ESTIMATING LINT YIELD AND REVENUE POTENTIAL FROM SMALL AUTONOMOUS ROBOTICS: LINEAR PROGRAMMING APPLICATION COMPARING SINGLE-PASS AND MULTIPLE-PASS COTTON HARVEST SYSTEMS

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Abstract

Improved equipment management has been a perpetual task of cotton producers due to specialized equipment used for the sole purpose of harvest. Questions regarding autonomous robotics replacing traditional cotton pickers are being evaluated by researchers. Evaluation of potential yield penalties between swarms of small autonomous robots and *status quo* equipment was conducted to ascertain economic benefits. Knowledge of the upper bounds of benefits provides parameters for other researchers to use in the development of technology. Given that the smallest autonomous robots harvest cotton one boll at a time rather than the entire population of opened bolls with a single-pass system, an opportunity exists to avoid yield and quality penalties during non-optimum harvest timing. Multiple-pass harvest systems comprised of many small autonomous robots may harvest cotton soon after bolls opening therefore decreasing yield penalties and minimizing risk. A linear programming model was developed to assess yield penalties based on yield adjustment sets for Midsouth harvest dates. Analysis compared gross revenue potential from single-pass and multiple-pass harvest systems. Results indicated that the single-pass harvest systems had $33,612 forgone gross revenue solely on non-optimal harvest weeks; a monetary loss that could have been avoided by harvesting opened bolls in more desirable weeks. Results are pertinent to robotics researchers and equipment manufacturers as the next machinery is developed. Researchers, farmers, and other agriculturalists can perform these and similar analyses using the interactive web dashboard.

Introduction

Improved harvest management may lead to increased profitability for cotton producers. Specialized cotton harvesting equipment only operated during a few weeks of the year lends itself to a risky endeavor. Traditional cotton harvest machinery is relatively expensive on a per acre basis, limited to a single harvest pass, and constrained to perform only one task. An alternative harvest system being evaluated by researchers is many small autonomous robots, i.e., swarms, to harvest cotton. Cotton lint quality has historically been given less consideration than the yield at the farm level because 1) the volume of production had the greatest impact on per acre value and 2) geo-referenced quality was difficult to track in addition to quality-affecting factors were not well understood. Multiple-pass harvest systems are the next generation of autonomy and can alternatively be thought of as a system of multiple machines continuously operating across fields until harvest is complete.

Agricultural autonomy began with automated guidance in the late 1990s. Benefits of replacing human capital on equipment with automated guidance reduced overlap and input use (Griffin et al., 2005) and mechanical control of herbicide-resistant weed infestations (Griffin and Lowenberg-DeBoer, 2017). At present, autonomous equipment are analogous to *status quo* technology with respect to capacity size (Janzen, 2022; McCormick, 2022); however, the next generation of autonomous machinery may remain the same, become larger, or much smaller (Barnes et al., 2019).

One persistent research question asks if many small autonomous robots can be deployed such that higher lint yield and fiber quality can be achieved to maximize profitability. Although small autonomous robotics are expected to increase the average quality of lint by picking opened bolls potentially during the "best" week after bolls opening for specific characteristics, quality impacts were beyond the scope of this paper. Lint quality is assumed to be the greatest on the day that the boll opens but deteriorates daily given exposure to uncontrollable environmental factors. To address study questions, yield penalties for each feasible harvest week were estimated.

This research evaluated the feasibility of several small autonomous robots in a multiple-pass harvest system for cotton production. Fully autonomous small robotics used for cotton harvest are tasked with picking cotton one row, plant, or boll at a time. Robots navigate in-between cotton rows to pick cotton on either side of the machine. Even though individual robots are only able to pick cotton from an adjacent row, multiple robotic machines may have similar capacity and performance metrics to traditional single-pass machinery. Overall, the cost-saving per unit acre is the key to determining the economic performance of the multiple-pass harvest systems. For that purpose, it is critical to explore the changes in gross revenue relative to *status quo* systems. Results are pertinent to cotton researchers, equipment developers, and manufacturers.

Background

Weather variation impacts farmers' ability to enter the field to conduct field operations (Griffin and Barnes, 2017). Griffin and Barnes (2017) analyzed weekly data from USDA National Agricultural Statistics Service (NASS) over the previous 20 years and reported the typical week of the year that farmers plant and harvest cotton in each of the cotton-producing states. The week of year, i.e., week number, is defined as the number of complete seven-day periods that have occurred January 1st, plus one (Grolemund and Wickham, 2011). Using these dates as upper and lower bounds, they summed the number of days suitable for fieldwork each year then estimated long-term probabilities. They calculated the number of acres that could feasibly be planted and harvested in a typical and a 'bad' weather year. Days suitable for fieldwork and the most active dates that fields are entered to conduct operations are a function of not only characteristics of crop physiological progress and soil properties, but also equipment characteristics, capacity, commodity prices, and yield penalties for non-optimal timing (Mensing, 2017). Given yield penalties for timeliness were held constant, cheaper cotton lint and more expensive equipment incentivizes farmers to conduct field operations over wider time windows; thus, the price ratio between cotton and equipment impacts farm operators' decision of when to enter the field impacting the observed statistics. Alternatively, if harvest equipment weighed less than the current *status quo*, the number of days suitable for harvest may be higher than currently observed; therefore, the number of days suitable for fieldwork and the most active field operation dates are likely to differ for each harvest system. Shifts in harvest systems from large modulating pickers to smaller machines may also impact the observed number of days between the first bolls opening and the end of harvest. When utilizing field-scale equipment with the intent of conducting single-pass harvest operations once each season, sacrifices are made when choosing optimal timing (Griffin and Zapata, 2016).

