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ECONOMICS & MARKETING

Dicamba-Based Herbicide Programs, Cropping Sequences, Tillage Types in Cotton – Profitability and Risk Efficiency Analysis

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ABSTRACT

Herbicide-resistant weeds threaten cotton production, and herbicides alone are not a sustainable remedy. Field trials at two locations, College Station and Thrall, Texas (2019-21), assessed dicamba-based herbicide programs in various crop sequences and tillage systems to identify sustainable weed management recommendations based on weed control and partial net returns. The study showed no-till cover cropping and conventional tillage had the highest aggregate partial net returns at College Station and Thrall, respectively. A cotton:sorghum:cotton rotation provided significantly higher partial net returns (>\$450 ha^{-1}) compared to continuous cotton only at Thrall. Partial net returns were significantly higher in a low input herbicide program (LI) compared to a high input herbicide program (HI) from 2019-21 only at Thrall. Herbicide programs showed a high degree of overlap and were indistinct in all tillage types at College Station based on CDFs graphs. Low input under cotton:sorghum:cotton rotation showed 100% probability of higher partial net returns compared to continuous cotton in all tillage types at Thrall. Stoplight charts showed LI provided greater than 50% probability of partial net returns greater than \$1,066 ha^{-1} across tillage types at College Station. In Thrall, LI under cotton:sorghum:cotton rotation offered 88% and 26% probability of partial net returns above \$1,066 ha^{-1} in conventional and strip tillage, respectively. Higher partial net returns for LI were mostly attributed to cost savings from using inexpensive herbicides rather than higher yields. Therefore, using less expensive herbicide programs and crop rotation appeared to be the most risk efficient strategy for managing weeds in irrigated and dryland cotton production.

The United States is the leading exporter of cotton (*Gossypium hirsutum* L.) in the world. During 2022, Texas planted an estimated 5.5 million hectares of upland cotton which was more than 50% of the total U.S. upland cotton acreage (USDA-National Agricultural Statistics Service, 2023). Cotton is an economically important crop. The gross value of U.S. cotton production was recently estimated at over \$4.7 billion, providing 130,000 jobs across the country (USDA-Economic Research Service, 2020). From 2016 to 2019, the average annual contribution of cotton to the Texas economy was \$1.42 billion in direct contribution, \$2.87 billion in total cash receipts, and \$3.41 billion as a total contribution to the state's GDP (McCorkle et al., 2020).

Uncontrolled weeds pose a severe threat to cotton production from early season competition and late season soil seedbank replenishment (Werner et al., 2019). In 2019, more than 90% of cotton acres across thirteen cotton producing states in the U.S were treated with herbicides for weed control (USDA-National Agricultural Statistics Service, 2020). Herbicides have been heavily relied upon due to their ease of use and lower cost compared to other weed management options. However, heavy reliance on herbicide-only based weed management, a reduction in herbicide discovery efforts, and company consolidations after the introduction of glyphosate-resistant (GR) crops, has left growers with very few new modes of action (MOA) to control GR weeds (Duke, 2012).

So far, more than ten weed species have evolved resistance to the most commonly used preemergence (PRE) herbicides and all postemergence (POST) herbicides used in U.S. cotton systems (Vulchi et al., 2022). This has led to the increased use of herbicides to manage resistant weeds, which has ultimately increased production costs (Sosnoskie and Culpepper, 2014). Consequently, a backward shift in utilizing

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herbicide programs with PREs, multiple MOAs, and tillage for managing weeds has been observed (Price et al., 2016; Whitaker et al., 2011). Empirical evidence suggests that using herbicides alone for weed control is not sustainable (Powles, 2008). Integrating control strategies like tillage and crop rotations with herbicide programs may be an effective way to manage herbicide resistant weeds (Norsworthy et al., 2012). Previous research investigating the integration of herbicides with tillage, crop rotations or cover crops showed greater potential for long-term weed control compared to any of those strategies alone (Aulakh et al., 2012, 2013; Farr et al., 2022).

Economics has been the driver for the adoption of these integrated management approaches at the grower level (Gianessi, 2005, 2008, Livingston et al. 2016). In recent studies conducted in the Texas High Plains, a no-till with cover crop regime produced lower net returns (\$346 – 389 ha^{-1}) compared to conventional tillage (\$454 ha^{-1}), and no-till without cover crop (\$461 ha^{-1}) under dryland conditions. Though planting a cover crop in a no-till system reduced the yield variation over time, risk-averse growers preferred no-tillage without a cover crop, due to the uncertainty of cover crop effects on cotton yields and cover crop planting and termination costs in dryland environments (Fan et al., 2020a). Similar observations were recorded in South Texas and West Tennessee, where risk-averse growers preferred no-tillage without cover crops over no-tillage with cover crops and conventional tillage (Boyer et al., 2018; Ribera et al., 2004). However, in the Texas High Plains under irrigated conditions, risk-averse growers preferred no-tillage with cover crops over no-tillage (Fan et al., 2020b).

No-till systems can improve the soil structure and increase water holding capacity, thereby increasing the probability for higher cotton yields when irrigation is not a limitation (Nouri et al., 2019). However, no-till systems favor the accumulation of weed seeds on the soil surface exposing them to conditions conducive for germination. Integrating cover crops into no-till systems during fallow periods not only provides soil health benefits (Acosta-Martinez and Cotton, 2017) but also prevents weed seed germination and aids in soil seedbank management (McVay et al., 2006; Schwartz et al., 2010). However, the amount of weed suppression provided by a cover crop is a function of biomass accumulation, which is dependent upon environmental conditions (Vulchi et al., 2022).

Conventional tillage is a common weed management option in Texas cotton production systems. Conventional tillage practices aid in the management of herbicide resistant weeds by burying weed seeds deep into the soil profile which deprives them of conditions necessary for germination (Farmer et al., 2017). However, repeated tillage practices over time can degrade soil health by exhausting soil organic matter content, which may negatively impact crop yields in the long run (Foster et al., 2018). The documented effects of no-till systems with cover crops compared to conventional tillage on crop yields and net returns are limited and variable, specific to cropping systems and locations in the U.S. (Boyer et al., 2018; DeLaune et al., 2020; Lewis et al., 2018).

