.10 are indicated by ***, ** and * respectively.
[b] In both HU* and yield functional forms the baseline location is Arkansas.

Table 4. Overall Agronomic Optimal Insecticide Termination Time at Different Periods

Period	$\overline{HU^*}_p$	$SE(\overline{HU^*})$	n_p	p-value
1995[a]	143.056	22.733	23	< 0.001
1996	120.672	49.531	42	0.002
1997	144.059	59.062	50	0.020
1998	216.675	20.608	51	0.001
1999	221.664	21.689	52	0.004

[a] The first period included experiment conducted at year 1995 and all earlier years (i.e., 1993 and 1994) due to multi-year model specification requirements.

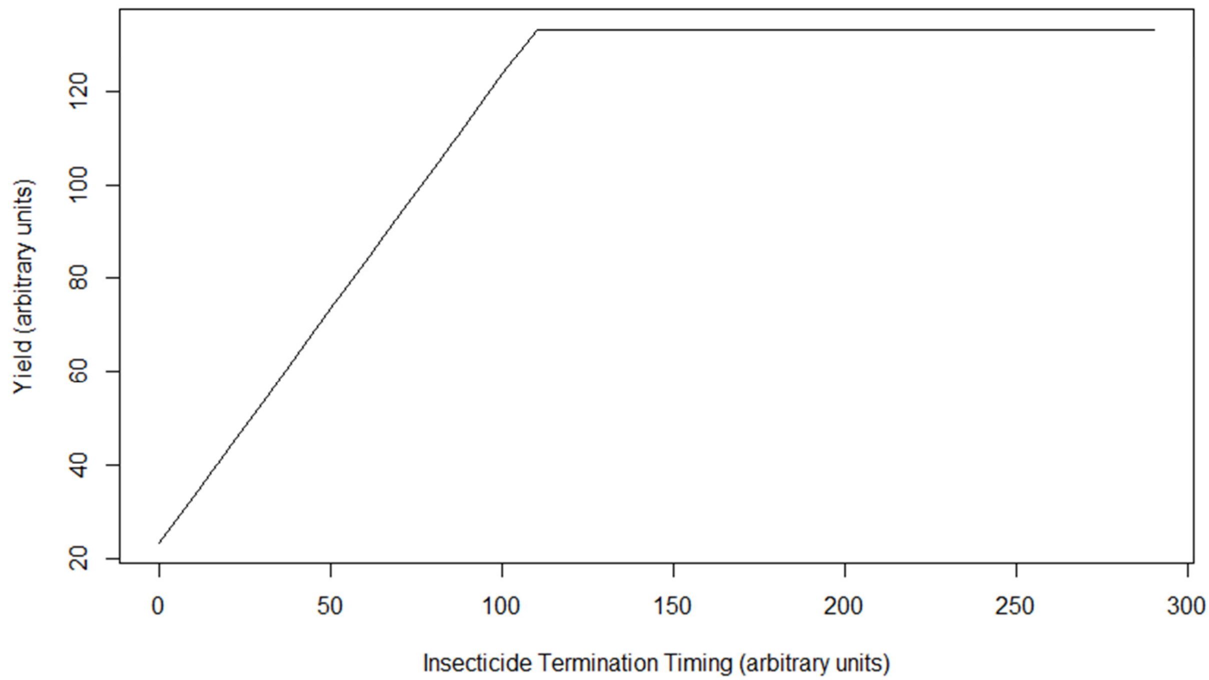

Figure 1. Stylized relationship between yield potential and insecticide termination timing

Table 3. Lint yield and percent lint turnout in the multi-state test of COTMAN insecticide termination rules based on plant monitoring, small plot test, TAES, Corpus Christi, Texas (Nueces Co.), 1995.

Treatment (Actual HU)*	% lint turnout	Lint yield lb/ac
1. NAWF = 5 + 0 HU (117.5)	35.5 a	753.3 a
2. NAWF = 5 + 200 HU (258.0)	35.6 a	768.9 a
3. NAWF = 5 + 350 HU (450.5)	35.7 a	782.0 a
4. NAWF = 5 + 500 HU (642.5)	36.2 a	765.2 a
5. NAWF = 5 + 650 HU (744.0)	36.3 a	736.8 a
LSD (0.05)	0.99 (NS)	96.6 (NS)
F test (P)	(0.3442)	(0.8746)

Means followed by different letters are significantly different (α=0.05) LSD, except where LSD value is followed by (NS).
* HU for last boll weevil insecticide application.