Cotton harvest processes have changed over time, in part due to less human labor and increased equipment capacity. From 1940 to 1975, the percentage of acreage mechanically picked increased from 0% to nearly 100% (Barnes et al., 2019). During that time, harvest systems went from harvesting individual bolls as they matured to entire fields with a single-pass system once a critical mass of mature bolls was achieved. Technological innovation has gone full circle by potentially reverting to the previous practice of individual row, plant, or boll harvest, with small autonomous robotic machines. As the proportion of mechanically harvested cotton acreage approached 100%, the total harvested acreage of cotton was declining to near levels of current production (Figure 1). In the U.S., harvested cotton acreage peaked in the 1920s and reached the current levels during the 1960s (Figure 1).

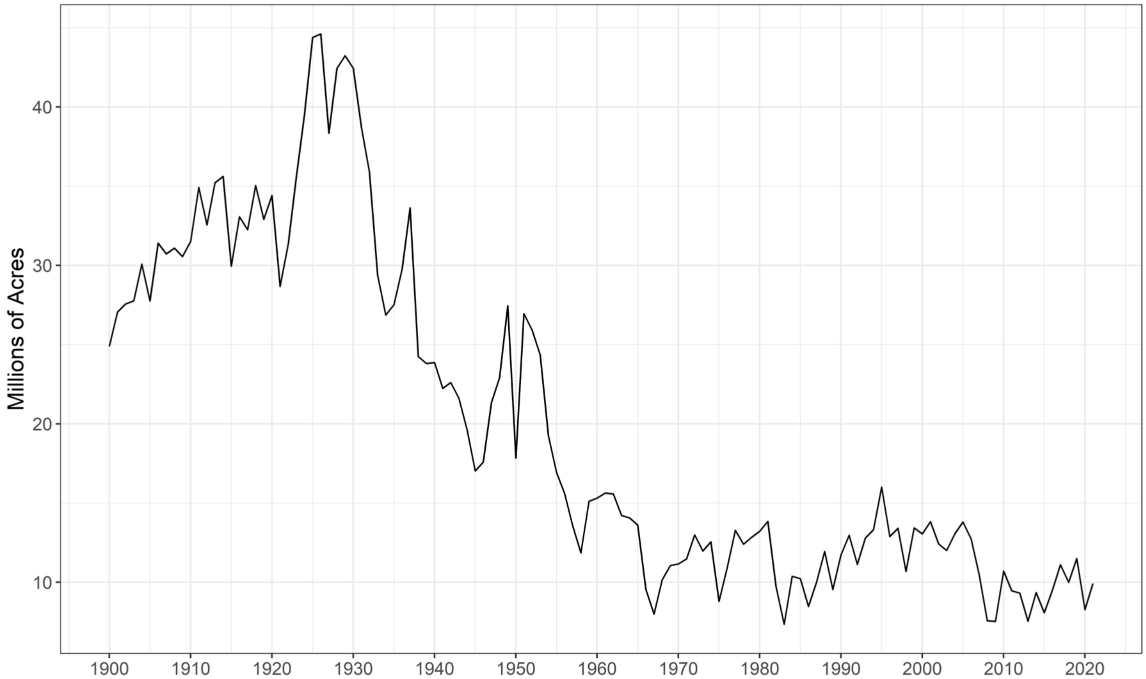

Figure 1. U.S. annual harvested cotton acreage, 1900 to 2021 (USDA NASS, 2017)

In 2021, there were 17 cotton-producing states (Table 1) mostly spread across the southern half of the U.S. from California to North Carolina (Figure 2). Texas had 5.3 million harvested acres of cotton in 2021 or 53% of the total U.S. acreage. Georgia had second-most acreage at 12% and the third-largest cotton acreage was harvested in Arkansas with 4.7% of the U.S. total. New Mexico was the 17th largest acreage of cotton harvested with 40 thousand acres or 0.4% of U.S. total acreage.

Table 1. U.S. harvested cotton acreage, 2021, USDA NASS

	acres (000s)	U.S. %	U.S. rank
Alabama	400	4.0	6
Arizona	128	1.3	11
Arkansas	470	4.7	3
California	109	1.1	12
Florida	89	0.9	15
Georgia	1,160	11.7	2
Kansas	101	1.0	14
Louisiana	105	1.1	13
Mississippi	430	4.3	4
Missouri	310	3.1	8
New Mexico	40	0.4	17
North Carolina	350	3.5	7
Oklahoma	415	4.2	5
South Carolina	205	2.1	10
Tennessee	270	2.7	9
Texas	5,266	53.1	1
Virginia	73	0.7	16