Crop rotation has been a sustainable method of managing diseases, pests, and improving soil water content in cotton systems in different parts of the U.S. (Bordovsky et al. 1994, Kirkpatrick and Sasser, 1984, Schwartz et al. 2010, Wheeler et al. 2012). A cotton:sorghum:cotton rotation is a popular cultural practice in Texas (Bordovsky et al., 2011; Foster et al., 2018). From an herbicide resistance management standpoint, crop rotation facilitates the use of different herbicide MOA over time, thereby reducing the probability of finding a resistance individual for any particular MOA.

In this study, dicamba-based herbicide programs, with and without residual herbicides, under continuous cotton and cotton:sorghum:cotton rotation in no-till cover cropping, strip tillage, and conventional tillage systems were evaluated, under irrigated and dryland environments from 2019 to 2021 in Texas (Vulchi et al., 2023). This paper presents an economic analysis of the multi-site year field studies of different weed management systems based on comparisons between mean partial net returns, cumulative distribution functions, and stoplight charts. A comparative economic evaluation of the potential gains from adopting different combinations of chemical, mechanical, and cultural weed control methods can assist cotton producers in making informed farm management decisions.

MATERIALS AND METHODS

Experimental Design and Yield Data Collection. Production data of field trials conducted from 2019 to 2021 at the Texas A&M AgriLife Extension Linear Farm at College Station, TX (30°30’40.3”N 96°25’06.7”W), and Stiles Farm at Thrall, TX

(30°36'04.4"N 97°18'06.5"W) were used for economic analysis. The College Station location had an overhead linear irrigation system (Valley®; Valmont Industries, Inc.; Valley, NE). The Thrall location was a rainfed/dryland environment. The experimental design was a randomized complete block design with split-split plot arrangement of treatments. No-till cover crop, strip tillage, and conventional tillage were the main plots, each measuring 24.4 m wide and 36.6 m long. The spring wheat variety 'Expresso' was planted as a cover crop during 2019 and 2021, while the variety 'LCS-Trigger' was planted during 2020 in no-till areas. Wheat cover crops were planted at 115 kg ha^{-1} at College Station and 70 kg ha^{-1} at Thrall following the forage seeding rates for irrigated and dryland environments in Texas (McCulloch and Noland, 2019). A lower seeding rate was followed at Thrall to minimize the influence of cover crop on soil moisture availability to the subsequent main crop. Glyphosate (Roundup PowerMAX, Bayer Crop Sciences, St. Louis, MO) at 1.54 kg ha^{-1} was used to terminate the cover crop approximately four weeks before planting the main crops every year. One strip tillage activity was carried out each year from 2019-21 at College Station. No strip tillage activity was carried out in Thrall in 2019 due to earlier wet conditions but one strip tillage activity was carried out each year during 2020 and 2021 cropping seasons. Only one disking activity was carried out in a conventional tillage block in 2019 due to earlier wet conditions during spring. Two disking activities were carried out each year from 2020 following the local production practices.

Cropping sequence served as the sub-factor with half of each tillage practice under continuous cotton and the other half under cotton:sorghum:cotton rotation over three years. The entire trial was planted with cotton during 2019. Half of each tillage type was then rotated with grain sorghum and the other half was planted with cotton during 2020. Finally, the entire trial was planted back with cotton during 2021. Each sub-factor plot measured 12.2 m wide and 36.6 m long. DP 1646 B2XF cotton variety was planted at 112,000 seed ha^{-1} and DK57-07 grain sorghum variety was planted at 170,000 seed ha^{-1}. A weedy check (WC), a weed-free check (WF), a low input herbicide program (LI), and a high input herbicide program (HI) were applied to sub-sub plots measuring 3 m wide and 9.1 m long and replicated four times. The WC and WF were maintained for weed control and yield comparisons, respectively. The WF were maintained by a combination of herbicides, complemented by hand weeding whenever necessary. All the WF plots received directed applications to the row middles using TTI 9504E nozzles covered by hoods so that crop health was not compromised. A total of 24 unique treatments (3 tillage systems x 2 cropping sequences x 4 herbicide programs) were evaluated at each location. Each herbicide program consisted of four rows of cotton and sorghum and were applied to the same area for three years. Individual herbicide components of the WF, LI, and HI programs and rates are listed in Table 1. All herbicide applications were made using a CO_2-pressurized backpack sprayer with an eight-nozzle boom delivering 140 L ha^{-1} at 234 kPa walking at a speed of 4.8 km h^{-1}.

Cotton was harvested using a four-row stripper in 2019 but hand harvested in 2020 and 2021 at College Station. Cotton was hand harvested for all site-years at Thrall. A sub-sample was collected by hand harvesting a 0.004 ha area of the middle two rows of each cotton plot. When machine harvested, 7.62 m of the center two rows in each plot were harvested. Sub-sample yield from each individual plot was extrapolated to per hectare yield and used for analysis. Grain sorghum was harvested from the middle two rows of each plot (7.62 m in length) using a Wintersteiger small-plot combine (Wintersteiger Inc., Salt Lake City, UT). Cotton samples were ginned on a 20-saw tabletop gin to calculate the lint percentage. Fiber quality of the collected lint samples was analyzed using High Volume Instrument testing at the Fiber and Biopolymer Research Institute at Lubbock, Texas.

Variable Cost Estimation. The herbicide costs for Roundup PowerMAX®, XtendiMax® with VaporGrip® and Warrant® were obtained from regional Bayer Technology Representative (G.L. Steele, personal communication). Prices for remaining herbicides were collected from a Nutrien Ag Solutions local distributor (Caldwell, TX). All the prices were obtained in 2019 and were used for the entirety of experiments under the assumption that the grower would buy herbicides in bulk and use them in the coming years. Bulk herbicide costs were prorated according to herbicide rates used in the experiments and used for economic analysis (Table 1). Location-specific individual field operation costs were estimated using the 2019, 2020, and 2021 Custom Rates Survey (Klose, 2018, 2020). Variable costs for field operations that varied between College Station and Thrall locations during each site-year included: cover crop seed and planting costs for no-till cover cropping, strip tillage with and without fertilization costs at College Station and Thrall, respectively for the strip till block, and moldboard shallow disking costs for the conventional tillage block (Table 2); cotton seed plus technology costs and cotton planting costs from 2019-21 for the continuous cotton rotation and cotton seed plus technology costs, grain sorghum seed costs, and cotton and grain sorghum planting costs from 2019-21 for the cotton:sorghum:cotton rotation (Table 3); and herbicides and their application costs for individual herbicide programs (Table 4). All cost measurements were used to estimate partial net returns to specified costs (see below). In addition to the costs described above, fertilizer and crop protection chemical costs, application costs, and irrigation costs ranged between \$246-275 ha^{-1} at College Station and \$82-122 ha^{-1} at Thrall from 2019-21. However, these common management costs to all treatments at each location were not included in the analysis to provide emphasis to factors that influence weed control directly than other agronomic costs.

