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ECONOMICS & MARKETING

Estimating Cotton Yield Response Surface to Planting and Harvest Dates in Arkansas

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ABSTRACT

Knowledge of anticipated long-run yield penalties over a range of planting and harvest time periods is necessary to formulate whole-farm planning models. Until now, gaps existed for several cotton (*Gossypium hirsutum* L.) planting-by-harvest-date combinations. Publicly available data from the Arkansas Cotton Research Verification and Sustainability Program deemed suitable for this research included 169 fields from 19 years and 22 counties. Given several relevant plant and harvest weeks had no observations, a response surface was estimated. Results indicated that planting during weeks 18 to 20 minimized yield penalties, but only when harvested in corresponding best weeks. Likewise, yield penalties can be avoided if harvested during weeks 40 to 43, but only when planted in respective best weeks. Ten planting-by-harvest-week combinations were associated with at least 98% attainable yield. Fields planted and harvested outside these 10 weeks were susceptible to yield penalties. Penalties during weeks adjacent to optimal combinations tended to be minor, usually less than 5% deviations, but more severe further from the top of the response surface. Fields planted during week 22 and harvested in week 42 expected 21% yield penalty. Current Extension recommendations based on heuristics were validated from these estimates. Results are of interest to equipment manufacturers, agricultural engineers developing machinery, agricultural lenders assessing the risk of equipment loans, farmers considering optimal equipment capacity for acreage, and farm management economists estimating whole-farm profitability. Response surface methods are useful to estimate yield penalties for planting and harvest date combinations via field-scale observations.

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Knowledge of potential yield penalties associated with nonoptimal planting or harvesting timing is important when equipping farm acreage. Timeliness penalties have not been well documented, at least in recent decades for current genetics and technology. A dataframe was constructed using the Cotton Research Verification and Sustainability Program (CRVSP) from the University of Arkansas. Detailed information was recorded by CRVSP Extension specialists for each field-scale observation, then evaluated to achieve research objectives. Objectives included estimating a smooth, yield response surface across relevant planting and harvest weeks, then reporting potential harvestable yield percentages for each feasible combination. Potential harvestable yield percentages are yield response surfaces that define 1) the beginning and ending weeks of feasible planting and harvesting activities, and 2) potential harvestable yield percentages for each feasible planting and harvest week combination. Potential harvestable yield percentages are relative to the harvested yield expected when field operations occur under desirable conditions. These percentages are used for long-run planning horizons, for example, three or more years, rather than for in-season decision making during any given year. Weather, environment, and various production or management practices influence year-specific yield penalties.

Equipment investment decisions are influenced by a variety of factors including expected yield penalties by planting and harvest timing and the cost of additional capacity. Planting and harvest dates have been evaluated separately for cotton production. Aguillard et al. (1980) reported yield differences among planting dates and cultivars from 1968 to 1972. They reported that 10 April to 10 May was the optimum window to plant cotton. However, no significant yield response was detected for three out of five years tested. Killi and Bolek (2006) reported reduced yields for delayed planting in 1999 and 2000. Butler et al. (2020) used field-scale data from 2016 to 2018 across 10 sites. Planting dates tested were recommended dates for Tennessee plus 7 and 14 days after 50% emergence.

Average yield from all planting dates ranged from 440 to 1,327 Mg ha^{-1}. Harvested seed cotton yields were stable for current planting date recommendations (Butler et al., 2020). Griffin et al. (2011) evaluated observational field-scale data from 1986 to 2010 to estimate yield response to planting dates. Fields north of I-40 in Arkansas were more sensitive to planting dates than southern Arkansas. Considerable yield penalties of 15 to 20% occurred in northern Arkansas, whereas 10% was the largest penalty between consecutive weeks in southern Arkansas. Planting dates may have greater impact on yield than cultivar selection (Boquet and Clawson, 2009). Wrather et al. (2008) investigated planting dates in Mississippi from 2001 to 2005. Planting in late April was associated with higher yield, whereas earlier planting dominated in most years. University Extension recommendations sometimes have been based on heuristics (e.g., rules of thumb). For cotton planting, common rules of thumb include 1) optimal planting occurs during the first 10 days of May (Robertson and Lorenz, 2003), 2) the desired planting dates in Arkansas range from 20 April to 20 May (Barber et al., 2011), and 3) a 2% yield loss per day is expected when planting after 20 May (Barber et al., 2011; Robertson and Lorenz, 2003). In general, studies indicated that early planting is usually associated with less penalties than delayed planting.