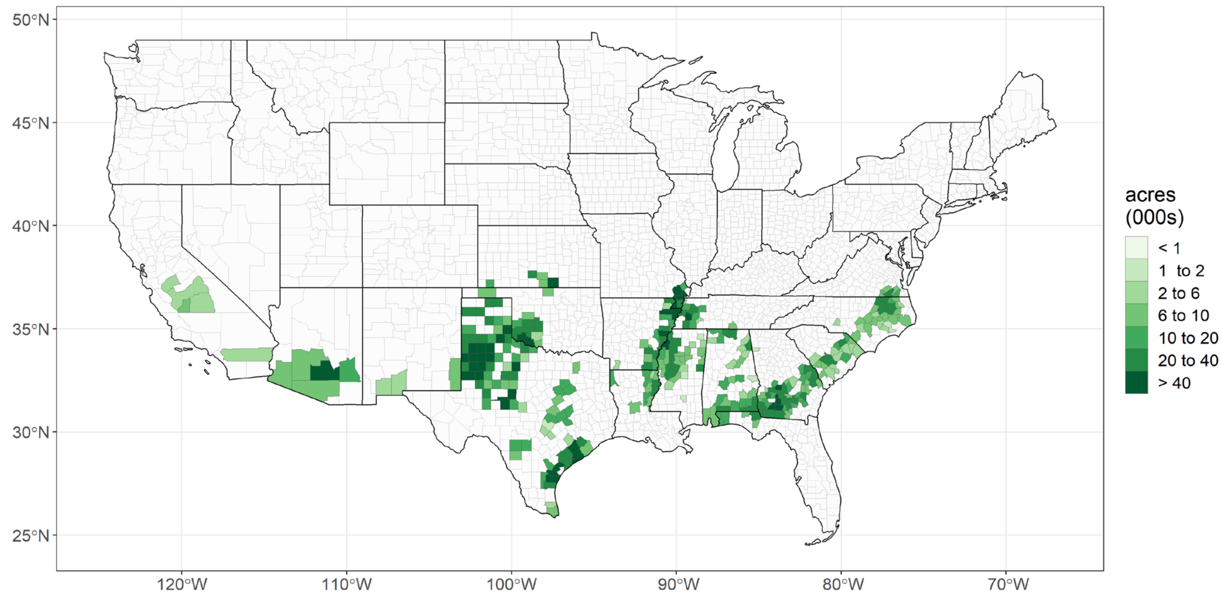

Figure 2. U.S. county harvested cotton acreage, 2020 (USDA NASS, 2017)

Typical single-pass harvest occurs after a critical mass of opened bolls are ready to be picked. Harvest usually occurs approximately 100 days after planting, typically 60 to 90 days after the first boll is mature (Snider and Oosterhuis, 2015). Griffin et al., (2019) reported no statistically significant yield difference between single- and multiple-pass harvest systems in Texas during 2018; however, higher lint quality was observed for multiple-pass harvest than single-pass systems. The highest lint yield and optimal fiber quality occur at different physiological stages of maturity (Bednarz et al., 2002). They found that maximum lint yield occurs when harvested during 76.5 to 89.0% bolls opening, but optimal fiber lengths can be achieved sooner at 40 to 60% bolls opening. Median bolls opening typically occur four to five weeks before the most active harvest dates begin (Figure 3, Table 2), therefore widening the harvest window by a month is feasible with multiple-pass harvesting systems. In Arkansas, significant yield loss was observed 21 days after defoliation in 2008. In Georgia, Meeks et al. (2017) reported no yield penalties from minor harvest delays, but statistically significant yield and quality penalties when harvest delays were excessive.

One advantage of small autonomous robots is the possibility of multiple passes into the field to revisit the same plant to harvest bolls shortly after opening. Yield and fiber quality penalties result when cotton is harvested before or after "best" weeks, a consequence of harvesting during non-optimal weeks of the year, a consequence of single-pass harvest systems. The overall crop yield and fiber quality are expected to be higher for multiple-pass harvest systems because cotton is harvested at the ideal timing after maturation. Harvesting soon after individual bolls open mitigates the risk of more severe wind or rain events that occur later in autumn. Multiple-pass harvest systems widen the harvest window by allowing additional harvest events during earlier weeks of year that reduces yield and quality from adverse weather. Assuming cotton harvest begins one week after bolls opening could shift the lower tail of the harvest progress curve to the left, i.e., earlier in the season, but remaining to the right of the cumulative bolls opening curve.

Table 2. Cotton planting, bolls opening, and harvest progress, 5-year average

	median plant ($\tilde{p}$) (week number)	median bolls opening ($\tilde{b}$) (week number)	begin harvest (h_{min}) (week number)	end harvest (h_{max}) (week number)	duration ($h_{min} - \tilde{b}$) (weeks)
Alabama	19	36	40	48	4
Arkansas	19	36	40	44	4
California	16	37	42	46	5
Florida	20	36	42	48	6
Georgia	20	36	41	47	5

Kansas	22	39	45	52	6
Louisiana	18	34	39	42	5
Mississippi	19	36	40	44	4
Missouri	19	37	41	45	4
New Mexico	18	38	43	48	5
North Carolina	20	37	42	47	5
Oklahoma	22	38	43	48	5
South Carolina	19	36	41	47	5
Tennessee	20	37	41	46	4
Texas	21	38	39	2	1
Min	16	34	39	2	1
Mean	19.5	36.7	41.3	43.6	4.5
Max	22	39	45	52	6

The agronomic and economic benefits of different harvesting systems can be estimated using mathematical programming methods. Specifically, a whole-farm linear programming model can compare the single-pass harvest system with multiple-pass harvest systems. Linear programming models have been used to evaluate various agricultural production issues. Linear programming methods have been applied to farm planning for three-quarters of a century (Heady, 1954). Recently, linear programming models have been parameterized to evaluate automated guidance (Griffin et al., 2005), mechanical weed control for herbicide-resistant weed infestations (Griffin and Lowenberg-DeBoer, 2017), inter-generational transition strategies for family farms (Rosburg and Griffin, 2018), and observing religious traditions of days of rest (Rosburg et al., 2019). Whole-farm linear programming models have been parameterized for Midsouth cotton production (Glaub, 1982; Wright et al., 2018). Available labor, machinery, days suitable for fieldwork, crop rotations, and available acreage were used to parameterize these linear programming models.

Data and Methods

Publicly available data were used in this study. Yield potential by harvest week was adapted specifically for this study while all other data were available from USDA NASS (2017) via an application programming interface (Dinterman and Eyer 2019) with R (R Core Team, 2021). For the purposes of his study, cotton harvest in Midsouth was evaluated, specifically Arkansas. Readers can follow along for their respective states of interest on the interactive web dashboard. Data described by this study were used to parameterize a harvest linear programming model.