Table 1. Herbicide programs, application timings, prices for active ingredients, rates used in cotton and sorghum from field trials conducted from 2019-21 at College Station and Thrall, TX.

Crop	Program	Timing	Herbicides	Active Ingredient	Rates used (kg a.i./a.e. ha^{-1})	Price (\$ ha^{-1})
Cotton	WC	-	-	-	-	-
	WF	PRE	Dual Magnum®	S-metolachlor	1.4	51.4
		EPOST	Roundup® PowerMAX® + Dual Magnum®	Glyphosate + Dicamba	1.54 + 1.4	16.7 + 29.4
		LPOST	Roundup® PowerMAX® + Dual Magnum®	Glyphosate + Dicamba	1.54 + 1.4	16.7 + 29.4
	LI	EPOST	XtendiMax® with VaporGrip® + Roundup® PowerMAX®	Dicamba + Glyphosate	0.56 + 1.54	29.4 + 16.7
		LPOST	XtendiMax® with VaporGrip® + Roundup® PowerMAX®	Dicamba + Glyphosate	0.56 + 1.54	29.4 + 16.7
	HI	PRE	Cotoran®	Fluometuron	1.12	29.8
		MPOST	XtendiMax® with VaporGrip® + Warrant® + Roundup® PowerMAX®	Dicamba + Acetochlor + Glyphosate	0.56 + 1.26 + 1.54	29.4 + 35.8 + 16.7
		Layby	Direx®	Diuron	1.12	16.8
Sorghum	WC	-	-	-	-	-
	WF	PRE	Huskie®	Pyrasulfutole & Bromoxynil	0.09, 0.5	35.8
		EPOST	Aatrex® + Huskie®	Atrazine + Pyrasulfutole & Bromoxynil	1.12 + 0.09, 0.5	12.4 + 35.8
		LPOST	Aatrex® + Huskie®	Atrazine + Pyrasulfutole & Bromoxynil	1.12 + 0.09, 0.5	12.4 + 35.8
	LI	EPOST	Aatrex®	Atrazine	1.12	12.4
		LPOST	Aatrex®	Atrazine	1.12	12.4
	HI	PRE	Outlook®	Dimethenamid-P	1.7	95.2
		MPOST	Aatrex® + Outlook®	Atrazine + Dimethenamid-P	1.12 + 1.7	12.4 + 95.2
		Layby	Aatrex® + Outlook®	Atrazine + Dimethenamid-P	1.12 + 1.7	12.4 + 95.2

Abbreviations: PRE, preemergence; EPOST, early-postemergence; MPOST, mid-postemergence; LPOST, late-postemergence; PDIR, post-directed; fb, followed by.

Table 2. Cover crop seed plus planting costs in no-till, tillage costs in strip till and conventional tillage area (\$ ha^{-1}) in field experiments conducted from 2019-21 at College Station and Thrall, TX.

Tillage type	College Station			Thrall		
	2019	2020	2021	2019	2020	2021
	\$ ha^{-1}					
No till cover cropping	111	99	99	84	96	96
Strip tillage	59	59	59	0	49	49
Conventional tillage	49	148	148	74	49	99

Table 3. Cotton seed trait and technology costs, grain sorghum seed cost and their planting costs ($ ha^{-1}) in field experiments conducted from 2019-21 at College Station and Thrall, TX.

Location	Continuous cotton			Cotton:sorghum:cotton		
	2019	2020	2021	2019	2020	2021
	$ ha^{-1}					
College Station	250	226	226	250	61	226
Thrall	237	240	240	238	73	239

Table 4. Herbicide and their application costs ($ ha^{-1}) for individual herbicide programs in field experiments conducted from 2019-21 at College Station and Thrall, TX.

Herbicide Program	Continuous cotton			Cotton:sorghum:cotton		
	2019	2020	2021	2019	2020	2021
College Station	$ ha^{-1}					
WC	0	0	0	0	0	0
WF	229	234	252	229	197	234
LI	122	122	125	122	54	122
HI	171	175	175	171	185	183
Thrall						
WC	0	0	0	0	0	0
WF	227	234	234	227	219	234
LI	124	124	127	127	59	127
HI	168	175	175	168	208	175

WC, Weedy check; WF, Weed free check; LI, Low input herbicide program; HI, High input herbicide program

Partial Net Returns Estimation. This paper focuses on partial net returns as a key variable of comparison. By so doing relevant differences in cost, yields, and grade effects were considered. To estimate and rank the economic benefits of the individual treatments mentioned above, seed cotton yield, lint yield, and selected fiber quality data (fiber length, elongation, micronaire, strength, and uniformity) was used from each location over the three years. Lint yield was obtained by ginning sub-samples from individual plots in the field experiments in each production season and extrapolating sub-sample lint yields to per hectare. These seed cotton yield and lint yields along with selected fiber quality parameters were entered into the Upland Cotton Loan Value Calculator in their respective years to calculate the USDA loan price per pound for each plot observation (Cotton Incorporated, 2020). A constant leaf grade of 4 and color grade of 41 was assumed during the entirety of the study to adjust for the confounding influences of weather variables across plot locations and the lack of lint cleaners on the tabletop gin used (J. Robinson, personal communication). The USDA loan calculator accepts seed cotton and lint yields in lbs/acre and gives out gross returns in $/acre, which were eventually converted to $/ha. Cotton gross returns were calculated as treatment yield times the USDA Commodity Credit Corporation loan value price, which incorporated adjustments for selected fiber quality premiums/discounts. Partial net returns above the previously described specific treatment costs were calculated as follows:

Partial net return ha^{-1} = gross return ha^{-1} – [chemical costs + treatment-specific field operations costs ha^{-1}].