Although some studies investigated planting timing, others evaluated yield response to harvest dates. Bednarz et al. (2002) reported harvest aids applied before bolls were 100% open led to greatest lint yields from 1998 to 2000 in Georgia. Kelley et al. (2002) reported reduced yield when harvest was delayed especially due to precipitation in Texas. Meeks et al. (2017) concluded that 7-week harvest delays resulted in significant yield reduction in Georgia. Williford (1992) investigated three different harvest systems across environments from 1983 to 1987, including single-pass, two-pass, and delayed harvest. The two-pass harvest produced the highest yield, whereas delayed harvest, 4 to 6 weeks after the first harvest in the two-pass system, resulted in the lowest yield. Average lint yield from delayed harvest was 924 Mg ha^{-1}, significantly lower than both the two-pass and single-pass systems of 1,049 and 996 Mg ha^{-1}, respectively. In Mississippi, rainfall adversely affected yields, regardless of whether it occurred in a single or multiple events (Williford, 1992). In North Carolina, Faircloth et al. (2004) reported yield losses occurred with even small amounts of wind and precipitation.

For cotton production, heat unit (HU) accumulation is important for crop development and farm management planning. The cotton cutout date is when plants reach nodes above white flower (NAWF) equal to 5 (Oosterhuis and Bourland, 2008). The latest possible cutout date is the date that a white flower has a high probability of developing into a boll suitable for harvest with respect to size and lint quality (Oosterhuis and Bourland, 2008). At least 850 degree-day heat units are required for the flower to develop into a mature boll prior to a pre-determined target harvest completion date, usually 1 November (Oosterhuis and Bourland, 2008). The latest possible cutout dates using a 50% probability of collecting 850 HU are 11 August at Keiser in northeast Arkansas, 14 August at Marianna in central Arkansas, and 19 August at Rohwer in southeast Arkansas (Oosterhuis and Bourland, 2008), an 8-day difference from north to south. Due to low probability of accumulating sufficient heat units during later weeks of the growing season, cotton is not recommended to be planted after the first week of June (Barber et al., 2011).

Previous studies focused on yield response to planting or harvest timing; however, none addressed both simultaneously. Until now, response surface methodology has not been applied to populate potential harvestable cotton yield percentage matrices for planting and harvest date combinations.

Arkansas Cotton Research Verification and Sustainability Program. The University of Arkansas Division of Agriculture CRVSP was created in 1980 and represents a public demonstration of the implementation of research-based recommendations in actual field-scale farming environments (University of Arkansas Division of Agriculture, 2024). During the late 1970s, farm profitability was adversely affected by declining crop yields, low commodity prices, and relatively high production costs. Due to uncertain crop response to inputs, producers requested that the University of Arkansas evaluate available technologies at field-scales to determine the expected profitability. In response to growers' concerns, the Arkansas Row Crop Research Verification Program (RVP) was developed; first for cotton (*Gossypium hirsutum* L.) in 1980, then rice (*Oryza sativa* L.) and soybean (*Glycine max* L. Merr.) in 1983, wheat (*Triticum aestivum* L.) in 1986, and corn (*Zea mays* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench] in 2000. The RVP originated as an on-farm demonstration of research-based practices and agricultural technologies recommended to optimize production and maximize profitability of Arkansas row crops. The overall goal of the CRVSP was to verify field-scale management according to university recommendations that could result in increased profitability relative to status quo producer practices. Secondary goals of CRVSP were to 1) establish an economic database, 2) demonstrate that high yields can be constantly achieved economically, 3) promote timeliness in management decisions, and 4) provide training and assistance to new county Extension agents. Today, the Arkansas Row Crop RVP is an interdisciplinary effort among producers, county Extension agents, Extension specialists, and experiment station research faculty.

Most RVP reports have been pertinent during the year of publication, however observational data have been evaluated for secondary research purposes. Watkins et al. (2014) calculated technical, allocative, economic, and scale efficiencies using data envelopment analysis. Henry et al. (2016) reported substantial water savings for rice grown using a zero-grade irrigation system. Griffin et al. (2011) estimated yield response to planting dates across 25 years.

MATERIALS AND METHODS

Data were extracted from three publicly available sources. This project was endowed with observations already coded into a dataframe from 1986 through 2010. Data from 2010 to 2013 were acquired from online CRVSP reports and data from 2014 to 2023 were obtained via electronic spreadsheets from the CRVSP coordinator (University of Arkansas Division of Agriculture, 2024) supplemented with information from university bulletins (Bourland, 2023, 2024). Data from 2010 to 2013 were manually entered by three separate analysts. Each analyst entered data into electronic forms replete with validation capabilities. Triple entry was employed so that dataframes could be subjected to data verification techniques to ensure accuracy. Data entry forms were developed such that entered data met predefined criteria such as numeric within specific range, calendar entry between feasible dates, and drop-down lists of known categorical options. Data entry formatting ensured consistency across dataframes as well as avoiding human error. Data were cross validated by evaluating identical records across dataframes entered by the three analysts. Cross validation software (Johnston et al., 2021) output reports of errors if dataframes were inconsistent across the three entries; and if so, the authors spot-checked discrepancies against source data to determine correct entries.