A set of data and modeling assumptions were assigned to guide this research. Some assumptions were common to both single-pass and multiple-pass harvest systems while other assumptions were specific to either single-pass or multiple-pass harvest systems.

Assumptions for both single-pass and multiple-pass harvest systems were:

1) Non-harvest field operations remain constant at sufficiently high capacity
2) Single-pass and multiple-pass harvest systems have same days suitable for fieldwork
    a. Days suitable for fieldwork were assumed to be at the 35th percentile
3) Percentile bolls opening were proxy for crop physiological progress in hypothetical set of farm fields
4) Whole-farm cotton acreage was set as acreage one 6-row modulating picker could pick in typical year
5) Expected yield when planted and harvested during “best” weeks was 1,500 lbs. acre^{-1}
6) Cotton lint price was \$1 lb^{-1}

Assumptions specific to single-pass harvest systems included:

1) 6-row modulating pickers harvest 8.0 acres hour^{-1} for up to 9 hours day^{-1}

Assumptions specific to multiple-pass harvest systems included:

1) Harvest season begins during week with at least 15th percentile bolls opening cumulative progress
2) Bolls can be harvested one week after opening (assuming after 15th percentile bolls opening)
3) Sufficient cotton to meet capacity for at least one machine before harvesters enter field
4) Days suitable for fieldwork are held constant, but hours available for harvest differ due to hours day^{-1}
5) Harvest initially limited to 9 hours day^{-1}

Additional details on data and modeling assumptions are below.

Data: Prices, Yields, and Revenues

Cotton lint price and yield were assumed for this analysis. Given the assumed "best" yield of 1,500 pounds acre^{-1} and lint price of $1 pound^{-1}, a maximum $1,500 acre^{-1} were possible in select weeks of the year. During the remaining weeks, maximum per acre revenue was less than $1,500.

Data: Acreage Harvested Each Week Based on Days Suitable for Fieldwork

Probabilities of being able to enter the field to conduct fieldwork were estimated using data observed in Arkansas from 1995 to 2021 (Griffin, 2009) (Table 3). Rather than planning on average or median conditions, days per week were estimated at each probability level from 0.10 to 0.55 in increments of 0.05 for a 7-day workweek (Table 3). The optimal probability level to use in farm management planning processes depends on value of cotton lint, yield penalty for harvesting too early or late, cost of equipment capacity, and risk preference of farm operator; therefore, no standard one-size-fits-all probability is correct. A range of days suitable probabilities were available for the decision maker (Table 3). For the purposes of this study, the 35th percentile was chosen to include in the remaining calculations. The 35th percentile days suitable for fieldwork during week 41 was 5.18 days week^{-1} (Table 3).

Table 3. Days suitable for fieldwork, 7-day weekly probabilities, Arkansas, 1995 to 2021

week number	probability									
	0.1	**0.15**	**0.2**	**0.25**	**0.3**	**0.35**	**0.4**	**0.45**	**0.5**	**0.55**
30	5.32	5.49	5.74	5.95	6.00	6.00	6.00	6.00	6.00	6.40
31	5.30	5.77	5.92	6.00	6.00	6.11	6.22	6.29	6.40	6.43
32	5.05	5.18	5.40	5.40	5.55	5.78	6.00	6.00	6.00	6.00
33	4.28	4.49	4.84	5.10	5.20	5.91	6.00	6.00	6.00	6.39
34	5.00	5.09	5.20	5.45	5.94	6.01	6.10	6.24	6.60	6.67
35	4.96	5.72	5.84	6.00	6.00	6.01	6.14	6.37	6.50	6.60
36	4.04	4.56	5.14	5.75	5.96	6.00	6.04	6.10	6.30	6.80
37	4.96	5.36	5.40	5.55	5.78	5.91	6.00	6.00	6.10	6.23
38	4.92	5.00	5.04	5.40	5.68	5.71	5.80	5.81	5.90	6.00
39	3.85	4.88	5.00	5.15	5.65	5.70	5.80	5.93	6.00	6.00
40	5.28	5.46	5.74	6.00	6.00	6.08	6.26	6.38	6.50	6.52
41	4.00	4.06	4.74	5.00	5.02	5.18	5.30	5.46	5.70	6.00
42	3.72	4.28	4.52	5.00	5.00	5.11	5.32	5.50	5.80	5.93
43	3.96	4.00	4.00	4.10	4.52	4.91	5.08	5.41	5.60	5.70
44	2.84	3.09	3.20	3.60	4.00	4.71	4.88	5.00	5.00	5.23
45	2.84	3.45	4.00	4.00	4.00	4.00	4.28	4.91	5.10	5.56
46	3.28	3.88	4.32	4.50	4.72	4.88	5.00	5.00	5.00	5.08
47	3.26	3.67	4.00	4.00	4.36	4.52	4.82	4.94	5.00	5.26
48	2.76	2.94	3.40	4.00	4.00	4.08	4.32	4.44	4.50	4.74
49	3.28	3.42	3.56	3.70	3.72	3.74	3.76	3.78	3.80	4.00

Days suitable for fieldwork must be adjusted for number of days week^{-1} that harvesters are operated (Rosburg et al., 2019) and the number of hours day^{-1} the machinery can be operated (Griffin and Barnes, 2017). For simplicity, 7 days week^{-1} were assumed for harvest equipment operation so a 7/7 multiplier was used to convert days suitable for fieldwork to days available for fieldwork. If the farm operator opted to harvest 6.5 days week^{-1}, then the 6.5/7 multiplier would be used instead of 7/7 .