Simulation Analysis. Simulation techniques were used to assess the economic risk associated with every weed control strategy in this study. Specifically, treatment expected partial net returns were simulated to estimate the probability of economic success (i.e., likelihood of obtaining an overall positive net return during 2019 – 2021). A total of 500 partial net returns were generated for each combination of planting year (2019 – 2021), tillage (no-till cover cropping, strip tillage, and conventional tillage), cropping sequence (continuous cotton and cotton:sorghum:cotton rotation), and herbicide program (WC, WF, LI and HI) at each location separately.

Simulated partial net returns were generated using the multivariate empirical simulation procedure proposed by Richardson et al. (2000). Observed partial net returns from the experiment replications were used to estimate the annual average partial net returns of each treatment and their corresponding covariance structure. Estimated annual average partial net returns by treatment served as the non-stochastic component of the forecasted partial net returns. Stochastic partial net returns for the years in question were added to estimate the random aggregated net return associated with each treatment. The simulated aggregated partial net returns were then used to estimate the corresponding cumulative distribution function (CDF) of each weed control strategy under irrigated and dryland environments and were used to evaluate the probability of obtaining a positive aggregated net return. Any point along a CDF graph of partial net returns shows the probability of partial net returns to be less than or equal to a specific value of the x-axis, which for this study measures partial net returns per ha. When comparing two CDF graphs, if the lines do not cross, the outer most (i.e., right) CDF graph is preferred to the ones closer to the Y axis. But if the CDF curves intersect, then there is no clear ranking and more integrated stochastic efficiency ranking is required.

Stoplight Charts. A stoplight chart illustrates the probability of a treatment expected partial net returns being above, below, or in between upper and lower bound values (Richardson et al., 2006). It is an intuitive and alternate method which is easy to read, requires minimal explanation, and is ideal for quickly conveying results to decision makers. The probability of a risky alternative generating a net return less than the lower bound value is illustrated by a red region on a bar graph. The probability of an alternative generating a net return greater than the upper bound value is illustrated by a green region. The region between the upper and lower bounds is yellow and shows the probability of partial net returns being between the upper and lower bounds. Hence, given a set of predefined bounds, alternatives with greater green areas (smaller red areas) are preferred. Stoplight chart analysis was conducted to illustrate the net return distribution of combinations of tillage-types, cropping sequences, and herbicide programs in both irrigated and rainfed environments.

RESULTS AND DISCUSSION

Variable Costs. At College Station, cost savings in conventional tillage were dependent on the number of tillage operations carried out during each year. In 2019, when only one tillage operation was carried out, conventional tillage (\$49 ha^{-1}) provided 126% cost savings per hectare compared to no-till cover cropping (\$111 ha^{-1}) in tillage costs alone. In the following years, when two disking operations were carried out each year, no-till cover cropping (\$99 ha^{-1}) provided 50% cost savings compared to conventional tillage (\$148 ha^{-1}) (Table 2). Similarly at Thrall, when only one disking operation was carried out during the first two years, cost savings from conventional tillage were 13 and 95% in 2019 and 2020, respectively, compared to no-till cover cropping. However, in 2021, costs were similar between no-till cover cropping (\$96 ha^{-1}) and conventional tillage (\$99 ha^{-1}) even when two disking operations were carried out (Table 2). Strip tillage costs remained \$59 and 49 ha^{-1} at College Station and Thrall, respectively, from 2019-21 (Table 2). These results indicate strip tillage is a more cost-friendly tillage operation in this study, and no-till cover cropping can be a more cost-effective option than multiple disking operations for growers. Under dryland environments production costs for using cover crops can be a barrier for adoption by growers adopting fewer tillage operations or no-till systems without cover crops (Prokopy et al., 2019; Ranjan et al., 2019). Planting sorghum during the alternate year instead of cotton provided a 210 and 228% cost savings at College Station and Thrall, respectively (Table 3). These costs were a function of seed plus technology costs for cotton, seed cost for sorghum, and planting costs from 2019-21. Cotton herbicide program prices remained static from 2019-21 at both locations. In 2020, using LI in sorghum (\$54-59 ha^{-1}) provided at least 106% cost savings in the herbicide program alone compared to LI in cotton (\$122-127 ha^{-1}) at both locations. However, using HI in sorghum (\$185-208 ha^{-1}) cost 5-19% more compared to HI in cotton (\$171-183 ha^{-1}) in 2020 at both locations (Table 4) which could be attributed to more expensive residual herbicides used in sorghum for extended weed control (Table 1). Also, when averaged over three years and across tillage types at each location, compared to using HI, cost savings in LI ranged from 10-13% under continuous cotton sequence and 20-26% under cotton:sorghum:cotton sequence (Vulchi et al., 2023). These results highlight the potential cost savings associated with using LI as herbicide program and introducing sorghum as a rotational crop into the cropping sequences which the growers may favor for their weed control needs.

Partial Net Returns Analysis and Treatment Comparisons. Tillage types and herbicide programs significantly influenced partial net returns annually, and when aggregated over three years at each location. Therefore, appropriate mean separation tests were conducted to identify which treatment means were significantly different.

At College Station, no-till cover cropping (\$1,340 ha^{-1}) provided significantly higher partial net returns compared to strip tillage (\$343 ha^{-1}) and conventional tillage (\$736 ha^{-1}) in 2019 averaged across herbicide programs (Table 5). In 2020, the COVID-19 pandemic reduced the potential yield by disrupting several farm operations and consequently led to negative net returns at both locations. Strip tillage (- \$142 ha^{-1}) provided comparable or significantly lower negative partial net returns compared to other tillage types averaged across other factors in 2020 (Table 5). In 2021, Strip tillage again provided (\$328 ha^{-1}) higher net returns compared to no-till cover cropping (\$117 ha^{-1}) and conventional tillage (\$166 ha^{-1}) when averaged across other respective factors (Table 5). Annual partial net returns were not significantly different between cropping sequences in 2020 and 2021 at College Station (Table 5). Lower inputs provided comparable or higher annual partial net returns than HI from 2019-21 averaged across other factors at College Station (Table 5). At Thrall, conventional tillage and strip tillage provided significantly higher partial net returns compared to no-till cover cropping when averaged across other factors in 2019 and 2020 (Table 5). In 2021, conventional tillage (\$205 ha^{-1}) provided significantly higher partial net returns compared to other tillage types averaged across other factors (Table 5). Cotton: sorghum: cotton rotation provided significantly higher partial net returns each year compared to continuous cotton sequence from 2019-2021 averaged across other factors (Table 5). Also, LI provided significantly higher partial net returns compared to HI each year from 2019-2021 averaged across other factors (Table 5).