Four variables were considered critical to estimate yield response by planting and harvest dates: yield, year, planting date, and harvest date. Observations were deemed suitable if all four critical variables were available. Field location county was an additional CRVSP variable presented here but was not explicitly included in the analysis. Yield data were self-reported by cooperating CRVSP farmers, usually via gin records. Once the final dataframe was populated with field data from 1986 to 2023, 169 commercial cotton fields were deemed suitable for planting-by-harvest-date analysis out of 368 fields coded into the initial dataframe.

Planting and harvest dates were partitioned into discrete time intervals equal to one week. Weekly intervals were preferred instead of daily because 1) they were sufficiently long to include a meaningful number of observations, 2) the probabilities of events occurring at less than weekly approached zero, and 3) they served as a common unit for combining data across years. The “month-day-year” date format of “week ending” was converted to weeks then assigned a week-of-year number following ISO 8601 standards (ISO, 2019). Dates when field activities occurred were converted to week numbers within respective years, so events were comparable across years. Week numbers defined by the ISO 8601 system were converted from dates using the isoweek() command in the lubridate (Grolemund and Wickham, 2011) contributed package to R (R Core Team, 2024). For example, the week ending Sunday, 12 January 2025, was week 2, and week ending Sunday, 9 March 2024, was week 10; week numbers associated with each week-ending date in 2025 are listed in Table 1.

In Arkansas, cotton is typically planted from 23 April (week 18) to the end of May (week 22), with most active dates from 30 April (week 19) to 23 May (week 21) (USDA NASS, 2010). Harvest usually begins 20 September (week 39) and lasts two months (week 47), with the most active harvest occurring from 29 September (week 41) to 6 November (week 45) (USDA NASS, 2010). Beginning and ending dates indicate when field activities are 5 to 95% complete, whereas the most active dates are the central 70% between 15 and 85% cumulative planted or harvested (USDA NASS, 2010). Due to technology, relative profitability of other crops and equipment costs, these dates have shifted over time (Burkhead, 1972).

Table 1. Week ending dates and week of year numbers, 2025, in ISO 8601 date and time format system

week ending	week	week ending	week	week ending	week	week ending	week
5-Jan	1	6-Apr	14	6-Jul	27	5-Oct	40
12-Jan	2	13-Apr	15	13-Jul	28	12-Oct	41
19-Jan	3	20-Apr	16	20-Jul	29	19-Oct	42
26-Jan	4	27-Apr	17	27-Jul	30	26-Oct	43
2-Feb	5	4-May	18	3-Aug	31	2-Nov	44
9-Feb	6	11-May	19	10-Aug	32	9-Nov	45
16-Feb	7	18-May	20	17-Aug	33	16-Nov	46
23-Feb	8	25-May	21	24-Aug	34	23-Nov	47
2-Mar	9	1-Jun	22	31-Aug	35	30-Nov	48
9-Mar	10	8-Jun	23	7-Sep	36	7-Dec	49
16-Mar	11	15-Jun	24	14-Sep	37	14-Dec	50
23-Mar	12	22-Jun	25	21-Sep	38	21-Dec	51
30-Mar	13	29-Jun	26	28-Sep	39	28-Dec	52

Descriptive Statistics. The annual number of CRVSP fields deemed suitable for this analysis is presented in Fig. 1. Most field observations occurred in 2016 with 12, and the least strictly positive number of fields was one in 1995, although 15 of the 33 years between 1990 to 2023 had no observations deemed suitable. The number of suitable fields per county is presented in Fig. 2 and mapped in Fig. 3. Desha County had the most fields with 46, the next two most represented counties were St. Francis and Mississippi, with 25 and 13 fields, respectively. The 22 counties with CRVSP fields suitable for this study are primarily in eastern Arkansas.

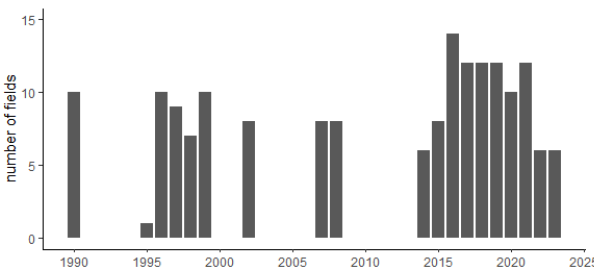

Figure 1. Field count by year, 1990 to 2023, n = 169.

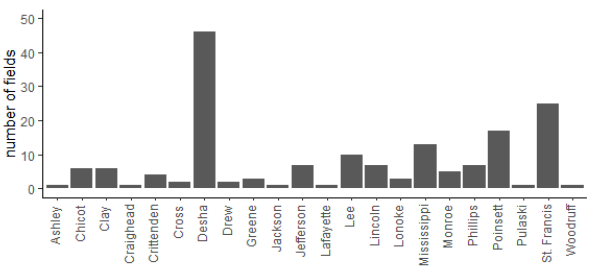

Figure 2. Frequency of fields by county, 1990 to 2023, n = 169.