Griffin and Barnes (2017) suggested that traditional single-pass harvesters can be operated nine hours day^{-1}. The days available for fieldwork were multiplied by nine hours day^{-1} to estimate the number of hours week^{-1} available. Finally, the hours available each week were multiplied by the working rate of the *status quo* machinery, or acres hour^{-1} machinery can harvest. Griffin and Barnes (2017) reported that on-board modulating single-pass system could harvest eight acres hour^{-1}.

The acreage upper bound that could be harvested are presented in Table 4. Keeping the same example as above, the 35th percentile for week 41 had 373 acres that could be harvested at 8 acres hour^{-1}, 9 hours day^{-1}, 7 days week^{-1} in Arkansas. Acreage upper bounds only apply to single-pass harvest systems.

Table 4. Acreage capacity upper bound, weekly probabilities, single-pass harvest systems, Arkansas

week number	probability									
	0.10	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.55**
30	383	395	413	428	432	432	432	432	432	461
31	382	415	426	432	432	440	448	453	461	463
32	364	373	389	389	400	416	432	432	432	432
33	308	323	348	367	374	426	432	432	432	460
34	360	366	374	392	428	433	439	449	475	480
35	357	412	420	432	432	433	442	458	468	475
36	291	328	370	414	429	432	435	439	454	490
37	357	386	389	400	416	426	432	432	439	449
38	354	360	363	389	409	411	418	418	425	432
39	277	351	360	371	407	410	418	427	432	432
40	380	393	413	432	432	438	451	459	468	469
41	288	292	341	360	361	373	382	393	410	432
42	268	308	325	360	360	368	383	396	418	427
43	285	288	288	295	325	354	366	390	403	410
44	204	222	230	259	288	339	351	360	360	377
45	204	248	288	288	288	288	308	354	367	400
46	236	279	311	324	340	351	360	360	360	366
47	235	264	288	288	314	325	347	355	360	379
48	199	212	245	288	288	294	311	320	324	341
49	236	246	256	266	268	269	271	272	274	288

Data: Bolls Opening and Harvest Progress

To intuitively understand how multiple-pass harvest systems impact harvest progress, consider the data reported by USDA NASS for eastern Arkansas graphically presented in Figure 3. Data representing single-pass harvest systems provides insights into the potential value of multiple-pass systems. The green cumulative distribution indicates the current 5-year average cotton harvest progress in Arkansas. The "most active" harvest dates are the central 70% between the 15th and 85th percentile indicated by the lower and upper horizontal dashed lines, respectively.

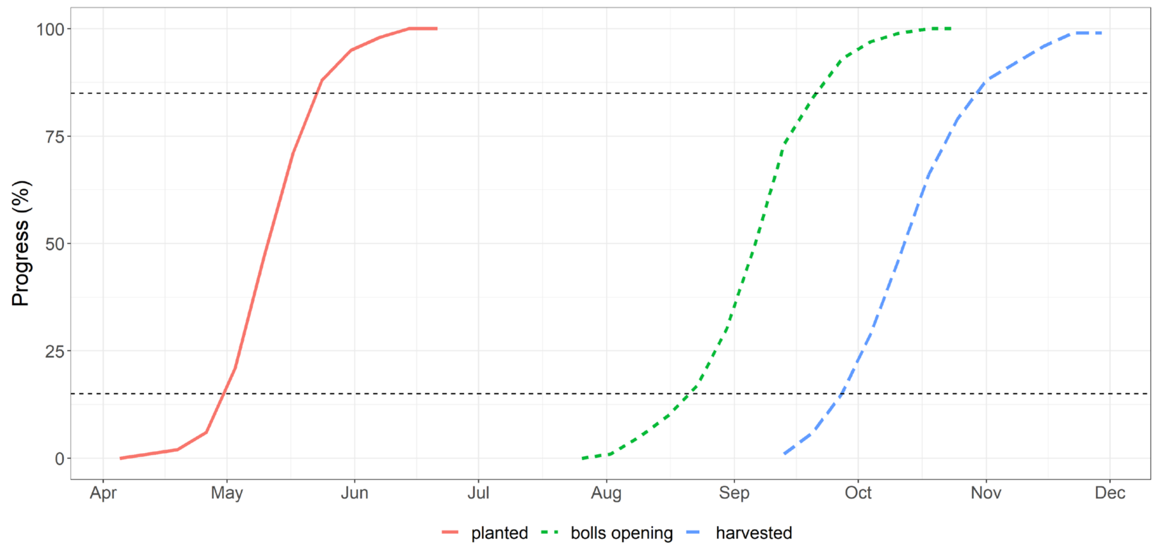

Figure 3. U.S. county harvested cotton acreage, 2020 (USDA NASS, 2017)

Based upon criteria that cumulative bolls opening was at least 15% before multiple-pass harvest began, the week ending August 23rd, alternatively week number 34, would be the first week that small autonomous robotics would enter the field to harvest cotton in Arkansas (Table 5). By 23rd August 10% of bolls were open for at least one week, and 5% of the field became ready during this week. The week ending September 20 had the largest percentage of bolls becoming ready to harvest with 23%. During the week ending October 25th, the small robotic harvesters would harvest the last 1% of bolls. Unharvested open bolls can be harvested after these dates in the far-right column but at increased risk of adverse weather events. For multiple-pass harvest operations, a discrete stock of open bolls was available to be harvested each week (Table 5). The most active harvest dates in Arkansas begins about 95% percentile bolls opening progress and lasts five weeks from the week ending October 4 to week ending November 1 (Table 2).