When aggregated over three years, no-till cover cropping (\$970 ha^{-1}) provided significantly higher partial net returns compared to other tillage types averaged across other factors at College Station (Table 6). This can be attributed to significantly higher cotton yields (> 3,300 kg ha^{-1}) under no-till cover cropping compared to other tillage types (1,100 – 2,500 kg ha^{-1}) in 2019 (Vulchi et al., 2023), followed by cost savings in tillage operations in the following years. Fan et al. (2020b) observed similar results in Texas where no-till cover cropping systems produced greater or similar partial net returns compared to conventional systems, primarily due to higher yields under irrigated conditions. No significant differences in partial net returns were observed between cropping sequences and herbicide programs (LI and HI) averaged across other respective factors at College Station (Table 6). Perhaps the irrigated environment at College Station masks some of the potential impacts of cropping sequences. At Thrall, when partial net returns were aggregated over three years, conventional tillage (\$510 ha^{-1}) provided significantly higher partial net returns compared to other tillage types averaged across other factors (Table 6). The cotton:sorghum:cotton rotation (\$491 ha^{-1}) provided significantly higher aggregate partial net returns compared to continuous cotton sequence (\$25 ha^{-1}) averaged across other factors (Table 6). Between herbicide programs, LI (\$716 ha^{-1}) provided significantly higher partial net returns compared to HI (\$370 ha^{-1}) averaged across other factors (Table 6). Using LI provided 58% higher aggregate partial net returns under conventional tillage and 20 times higher partial net returns under no-till cover cropping, compared to using HI (Table 7). Aggregated partial net returns were comparable between LI and HI in strip tillage at Thrall (Table 7). All the herbicide programs provided significantly higher aggregate partial net returns under the cotton:sorghum:cotton rotation compared to the continuous cotton sequence (Table 8), which can be mostly associated to savings from herbicide and seed costs. These results indicate, partial net returns are directly correlated to cost savings associated with each system and using cheaper herbicide programs and diversifying cropping sequences over time can lower grower's production risk in unprecedented situations (Ribera et al., 2004).

Cumulative Distribution Function (CDF) Analysis. As seen above with statistical comparisons, using low-cost herbicide programs and including sorghum as a rotational crop in the cropping sequence provided higher partial net returns annually and when aggregated over three years. Using simulation results to examine and rank the riskiness of net return outcomes is an additional approach to guide growers on weed management decisions. The CDF graphs represent the range (x-axis) and cumulative probabilities (y-axis) of simulated partial net returns of alternative weed management systems in this study. Figures 1 and 2 illustrate the CDFs for combinations of herbicide programs and cropping sequence under each tillage practice and location separately.

Table 5. Partial net returns ($ ha^{-1}) to specified costs between tillage-types, cropping sequences and herbicide programs averaged across other respective factors during 2019-21 at College Station and Thrall, TX.

Treatment	College Station			Thrall		
	2019	2020	2021	2019	2020	2021
Tillage Type	$ ha^{-1}					
No till cover cropping	**1,340 a**	**-185 b**	**117 b**	**269 b**	**-498 b**	**-2.5 b**
Strip tillage	**343 b**	**-142 a**	**328 a**	**351 a**	**-116 a**	**7 b**
Conventional tillage	**736 b**	**-174 ab**	**166 b**	**398 a**	**-94 a**	**205 a**
Cropping Sequence						
Continuous cotton	**840 a**	**-173 a**	**163 a**	**309 b**	**-319 b**	**35 b**
Cotton:Sorghum:Cotton	**779 a**	**-161 a**	**245 a**	**371 a**	**-2.5 a**	**124 a**
Herbicide Program						
Weedy check	**-18 b**	**-205 b**	**303 c**	**195 c**	**-82 a**	**-257 d**
Weed free check	**967 a**	**-196 b**	**482 a**	**324 b**	**-277 c**	**40 c**
Low input program	**1,208 a**	**-79 a**	**388 ab**	**464 a**	**-94 a**	**343 a**
High input program	**1,068 a**	**-188 b**	**248 b**	**375 b**	**-195 b**	**190 b**

[b] **Values followed by the same letter were statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.**

Table 6. Aggregate partial net returns ($ ha^{-1}) to specified costs between tillage-types, cropping sequences and herbicide programs averaged across other respective factors during 2019-21 at College Station and Thrall, TX.

Treatment	College Station		Thrall	
Tillage Type	$ ha^{-1}			
No-till cover cropping	**970**	**a**	**-5**	**c**
Strip tillage	**59**	**b**	**270**	**b**
Conventional tillage	**388**	**b**	**510**	**a**
Cropping Sequence				
Continuous cotton	**429**	**a**	**25**	**b**
Cotton:sorghum:cotton	**515**	**a**	**491**	**a**
Herbicide Program				
Weedy check	**-428**	**b**	**-142**	**d**
Weed free check	**575**	**a**	**89**	**c**
Low input program	**1,049**	**a**	**716**	**a**
High input program	**693**	**a**	**370**	**b**

[a] **Values followed by the same letter were statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column.**

Table 7. Aggregate partial net returns ($ ha^{-1}) between herbicide programs as influenced by tillage-types at Thrall, TX.

Herbicide program	No-till cover cropping			Strip tillage			Conventional tillage		
	$ ha^{-1}								
Weedy check	**-292**	**c**	**A**	**-191**	**c**	**A**	**5**	**c**	**A**
Weed free check	**-239**	**bc**	**B**	**162**	**b**	**A**	**395**	**b**	**A**
Low input program	**488**	**a**	**B**	**656**	**a**	**B**	**1,003**	**a**	**A**
High input program	**23**	**b**	**B**	**451**	**ab**	**A**	**636**	**b**	**A**

[a] **Values followed by the same letter were statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column; uppercase letters compare means within the same row.**

Table 8. Aggregate partial net returns ($ ha^{-1}) between herbicide programs as influenced by cropping sequences at Thrall, TX.

Herbicide program	Continuous cotton			Cotton:Sorghum:Cotton		
	$ ha^{-1}					
Weedy check	-468	d	B	184	c	A
Weed free check	-163	c	B	339	bc	A
Low input program	497	a	B	934	a	A
High input program	234	b	B	506	b	A

[a] Values followed by the same letter were statistically similar based on Tukey's least significant difference (α = 0.05): lowercase letters compare means within the same column; uppercase letters compare means within the same row.