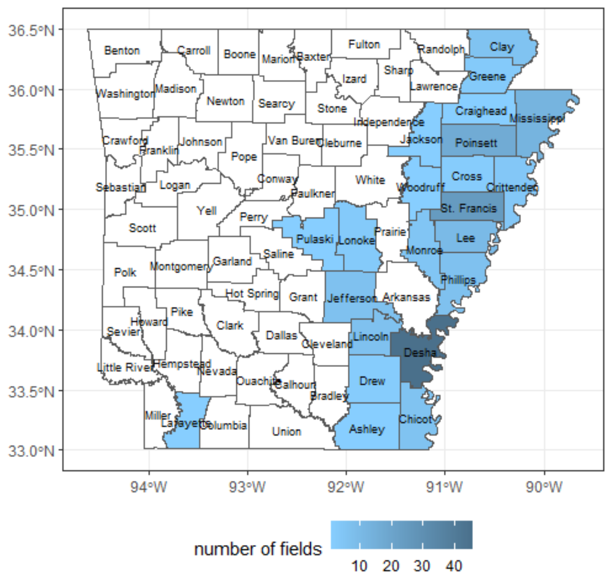

Figure 3. Frequency of counties represented in sample data, 1990 to 2023, n = 169.

The frequency of fields planted and harvested by week are represented in Fig. 4 and Fig. 5, respectively. Shaded areas represent the most active and usual crop progress in dark gray and light gray, respectively. Planting dates ranged from week 15 to week 22. Weeks 18 and 19 were the most common to plant followed by weeks 20, 17, and 21. The least common planting occurred at the extremes of weeks 15 and 22 (Fig. 4). CRVSP fields tended to be planted earlier than the most active beginning dates (USDA NASS, 2010).

Harvest ranged from week 37 to week 51 (Fig. 5). More than half of fields were harvested during weeks 40, 41, and 42. Weeks 43 and 39 were the next most common harvest weeks. Although two fields were harvested during week 51, no fields were harvested in the earlier weeks of 46, 48, 49, and 50. Week 47 had the least non-zero observations with only one field (Fig. 5). Most CRVSP fields were harvested during the usual harvest dates reported by USDA NASS (2010) but were harvested slightly earlier than the most-active dates for Arkansas.

The number of CRVSP field observations for each combination of planting and harvest weeks is presented in Table 2. Thirty-six combinations had at least one field observation. Planting during week 18 and harvesting in week 40 was the most common combination with 17 fields. The next most common combination was planting during week 19 then harvesting in week 42 with 15 fields. Four combinations had three fields. Nine combinations had two fields. Five combinations had only one observed field.

Descriptive statistics for yield, planting week, and harvest week are presented in Table 3. The highest yield, 2,369 Mg ha^{-1}, and the highest average yield, 1,894 Mg ha^{-1}, were both in 2018. The minimum yield, 438 Mg ha^{-1}, occurred in 1998, when the average yield was 917 Mg ha^{-1}. The lowest average yield was in 1995 at 915 Mg ha^{-1}. Yields for observed CRVSP fields were slightly higher than overall state average but with similar trendline slopes (Fig. 6). The overall state average increased by 19.9 Mg ha^{-1} each year, whereas the CRVSP fields increased by 23.2 Mg ha^{-1} each year, both statistically significantly different from zero at $p < 0.01$. Given trendline slope was statistically significantly different from zero, yields were detrended with respect to base year of 2021 to improve estimation results (Swinton and King, 1991).

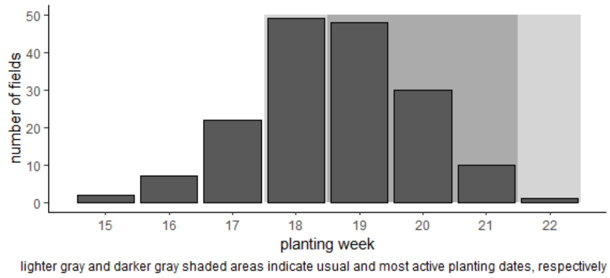

Figure 4. Frequency of fields planted by week, 1990 to 2023, n = 169.

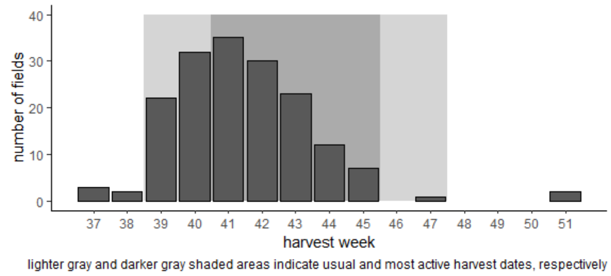

Figure 5. Frequency of fields harvested by week, 1990 to 2023, n = 169.