Table 5. Bolls opening progress, 5-year average, Arkansas, 2016 to 2020, USDA NASS (2017)

week ending	week number	cumulative bolls opening (%)	cumulative harvestable bolls (%)	bolls became harvestable this week (%)
26-Jul	30	0	0	0
2-Aug	31	1	0	0
9-Aug	32	5	1	1
16-Aug	33	10	5	4
23-Aug	34	17	10	5
30-Aug	35	30	17	7
6-Sep	36	50	30	13
13-Sep	37	73	50	20
20-Sep	38	84	73	23
27-Sep	39	93	84	11
4-Oct	40	97	93	9
11-Oct	41	99	97	4
18-Oct	42	100	99	2
25-Oct	43	100	100	1
1-Nov	44	100	100	0
8-Nov	45	100	100	0
15-Nov	46	100	100	0

22-Nov	47	100	100	0
29-Nov	48	100	100	0
6-Dec	49	100	100	0

Data: Yield Potential by Harvest Date

The yield adjustment set defines 1) the weeks of the year that harvest is feasible and 2) the yield potential as a percentage of "best yield" when operations occur under desirable conditions. Yield adjustment sets are unique to each geographic region, bundle of cultivar maturities, production practices, and harvest system. Given the absence of field research reporting yield potential by planting and harvest dates for each geographic region, an indirect technique was employed to populate the yield adjustment set matrix.

Two cotton yield adjustment sets were estimated for Arkansas. The initial yield adjustment set was populated via quasi mini-Delphi techniques for Midsouth cotton harvest based on decades of unpublished research, anecdotal casual observation, and discussion with a wide range of experts (Wright et al., 2018) (Table 6). As a simplified example, cotton was assumed to have been planted during median planting progress, i.e., week ending May 3. Yield adjustment sets were assigned 100% for the most active harvest dates when planted during the median planted progress. Harvesting the week immediately before most active harvest dates were assigned 90%. Delayed harvest during the two weeks immediately following most active harvest dates were assigned 80%, and the following two weeks after that were assigned 70% potential. Remaining harvest dates when planted during week ending May 3 were assigned 0% (Table 6). The entirety of the field can be harvested with single-pass harvest systems during any week with non-zero yield potential.

The second yield adjustment set was developed for multiple-pass harvest systems by modifying the single-pass yield adjustment set. The multiple-pass yield adjustment set assumes that individual bolls can be harvested, setting the weekly bounds for earlier harvest (Table 7). In Arkansas, bolls opening surpass 15th percentile during the week ending August 23; therefore the 100% yield potential was extending from the existing 100% yield potential to earlier weeks up to week ending August 23. Yield potential for weeks after 100% for single-pass harvest systems (Table 6) remained the same for multiple-pass harvest systems. Yield adjustment sets were assigned 0% for harvest weeks sooner than week ending August 23 for cotton planted week ending May 3 (Table 7). For earlier or later planting dates, harvest yield potential may differ relative to the week ending May 3.

Table 6. Cotton yield adjustment set, single-pass harvest systems, Arkansas

Planting date (week ending)	harvest date (week ending)																	
	16-Aug	**23-Aug**	**30-Aug**	**6-Sep**	**13-Sep**	**20-Sep**	**27-Sep**	**4-Oct**	**11-Oct**	**18-Oct**	**25-Oct**	**1-Nov**	**8-Nov**	**15-Nov**	**22-Nov**	**29-Nov**	**6-Dec**	**13-Dec**
19-Apr	0	0	0	0	0	0	90	95	95	95	95	95	90	90	80	80	0	0
26-Apr	0	0	0	0	0	0	95	100	100	100	100	100	85	85	80	80	0	0
3-May	0	0	0	0	0	0	95	100	100	100	100	100	80	80	70	70	0	0
10-May	0	0	0	0	0	0	90	100	100	95	95	95	75	75	70	70	0	0
17-May	0	0	0	0	0	0	90	95	95	90	90	90	75	75	70	70	0	0
24-May	0	0	0	0	0	0	80	85	85	90	90	90	75	75	70	70	0	0
31-May	0	0	0	0	0	0	75	80	80	85	85	85	70	70	65	65	0	0
7-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 7. Cotton yield adjustment set, multiple-pass harvest systems, Arkansas

Planting date (week ending)	harvest date (week ending)																	
	16-Aug	**23-Aug**	**30-Aug**	**6-Sep**	**13-Sep**	**20-Sep**	**27-Sep**	**4-Oct**	**11-Oct**	**18-Oct**	**25-Oct**	**1-Nov**	**8-Nov**	**15-Nov**	**22-Nov**	**29-Nov**	**6-Dec**	**13-Dec**
19-Apr	0	95	95	95	95	95	95	95	95	95	95	95	90	90	80	80	0	0
26-Apr	0	100	100	100	100	100	100	100	100	100	100	100	85	85	80	80	0	0
3-May	0	100	100	100	100	100	100	100	100	100	100	100	80	80	70	70	0	0
10-May	0	100	100	100	100	100	100	100	100	95	95	95	75	75	70	70	0	0
17-May	0	95	95	95	95	95	95	95	95	90	90	90	75	75	70	70	0	0
24-May	0	85	85	85	85	85	85	85	85	90	90	90	75	75	70	70	0	0
31-May	0	80	80	80	80	80	80	80	80	85	85	85	70	70	65	65	0	0
7-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Methodology: Linear Mathematical Programming