Figure 2. Stylized example of primary study results. (copied from Benedict et al., 1997)

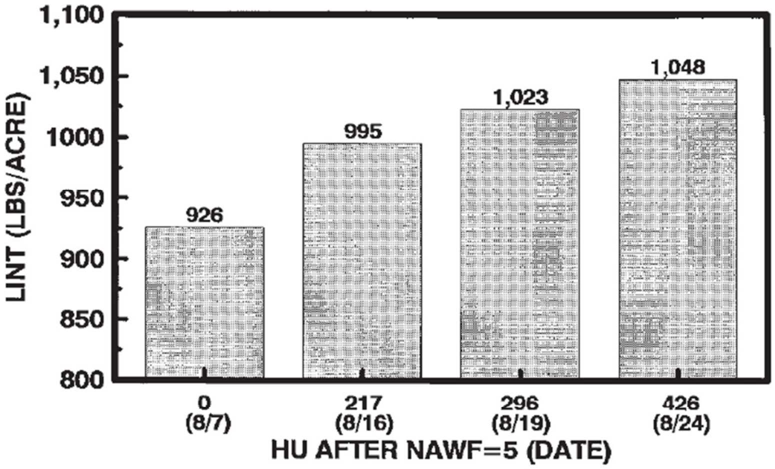

Figure 2. Average lint per acre yield for cotton insecticide termination treatments, DES 119 cotton variety, 1993 experiment at Stoneville, MS. Harvested Oct. 11. LSD (p=.05) = 42 and CV = 3.4.

Figure 3. Stylized example of primary study results (copied from Harris et al., 1997)