Table 2. Frequency of fields by planting and harvest week combination, 1990 to 2023, n = 169

planting week	harvest week														
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
15			2												
16			3	3		1									
17	2		7	2	7	4									
18		2	5	17	12	4	7	2							
19	1		5	6	13	15	4	4							
20				2	3	5	11	4	5						
21				2		1	1	2	2						2
22											1				

Detrended yields were standardized by normalizing relative to proportion of highest yield each year. Normalized yields, $\tilde{y}$, are expressed as a percentage and are naturally censored by the closed standard unit interval, [0,1]. The simple average of normalized yields for all observations in each week combination are presented in Table 4. Yield penalties are sensitive to both planting (Fig. 7) and harvest timing (Fig. 8).

Statistical Analysis. Two second-order polynomial model specifications were evaluated. Polynomial functional forms are additive; and if interaction terms are omitted, predictor variables will not have a synergistic impact on dependent variable responses (Debertin, 2012). If interaction terms are omitted, the marginal product of planting week is not linked to harvest week, and vice versa.

Model specification included the quadratic and square root functional forms. Models were chosen

Table 3. Descriptive statistics: yield, planting week, and harvest week by year, n = 169

	lint yield (Mg/ha)			planting week			harvest week			
year	min[z]	mean	max	min	median	max	min	median	max	n
1990	648	976	1,307	18	19	22	40	42	47	10
1995	915	915	915	20	20	20	41	41	41	1
1996	738	1,005	1,166	17	18	19	39	40	42	10
1997	998	1,186	1,379	19	19	20	40	41	43	9
1998	438	917	1,116	19	19	20	37	40	42	7
1999	572	926	1,256	18	19	19	38	40	43	10
2002	811	1,124	1,305	17	19	21	40	41	43	8
2007	1,048	1,324	1,695	16	18	19	39	40	41	8
2008	900	1,284	1,564	18	20	21	40	41	43	8
2014	1,073	1,454	1,678	19	19	20	41	42	45	6
2015	1,081	1,324	1,570	18	18	19	40	41	42	8
2016	1,000	1,298	1,467	17	17	19	37	39	42	14
2017	812	1,398	1,923	15	16	21	39	40	45	12
2018	1,270	1,894	2,369	18	18	20	40	42	44	12
2019	1,260	1,682	2,062	17	18	21	39	42	51	12
2020	1,313	1,541	1,733	18	18	21	42	43	45	10
2021	1,039	1,351	1,634	17	20	20	41	42	45	12
2022	980	1,570	1,919	18	19	19	39	42	44	6
2023	1,530	1,714	1,904	18	18	20	41	42	43	6

[z]min = minimum, max = maximum, n = sample size

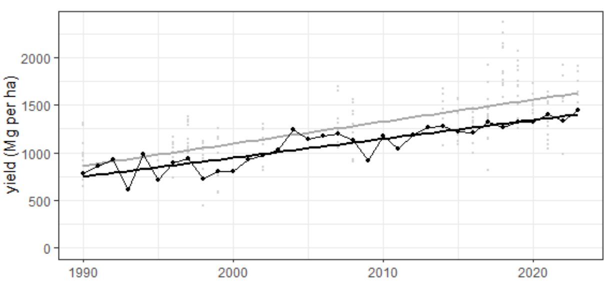

Figure 6. Trendline yields for sample (gray) and statewide (black), 1990 to 2023.

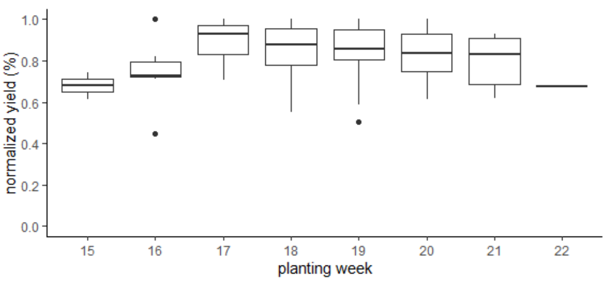

Figure 7. Normalized yield by planting week, 1990 to 2023, n = 169.

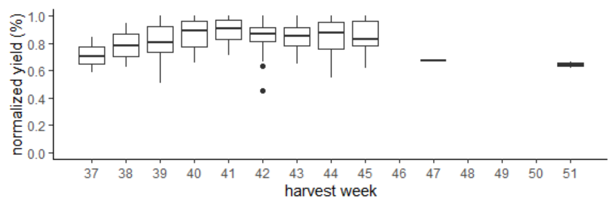

Figure 8. Normalized yield by harvest week, 1990 to 2023, n = 169.

due to the expected non-linear relationship of yield response to planting and harvest dates. In general, a second-order multivariate polynomial including a two-way interaction term specified as quadratic (Equation 1) is expressed as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 + \epsilon \quad (1)$$

and square root (Equation 2) as:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11}\sqrt{x_1} + \beta_{22}\sqrt{x_2} + \beta_{12}\sqrt{x_1}\sqrt{x_2} + \epsilon \quad (2)$$

where y is a n×1 vector of observations on the dependent variable, x is $k \times n$ matrix of explanatory variables, β is $k \times 1$ vector of estimated coefficients, ϵ is $n \times 1$ vector of residuals, n is number of observations, and k is number of coefficients to be estimated.