Linear programming is a mathematical tool for solving an objective function such as maximizing returns to fixed costs with respect to a set of constraints on land, unpaid labor, and capital under a given weather regime (Dantzig, 1949, 1963). Difference in gross revenue between single-pass and small multiple pass harvesters were evaluated by specifying the optimization problem as a linear programming model (Boehlje and Eidman, 1982, pages 404-405) as:

$$Max\ \Pi = \sum_{j=1}^{n} c_j X_j \quad (1)$$

subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \leq b_i\ \#\quad i = 1\#\quad m \quad (2)$$

$$X_j \geq 0\ \text{ir u} j = 1 \ldots n \quad (3)$$

where:

X_j = the level of the j^{th} production process or activity
c_j = the per-unit return to the unpaid resources (b_i's) for the j^{th} activity
a_{ij} = the amount of the i^{th} resource required per unit of the j^{th} activity
b_i = the amount of the i^{th} resource available

The objective function (Equation 1) maximizes per unit returns (c_j) from all activities (X_j). Equation 2 defines the constraints on how many units of each activity can be in the optimal solution. The *j* activities include the production of cotton. The *i* resources include 1) land available for crop production, 2) available labor expressed as a combination of the number of people, number of hours day^{-1}, and number of days suitable for fieldwork each time period, and 3) the availability of machinery based on number of machines of each type, number of hours day^{-1} that the machine is available, and working rates expressed as acres hour^{-1} for each crop production task. The remaining variables, *a* and *b*, are the production process or activity resource requirements, and resource availability constraints, respectively. The production season was segmented into one-week increments. Equation 3 prevents negative production. The contribution margin (À) is the objective to be maximized and can be thought of as returns to unpaid resources.

One known limitation of the whole-farm linear programming model has been the requirement to have identically one harvest event for each planting activity; therefore, activities were constrained to occur if and only if sufficient cotton were available to meet capacity of the machine. Given the focus on harvest systems, all other field operations were held constant at levels sufficiently high and assumed to be at sufficient capacity such that shadow values were zero.

Analysis and Results

Results are reported for single-pass harvest systems to form the basis of comparison for a series of what–if scenarios surrounding multiple-pass harvest systems. The single-pass harvest system analysis evaluated a typical Arkansas cotton farm with 2,163 acres. What-if analyses evaluated conditions when multiple-pass harvest systems equated to or surpassed yield and gross revenues of the base single-pass harvest system.

Results of Linear Programming Analysis for Single-Pass Harvest Systems

Cotton lint yield is a user-defined input in the interactive web dashboard tool. Weekly expected yield was estimated by multiplying the user-defined "best yield" by the yield adjustment set percentage (Table 8). The hypothetical farm had 2,163 acres of cotton based on the number of acres that modulating cotton pickers could cover 2,163 acres in Arkansas (Griffin et al., 2015). Summing acreage capacity for the five harvest weeks at 100% yield potential, 1,722 acres could be harvested leaving 441 acres to be harvested in next best week. Since week ending September 27 has higher yield potential than week ending November 8, 438 acres would be harvested during week ending September 27 with remaining four acres harvested during the next best harvest week during weeks ending November 8 or November 15. Shadow prices were estimated for the six weeks with no remaining acreage capacity. Rather than the farm operator harvesting 1,500 pounds of cotton across the entire 2,163-acre farm, the whole-farm average was 1,484 pounds acre^{-1} for gross revenue of \$3,210,888. Given that cotton was potentially worth \$3,244,500 if harvested in the best weeks of the year, \$33,612 was foregone due to non-optimal harvest timing.

Table 8. Yield potential and acreage capacity, single-pass harvest systems

week ending	yield potential (%)	yield potential (lbs. ac^{-1})	capacity (ac week^{-1}) available	capacity (ac week^{-1}) used	capacity (ac week^{-1}) remaining
16-Aug	0	0	433	0	433
23-Aug	0	0	433	0	433
30-Aug	0	0	432	0	432
6-Sep	0	0	426	0	426
13-Sep	0	0	411	0	411
20-Sep	0	0	410	0	410
27-Sep	95	1425	438	438	0
4-Oct	100	1500	373	373	0
11-Oct	100	1500	368	368	0
18-Oct	100	1500	354	354	0
25-Oct	100	1500	339	339	0
1-Nov	100	1500	288	388	0
8-Nov	80	1200	351	4	348
15-Nov	80	1200	325	0	325
22-Nov	70	1050	294	0	294
29-Nov	70	1050	269	0	269

One substantive difference between single-pass and multiple-pass yield adjustment sets is that the stock of cotton yet to be harvested is logged for multiple-pass systems while all bolls are assumed to be harvested during single-pass harvest system operation. The entire amount of cotton to be harvested is not harvested with a single harvest pass of multiple-pass harvest systems. Unlike single-pass harvest systems, the totality of bolls to be harvested cannot be harvested in the earliest weeks in the yield adjustment set since some portion of bolls will not have yet opened. Therefore, the stock of cotton available to be harvested with multiple-pass systems during each week was estimated using data from Table 4, Table 5, and Table 7.

Results of Linear Programming Analysis for Multiple-Pass Harvest Systems

One requirement of small autonomous robots in a multiple-pass harvest system was to harvest all bolls during the week that the cotton becomes ready, i.e., one week after bolls open. Bolls ready to be harvested each week (Table 5) were modified for Table 9; specifically harvest of any opened bolls before entire field was at 15th percentile bolls opening would be delayed; therefore, bolls becoming ready prior to week ending August 23 could be harvested along with the 5% opening that week for a total of 10%. Rather than using capacity as acreage available for harvest fieldwork, the hours week^{-1} were considered for multiple-pass harvest systems. Given the capacity in hours and acreage ready based on bolls becoming ready each week, the working rate of the multiple-pass harvest system was calculated for each week. The highest working rate requirement was calculated as 9.7 acres hour^{-1} for week ending September 20 when 23% of bolls were expected to become ready to harvest (Table 9). Compared to single pass harvest machinery at 8 acres hour^{-1}, the additional 1.7 acres hour^{-1} may be a development challenge. Week ending September 13 also requires working rate greater than 8.0 acres hour^{-1} at 8.4 acres hour^{-1}. The average non-zero working rate was 4.2 acres hour^{-1}, nearly half of single-pass harvest systems.