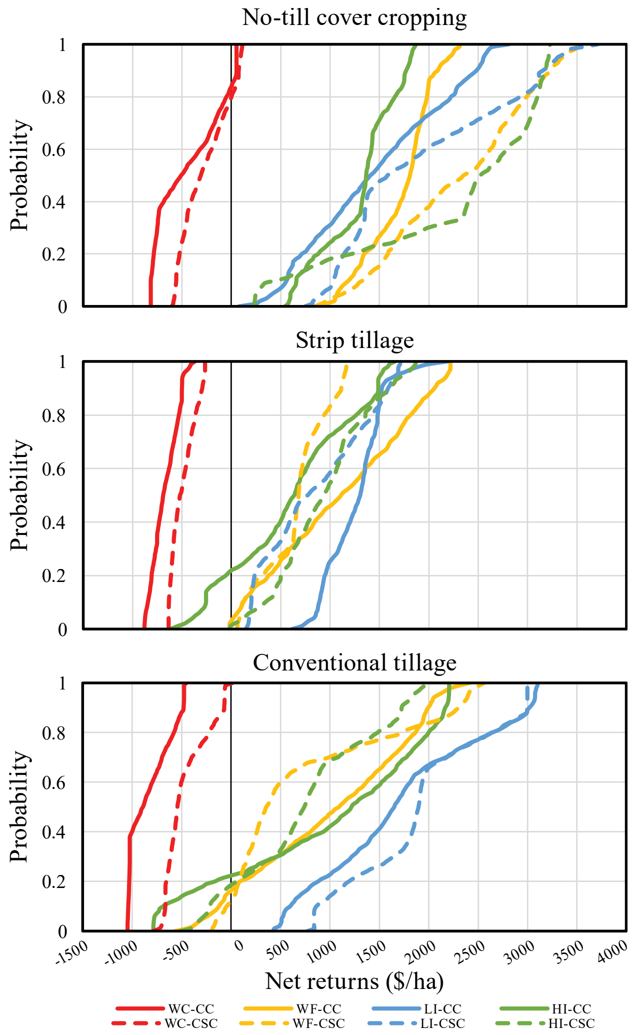

Figure 1. Cumulative distribution functions (CDF) of partial net return of herbicide program (weedy check - WC, weed-free check - WF, low input herbicide program, - LI, high input herbicide program - HI) and cropping sequence (continuous cotton – continuous lines; cotton:sorghum:cotton – dotted lines) under no-till cover cropping, strip tillage, and conventional tillage for experiments conducted from 2019 – 2021 at College Station, TX (Irrigated).

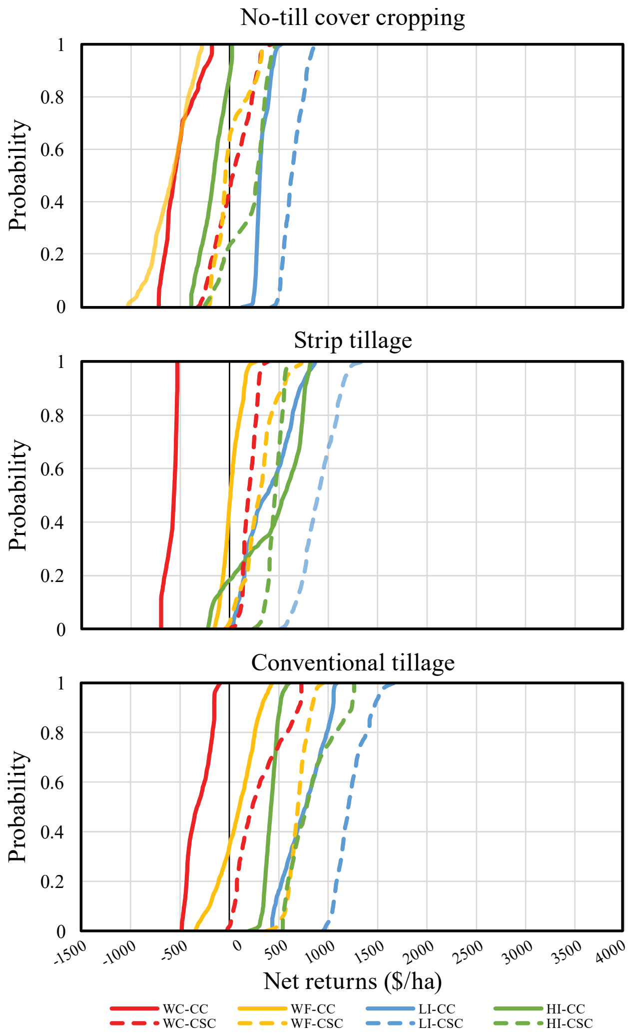

Figure 2. Cumulative distribution functions (CDF) of partial net return of herbicide program (weedy check - WC, weed-free check - WF, low input herbicide program, - LI, high input herbicide program - HI) and cropping sequence (continuous cotton – continuous lines; cotton:sorghum:cotton – dotted lines) under no-till cover cropping, strip tillage, and conventional tillage for experiments conducted from 2019 – 2021 at Thrall, TX (Dryland).

College Station. College Station showed a probability of greater net returns compared to Thrall. All three tillage types in Figure 1 show the CDF of partial net returns for WC + continuous cotton situated entirely to the left of all the other distributions. The next left-most distribution is WC + cotton:sorghum:cotton rotation which is mostly to the left of the remaining distributions. This means that each of the other distributions are superior to either WC distribution because at any cumulative probability value, WC + continuous cotton has the lowest net return while WC + cotton:sorghum:cotton rotation has the next lowest net return. Such clear rankings reflect first degree stochastic dominance and are independent of the decision maker's risk preferences.

Beyond the two WC treatments at College Station, there was no clear separation between herbicide programs in no-till cover cropping, strip tillage, or conventional tillage (Fig. 1) groupings. This makes it difficult to identify dominant strategies short of assuming grower risk aversion and determining second degree stochastic dominance. In the case of no-till cover cropping at the College Station location, herbicide programs do show greater probability of higher partial net returns under cotton:sorghum:cotton rotation compared to continuous cotton. This is evident from the three dashed CDFs forming the right-most frontier. These results indicate growers adopting no-till cover cropping under irrigated conditions should follow crop rotation practices frequently for higher partial net returns. These results agree with (Goplen et al., 2018) who observed adding a low-cost rotational crop like alfalfa provided higher net returns while mitigating risk of herbicide resistant weeds.