Table 4. Simple average of normalized yield by planting and harvest week, 1990 to 2023, n = 169

planting week	harvest week														
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
15			68												
16			75	83		45									
17	78		89	88	94	88									
18		78	87	88	84	93	87	61							
19	59		71	87	91	86	86	86							
20				91	90	78	82	94	85						
21				78		88	91	85	85						64
22											67				

Model specifications included normalized yield, $\tilde{y}$, as a function of planting, P_w, and harvest, H_w, weeks, their squares or square roots, and the two-way interaction term (Equation 3) written as:

$$\tilde{y} \sim P_w + P_w^2 + H_w + H_w^2 + P_w H_w \quad (3)$$

for the quadratic or for the square root as:

$$\tilde{y} \sim P_w + \sqrt{P_w} + H_w + \sqrt{H_w} + \sqrt{P_w}\sqrt{H_w} \quad (4)$$

where $\tilde{y}$ is normalized yield, w is week of year, P_w is week the field was planted, and H_w is the week the field was harvested.

Given that the dependent variable, $\tilde{y}$, is continuous but censored at the closed interval [0,1], the familiar ordinary least squares (OLS) estimator is biased and inconsistent, therefore alternative statistical estimation tools were considered. Multivariate response surface (Box and Draper, 1987) using censored (Greene, 2003; Tobin, 1958) and beta regression (Ferrari and Cribari-Neto, 2004; Simas et al., 2010) were conducted to evaluate normalized yield with respect to planting and harvest timing. Beta regression (Cribari-Neto and Zeileis, 2010) has been applied to various agricultural analyses (Geissinger et al., 2022; Khuri, 2017; Yellareddygari et al., 2016) and is appropriate when the dependent variable is continuous but censored at the closed unit interval [0,1], for example, percentages. Tobit (Tobin, 1958) is a censored regression technique that has been applied to agricultural production functions (Dhakal and Lange, 2021; Tembo et al., 2008). When the dependent variable is censored at the closed standard unit interval, [0,1], the two-limit tobit is performed with left and right set at 0 and 1, respectively. The betareg (Kleiber and Zeileis, 2008) and censReg (Henningsen, 2024) functions from their respective contributed packages to R (R Core Team, 2024) were used in the operational procedures of this study and both estimated as maximum likelihood.

Estimated coefficients for both tobit and beta regression are presented in Table 5. For the quadratic functional form estimated as tobit or beta, the planting week coefficients were not statistically significantly different from zero. However, both linear variables were significant at $p < 0.01$ for the square root model specification. The Akaike Information Criterion (AIC) was lower for the tobit models than the beta regression. Within either estimation technique, AIC was lower for square root than the quadratic functional form. Therefore, the square root functional form model specification estimated as a two-limit tobit censored regression was chosen to populate the potential harvestable yield percentages matrix.

Estimated coefficients reported in Table 5 were transformed into a response surface for all feasible Cartesian products (Table 6). Cartesian products, or cross joins, return product sets of two vectors and generate all possible combinations of the variables of interest. Cartesian products of the two sets for plant, p, and harvest, h, denoted by $P \times H$, are defined as the set consisting of all ordered pairs (p, h) for which $p \in P$ and $h \in H$. Extrapolating estimates across Cartesian products populated each feasible week combination of the potential harvestable yield percentage matrix. The response surface was fitted across all elements of the Cartesian product regardless of whether CRVSP fields were observed for that particular combination of weeks.

RESULTS AND DISCUSSION

Planting or harvesting beyond optimum times induces yield penalties. Results of this study supported long-standing university Extension recommendations based on rules of thumb. Planting during weeks with near 100% potential harvestable yield ranged from

Table 5. Yield response to planting and harvest week, n = 169

	dependent variable: normalized yield			
	two-limit tobit		beta regression	
	quadratic	square root	quadratic	square root
planting week (P_w)	0.065	-1.455^{***z}	1.752	-4.988**
	-0.199	-0.427	-1.3	-2.318
harvest week (H_w)	0.257***	-1.190***	2.036***	-4.860*
	-0.091	-0.306	-0.073	-2.68
P_w^2	-0.019***		-0.158***	
	-0.006		-0.041	
H_w^2	-0.007***		-0.046	
	-0.002			
$P_w H_w$	0.016**		0.097***	
	-0.006		-0.004	
$\sqrt{P_w}$		0.573		29.027
		-3.443		-19.749
$\sqrt{H_w}$		7.364***		54.362
		-2.431		-34.358
$\sqrt{P_w}\sqrt{H_w}$		1.858***		2.12
		-0.718		-4.136
intercept	-5.134**	-24.188**	-56.918***	-238.111*
	-2.411	-9.599	-10.74	-131.844
AIC	-150.1	-151.4	-53.6	-141.8