Table 9. Yield potential and acreage capacity metrics, multiple-pass harvest systems

week ending	yield potential (%)	yield potential (lbs. ac^{-1})	bolls harvestable (%)	acreage harvestable (ac)	capacity available (hrs.)	required working rate (ac hr^{-1})
16-Aug	0	0	0	0	54	0.00
23-Aug	100	1500	10	216	54	4.00

30-Aug	100	1500	7	151	54	2.80
6-Sep	100	1500	13	281	53	5.29
13-Sep	100	1500	20	433	51	8.42
20-Sep	100	1500	23	497	51	9.70
27-Sep	100	1500	11	238	55	4.35
4-Oct	100	1500	9	195	47	4.18
11-Oct	100	1500	4	87	46	1.88
18-Oct	100	1500	2	43	44	0.98
25-Oct	100	1500	1	22	42	0.51
1-Nov	100	1500	0	0	36	0.00
8-Nov	80	1200	0	0	44	0.00
15-Nov	80	1200	0	0	41	0.00
22-Nov	70	1050	0	0	37	0.00
29-Nov	70	1050	0	0	34	0.00
6-Dec	0	0	0	0	0	0.00
13-Dec	0	0	0	0	0	0.00

Relaxing the requirement that cotton must be harvested one week after opening such that bolls can be harvested during that week or later weeks provided flexibility.

Discussion and Conclusions

The overall goal of this research was to challenge the current cotton harvest practices and estimate changes in gross revenues from multiple harvest passes of many small autonomous robots. Two generalized harvest systems were considered with the traditional single-pass harvest equipment as a baseline for comparison against small autonomous multiple-pass systems harvesting cotton from numerous passes through the field. Small autonomous robots operate as single-row equipment with anthropomorphic capabilities. Various methodologies can be applied to the evaluation of multiple-pass cotton harvest systems; here we applied linear programming methods. Weeks 30 to 49 were reported for Arkansas; other states may have fewer or more weeks relevant to harvest operations. Although the results reported in this paper were for a specific instance in only one state, the methodology can be applied to many unique situations via an interactive web dashboard. Field experiments in Georgia are underway to assess yield and quality potential by delayed harvest (Meeks et al., 2017). A wide range of permutations for individual farming operations and candidate prototype development could be evaluated using the same techniques, models, and interactive dashboards.

Revenue from cotton is a function of yield and quality. Multiple-pass harvest systems are expected to have fewer yield losses and higher lint quality than single-pass harvest systems; therefore, gross revenues are expected to be at least as high for multiple-pass than single-pass harvest systems and the same cost per unit acre leads to higher profitability for multiple-pass systems. For these reasons, it logically follows small autonomous robotic systems are associated with higher revenue than single-pass harvest systems when per acre costs are similar; however, the magnitude of these revenue differentials has yet to be observed.

Results are pertinent to cotton researchers, equipment developers, and manufacturers. Producers of other crops may be interested in methodologies employed here, especially for crops and fresh produce with multiple harvest events after a single planting event including alfalfa, fresh vegetables, and orchard fruits.

The commercialization possibility of small autonomous robotics has increased the precision of collecting site-specific yield and quality data that can be used in the evaluation of on-farm experiments or general farming practices. The absolute yield and quality measures associated with smaller sub-field geographic areas allow more precise exploration of environmental and cultural practices that influence cotton lint quality. Although yield data based on cotton bale data are associated with discrete geographic areas of the farm field, supporting information such as soil chemical analyses, electrical conductivity, elevation, remotely sensed data, rates and timing of inputs, and other factors potentially explaining yield and quality differences must be collected. The use of RFID, barcode or similar technology may be used to automatically link the data collected at cotton gins and cotton warehouses back to sub-field areas at the farm level (Griffin et al., 2021). Once field data becomes available, the gain in the precision with which cotton quality and yield data is collected will be quantified.

Results are sensitive to the assumed yield adjustment set. Given that the yield adjustment set is used for planning purposes, i.e., five or more years planning horizon, weather, and production practices in the next several years will impact yield penalties by planting and harvest dates. One limitation of this study was the reliance on the yield adjustment sets for only one geographic region; analysis for the other states could be conducted if reliable data were available to populate the yield adjustment set matrices. Researchers in each cotton-producing state are encouraged to conduct field experiments and gather observation farm data to recommend yield adjustment sets for their respective locations and production practices.

Multiple-Pass Harvest System Characteristics not Evaluated

Several characteristics of multiple-pass harvest systems were worthy of evaluation; however, were deemed beyond the scope of the current paper so were not explicitly modeled in this study. Stochastic downside risk and probabilities of downtime were not directly modeled.

Downtime is a concern for cotton producers with respect to the functionality of multiple-pass harvest systems. The question was asked, what happens when the machine(s) are out of service and unable to perform tasks. When one of many robots fails, less impact on the overall task being performed is realized compared to a single harvester experiencing downtime (Barnes et al., 2019). Multiple-pass harvest systems could allow farm operators to choose alternative planting timing and mid-season field activities that could impact harvest systems and crop maturity. The analysis and associated interactive web dashboard are deterministic in addressing risk as only the probability of having days suitable for fieldwork. The risk and uncertainty for unharvested bolls subjected to potentially adverse weather conditions when in the field for longer than necessary was beyond the scope of this research.

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