Thrall. In contrast to College Station, the CDF graphs for Thrall (Fig. 2) show one treatment, LI under the cotton:sorghum:cotton rotation, having first degree stochastic dominance in all three tillage groupings. This is graphically indicated by this distribution positioned on the right most side, reflecting relatively higher partial net returns at any given cumulative probability level. This risk efficiency can be attributed to relatively lower herbicide costs associated with LI compared to HI and WF, cheaper seed prices for rotational crops like grain sorghum compared to the higher seed and technology costs of dicamba-resistant cotton (Table 4). Also, conventional tillage showed that the probability of getting higher partial net returns under conventional tillage was higher compared to no-till cover cropping and strip tillage. These results agree with Fan et al. (2020a) who observed conventional tillage showing a higher chance of getting a higher partial net return compared to no-till cover cropping under dryland environments in Texas.

Stoplight Charts. Figures 3 and 4 show stoplight charts for College Station and Thrall, respectively. Each chart shows twelve treatments comprised of the four herbicide programs, for each of three tillage types. Figure 5 shows treatments at Thrall reflecting combinations of two herbicide programs, two rotation sequences, and three tillage groupings. The lower and upper bound values of all stoplight charts were determined using average partial net returns of all the treatments at the 25th (<–$90 ha^{-1}) and 75th (>$1,066 ha^{-1}) percentiles (Richardson, 2010).

The stoplight charts of herbicide programs reinforce the results from the CDFs and ANOVA discussed above. At College Station, WC did not show a green region in all tillage types. In strip tillage and conventional tillage systems, LI showed a higher greener region compared to HI and WF. In the strip tillage system, LI has a 54% probability of producing greater than $1,066 ha^{-1} compared to only 33% with HI. In conventional tillage, LI has 79% probability of partial net returns greater than $1,066 ha^{-1} compared to only 43% probability for HI. The HI in no-till cover cropping (77%) showed the highest probability of partial net returns greater than $1,066 ha^{-1} compared to HI in other tillage types. Overall, herbicide programs showed higher probability of getting net returns above $1,066 ha^{-1} under no-till cover cropping compared to other tillage types (Fig. 3). These results agree with Fan et al. (2020b) who observed higher probability of positive net returns in no-till with cover crops compared to conventional tillage or no-till without a cover crop under irrigated cotton production in Texas.

At Thrall, no herbicide program treatment resulted in a green region when coupled with no-till cover cropping. LI was the only herbicide program with non-red region showing a 100% probability of producing partial net returns between –$90 and 1,066 ha^{-1}. In the strip tillage system, LI was the only herbicide program with green region showing a 13% probability of producing partial net returns greater than $1,066 ha^{-1}. Overall, herbicide programs showed higher green region or lower red region under conventional tillage compared to other tillage types. In conventional tillage, both LI and HI showed green regions with a 46 and 10% probability of producing partial net returns greater than $1,066 ha^{-1}, respectively (Fig. 4). These results agree with Fan et al. (2020a) who observed smaller red region in conventional tillage compared to no-till cover cropping with cover crops under dryland conditions in Texas. Also at Thrall, when LI and HI were used in a cotton:sorghum:cotton rotation, green regions expanded by 84 and 4% probability with conventional tillage, respectively. The rotational sequence also reduced the red area by 54% probability in HI under no-till cover cropping and expanded the green area by 26% probability in LI in strip tillage compared to a continuous cotton sequence (Fig. 5).

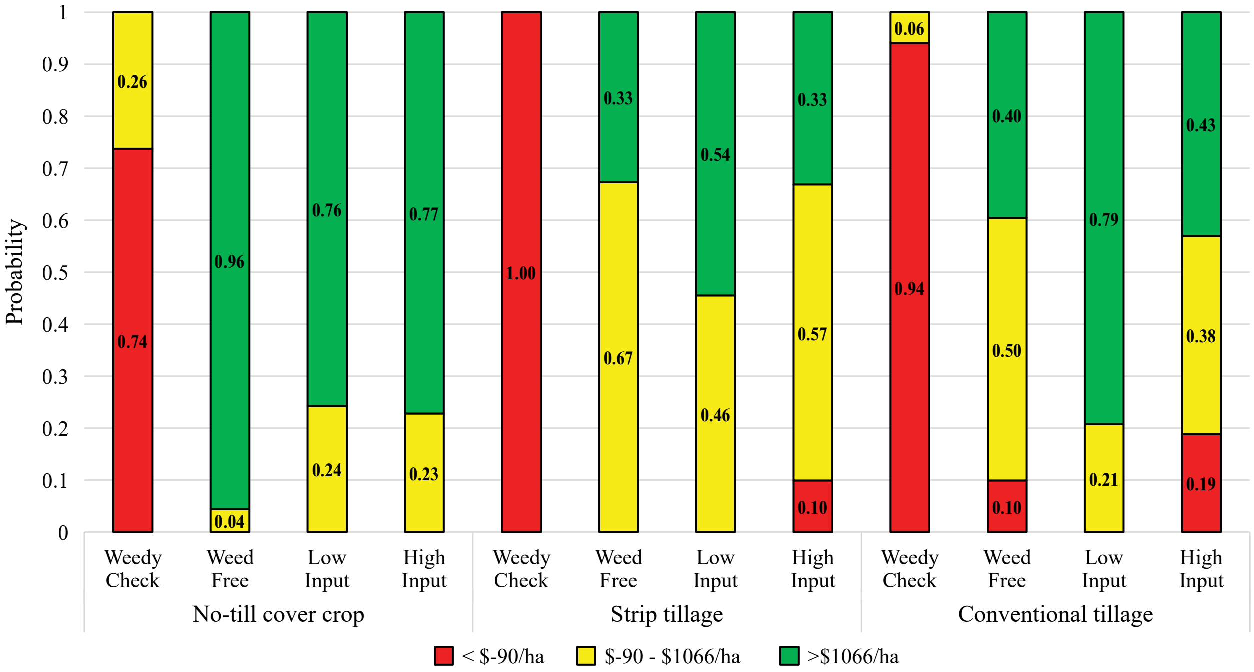

Figure 3. Stoplight chart for probabilities of partial net return < $-90 and > $1066 ha^{-1} for herbicide programs under no-till cover cropping, strip tillage, and conventional tillage scenarios for experiments conducted from 2019 – 2021 at College Station, TX.