$^{z*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$

Table 6. Potential harvestable yield percentages by planting and harvest week

planting week	harvest week														
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
15	83	83	81	77	72	66	57	48	37	24	11	0	0	0	0
16	89	91	91	90	87	82	76	68	59	49	37	24	10	0	0
17	90	94	96	97	96	93	89	83	76	67	57	46	34	20	5
18	85	92	96	99	99	99	96	93	87	81	73	63	53	41	28
19	77	85	92	96	99	100	100	98	94	89	83	75	66	56	45
20	65	75	83	89	94	97	98	98	96	93	89	83	76	67	57
21	49	61	71	79	85	90	93	95	95	93	90	86	81	74	66
22	29	43	55	65	73	79	84	87	89	89	88	86	82	76	70

18 to 20, the same as the rule of thumb reported by Robertson and Lorenz (2003), for example, the first 10 days of May, but only when harvested in respective best weeks (Table 6). When planting from week 18 through week 20, less than 2% yield penalty was expected when harvesting during appropriate weeks. When planting in week 20, then harvesting during week 43, a negligible 2% penalty is expected. When planting in week 19, then harvesting in week 44, 98% potential harvestable yield might be realized. When planting during week 21, the highest potential harvestable yield was 95% when harvested during week 44 or week 45. If planted in week 22, then harvested during week 43, a 16% yield penalty was expected. When considering usual and most active planting dates, a 21% yield penalty might be expected when planted during week 21, then harvested in week 40. Examining harvesting before the end of week 44 (1 November), the difference in penalties between planting during week 21 and week 22 averaged 13.5% or 1.9% per

day, consistent with the 2% per calendar day yield loss after the 20 May rule of thumb.

Results indicated that 100% potential harvestable yields were expected when harvesting during weeks 42 and 43 if planted during the corresponding best week, week 19. This is consistent with the Extension recommendation of having a target harvest completion date of 1 November (week 44). During the final two weeks of the usual harvest dates, week 46 and week 47, only one CRVSP field was observed.

Results were similar to previous CRVSP studies. Week 18 had the most observations followed closely by week 19, with week 20 and week 17 coming in distant at third and fourth most common planting weeks. Griffin et al. (2011) reported week 19 had by far the most field observations followed by week 18 then week 20. Potential harvestable yield percentages presented in Table 6 are consistent with previous research that focused on either planting or harvest timing. Unlike Griffin et al. (2011), who reported that planting during weeks 17 and 18 were associated with the highest yield, our results indicated more than 99% yield potential was only attainable during week 18 and week 19. Aguillard et al. (1980) suggested a relatively wide window for optimum cotton planting dates of April 10 to May 10, for example, weeks 15 through 19 in Louisiana, although those dates correspond to most-active dates for Louisiana and are nearly as wide as the entire range of weeks 15 to 22 in Arkansas. Geography, in particular, latitude, is known to influence crop development.

Potential harvestable yield percentages can be consulted to identify combinations of planting and harvest weeks to optimize equipment capacity to acreage or assess weeks that expected yield penalties might be offset by capital recovery costs. A practical farm management example illustrates the usefulness of potential harvestable yield percentages. Consider a typical-sized 1,040-acre cotton farm (McFadden et al., 2023) with one 6-row harvester. Assuming 2.3 hectares per hour effective field capacity, harvesting the entire acreage during weeks with minor yield penalties is likely unfeasible (Griffin and Barnes, 2017). Therefore, accepting some amount of foregone yield and revenue is rational if outweighed by equipment expenses.

Borrowing yield and price parameters from Watkins (2024) for furrow-irrigated cotton, a 1.35 Mg lint yield, y, at $1,764 per Mg, P_y, with $243 cottonseed, cs, value per Mg, 40% turnout, l_{to}, and total operating expenses of $2,368.55 per hectare were assumed. The general equation for returns above operating expenses (RAOE) is presented as:

$$y \cdot APY \cdot P_y + cs \cdot APY \cdot l_{to} \cdot P_{sc} - TOE = RAOE \qquad (5)$$

Under the best-case scenario with 100% potential harvestable yield, returns above operating expenses are $505 per hectare for a 1.35 Mg yield (Equation 6).

$$1.35 \text{ Mg} \cdot 100\% \cdot \frac{\$1764}{Mg} + 1.35 \cdot 150\% \cdot 100\% \cdot \$243 - \$2369 = \$505 \qquad (6)$$

Assuming a modest 18% yield penalty from planting during week 16 then harvest in week 42 (Table 6), returns above operating expenses become negative at $-12 per hectare (Equation 7).