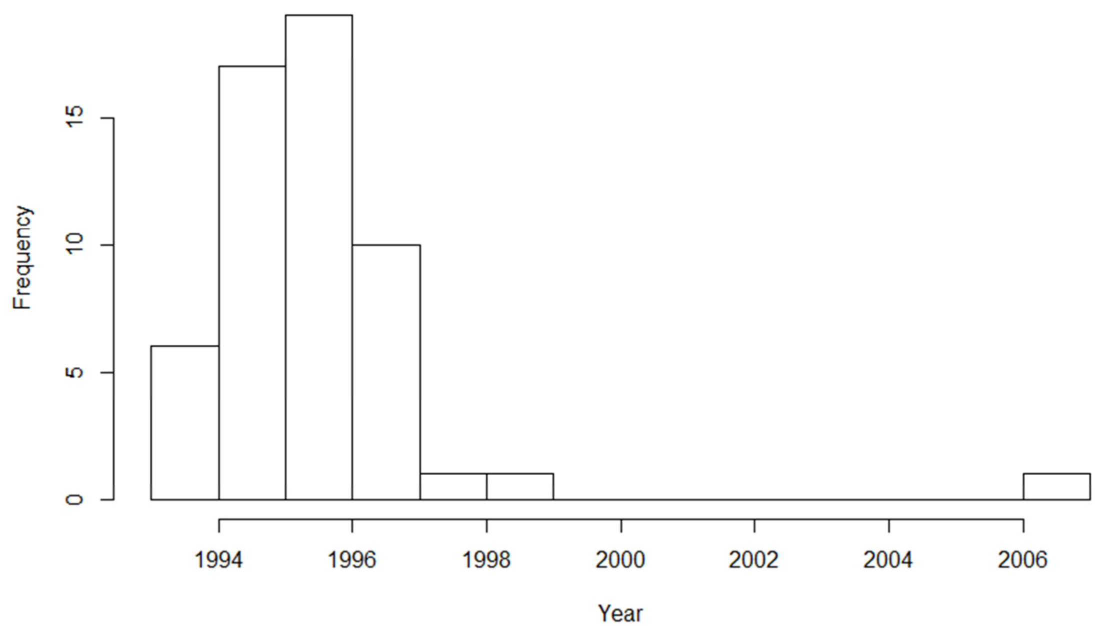

Figure 4. Histogram of field study observations across time

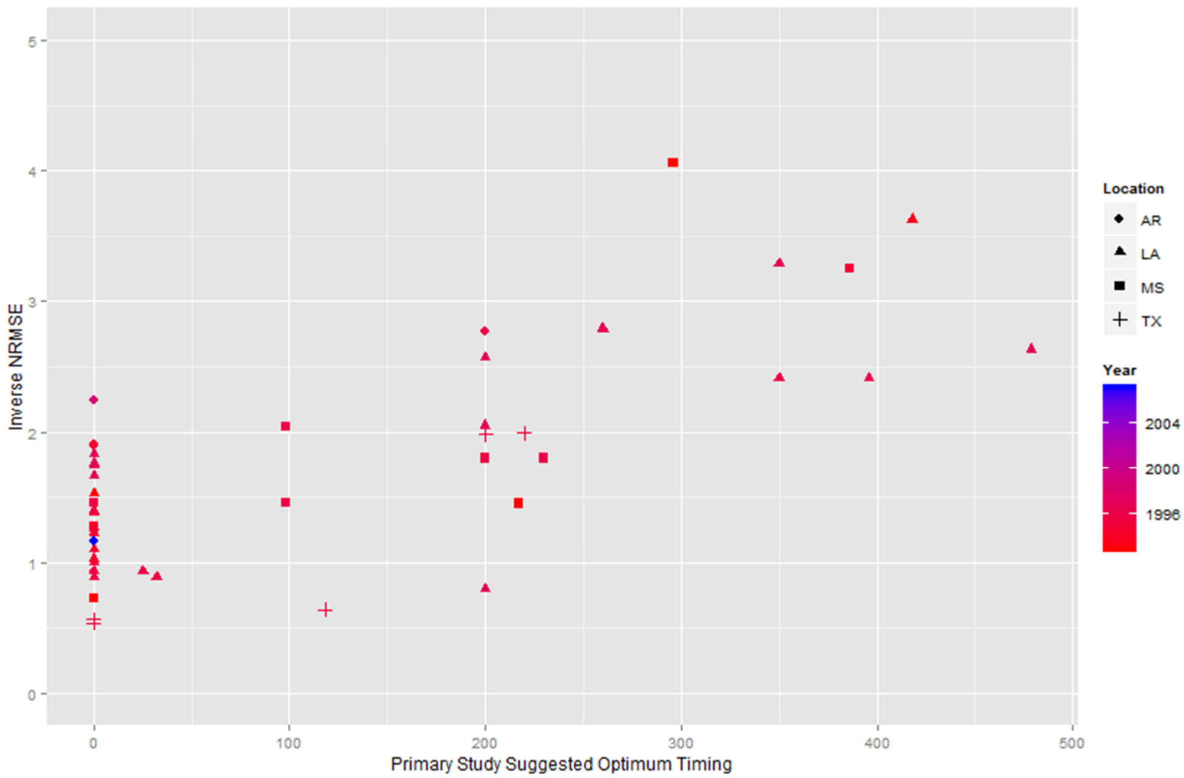

Figure 5. Relationship between study location and inverse normalized root mean squared error (NRMSE) over time. Point shapes indicate location of study.