$$1.35 \text{ Mg} \cdot 82\% \cdot \frac{\$1764}{Mg} + 1.35 \cdot 150\% \cdot 82\% \cdot \$243 - \$2369 = \$\text{-}12 \qquad (7)$$

Applying this logic across the entire yield response surface (Table 6) and omitting negative values demonstrates the range of profitable planting and harvest week combinations. Rational decision makers match acreage to equipment capacity that results in strictly positive returns above operating expenses, for example, covering variable costs (Table 7). Rational decision makers plan to plant and harvest only during weeks with strictly positive returns, therefore reducing the economically feasible combinations. Typical-sized cotton farms are not likely to have capacity sufficient to plant or harvest entire acreage during the few weeks with no yield penalties. Investing in additional equipment capacity could avoid the penalties associated with planting or harvesting at inopportune times; however, fixed machinery costs would increase. If the decision maker has the goal to cover all costs rather than only covering variable costs, fewer economically feasible combinations are available as fewer options of planting or harvesting during high-penalty weeks will meet the more restrictive criteria.

Because the whole-farm average yield was 1.35 Mg ha^{-1}, some fields had yields greater than 1.35 Mg ha^{-1} such that whole-farm average was 1.35 Mg. Instead of 1.35 Mg ha^{-1}, a 1.65 Mg ha^{-1} yield was assumed (Table 8). Additional week combinations became economically feasible when higher yields were assumed (Table 8). When planted in week 19 and harvested in week 42 (e.g., 100% potential harvestable yield), returns above operating expenses were $1,143 ha^{-1}. Once fieldwork capacity has been exhausted during weeks with 0% yield penalties, weeks with 1% yield penalties were chosen and so on until economically feasible week combinations, or acreage, are exhausted.

Table 7. Per hectare returns above operating expenses by planting and harvest week, 1.35 Mg yield. Crop price = $1,764 per Mg; operating expenses = $2,368.55 per ha

planting week	harvest week														
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
15	87	85	41												
16	228	276	283	249	176	66									
17	245	343	399	413	388	325	226	91							
18	150	296	399	460	482	465	410	320	195	37					
19		144	293	400	467	494	484	437	355	239	90				
20			90	242	352	423	455	451	410	336	228	88			
21					144	257	332	368	369	335	267	166	34		
22						5	120	197	238	243	214	152	58		

Table 8. Per hectare returns above operating expenses by planting and harvest week, 1.65 Mg yield. Crop price = $1,764 per Mg; operating expenses = $2,368.55 per ha

planting week	harvest week														
	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51
15	644	641	587	484	335	140									
16	816	876	884	842	753	618	439	217							
17	838	958	1026	1044	1013	936	814	648	441	193					
18	721	900	1026	1102	1128	1107	1040	929	776	582	348	75			
19	477	714	897	1028	1109	1143	1130	1073	972	830	648	426	166		
20	117	409	647	833	968	1055	1095	1090	1040	949	817	645	434	187	
21			287	526	714	852	944	989	990	948	864	741	579	379	142
22				115	354	543	684	779	829	835	800	723	608	454	264

Sophisticated farm management analysis such as linear programming methods are necessary to calculate whole-farm yields and revenues (Boehlje and Eidman, 1984). Due to equipment capacity constraints and weekly fieldwork probabilities, advanced analyses are beyond the scope of this research. However, tools suitable for advanced analyses can make practical use of our results and have been developed into desktop software and interactive web dashboards. Thousands of farms have used potential harvestable yield percentages for corn, soybean, and wheat in specialized software (Doster et al., 2006). The potential harvestable yield percentages reported by Doster et al. (2006) have similar week combinations as our estimates with zeros and non-zero elements.

CONCLUSIONS

In the absence of controlled yield-response-to-timing experiments, field-scale observational data were evaluated to estimate a yield response surface. Historical CRVSP data empowered the estimation of a yield response surface with respect to planting and harvest dates. We coded 169 field observations from the publicly available University of Arkansas CRVSP into a dataframe. Each data point was replete with yield, year, planting date, harvest date, and county. Yields were normalized by year and a model was specified as the square root functional form estimated as a two-limit tobit. Estimated coefficients were used to calculate potential harvestable yield percentages across the range of feasible planting and harvest week combinations. Results presented here were consistent with existing university Extension heuristics and can parameterize advanced economic models such as whole-farm linear programming tools. Knowledge of possible yield penalties is important when considering the equipment capacity necessary to plant and harvest crops across the entire farm acreage in a timely manner. With this information, farmers can optimize their operations with respect to machinery investment, acreage, and acceptable foregone yield.

Future Work. Results from this study can be extrapolated to other regions especially if results are correlated to publicly available planting and harvest progress. Equipment investment can be evaluated given knowledge of yield penalties associated with effective field capacity of planting and harvesting equipment. An interactive web dashboard that provides users with the opportunity to evaluate different cotton harvest systems under a range of scenarios will use results presented here.

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