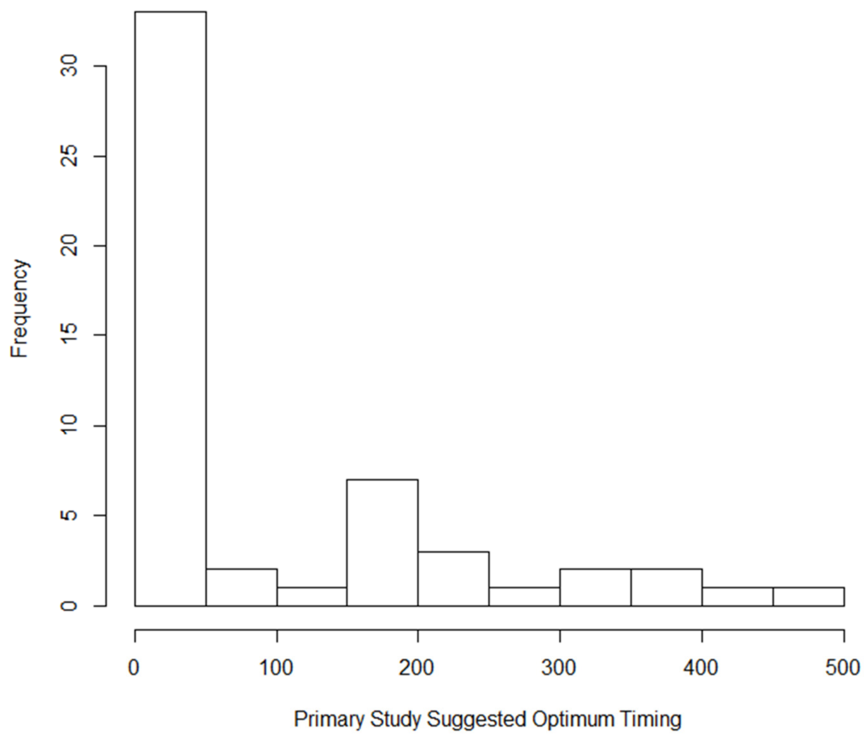

Figure 6. Histogram of earliest timing (yields not different from maximum yield) based on primary study results

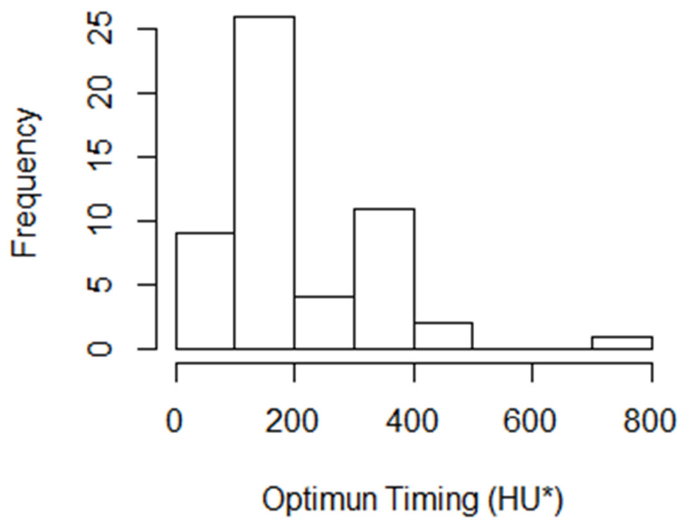

Figure 7. Histogram of agronomic optimal insecticide termination times (HU^*) by the Meta Plateau Model.

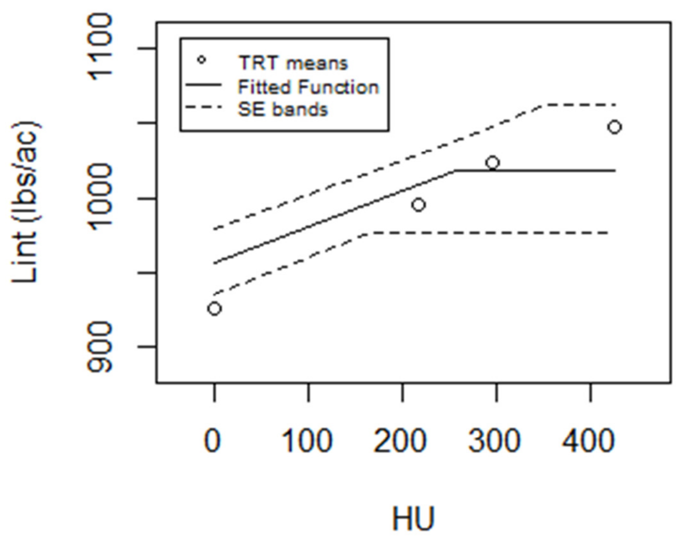

Figure 8. Predicted meta plateau function for the Harris_Y1997_3 experiment in Harris et al. (1997).

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APPENDIX

Appendix A List of Primary Studies use in Meta-analysis

Benedict, J., C. Correa, R. Huffman, R. Parker, M. Cochran, P. Tugwell, P. O'Leary, and S. Hopkins. 1997. Use and validation of COTMAN to terminate insecticide applications in south Texas. Proceedings of the Beltwide Cotton Conferences, National Cotton Council, Memphis, TN, 2:949-953.

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