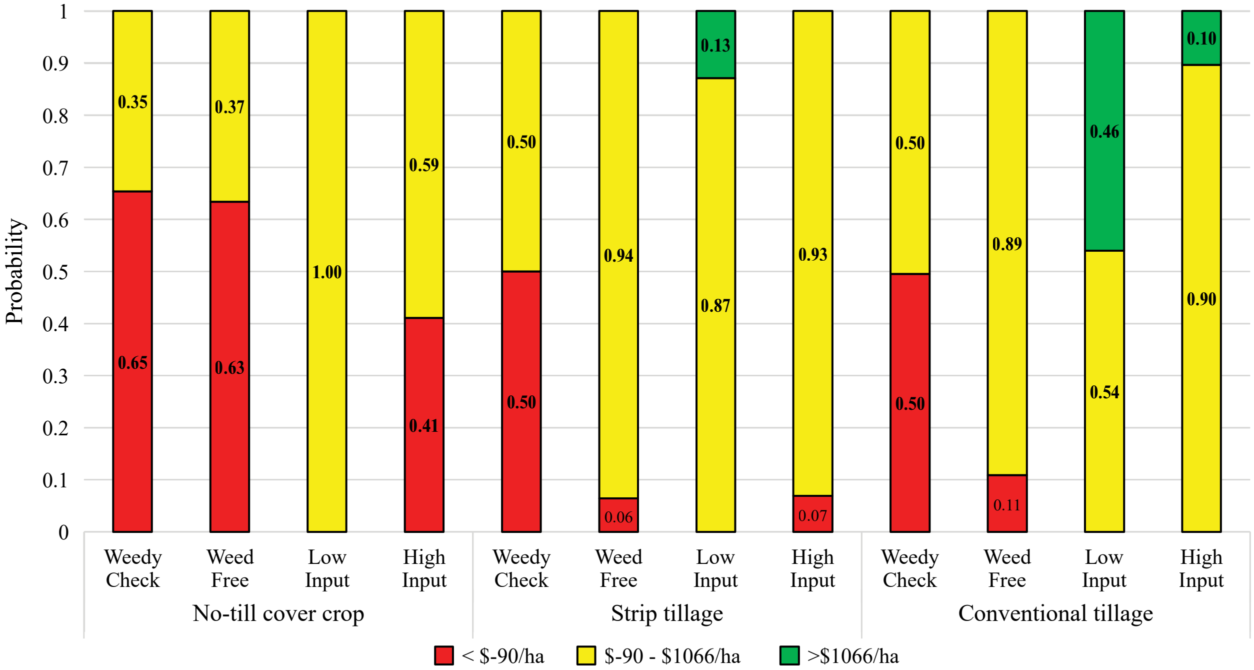

Figure 4. Stoplight chart for probabilities of net return < $-90 and > $1066 ha^{-1} for herbicide programs under no-till cover cropping, strip tillage, and conventional tillage scenarios for experiments conducted from 2019 – 2021 at Thrall, TX.

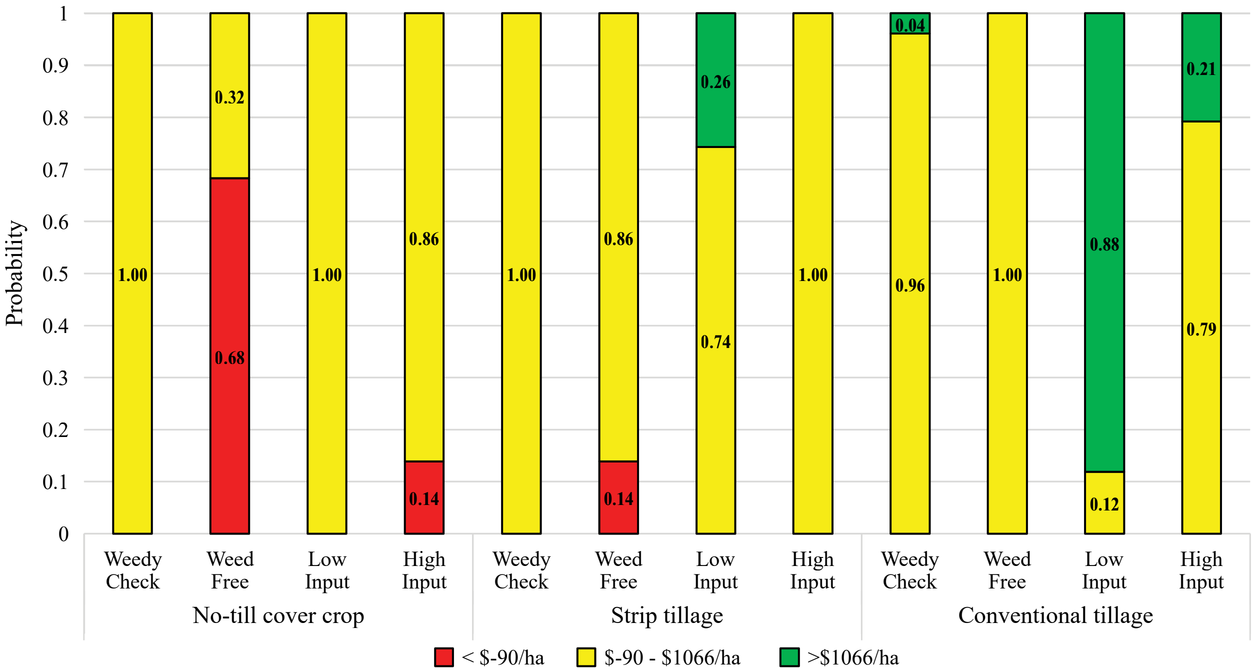

Figure 5. Stoplight chart for probabilities of net return < $-90 and > $1066 ha^{-1} for herbicide programs under continuous cotton sequence (CC) and cotton:sorghum:cotton rotation (CSC) in no-till cover cropping, strip tillage, and conventional tillage scenarios for experiments conducted from 2019 – 2021 at Thrall, TX.

CONCLUSIONS

Integrated weed management strategies that combine herbicide programs with non-chemical strategies like cropping sequences and tillage types are important to manage herbicide resistant weeds in cotton production. Economic analysis of field studies that includes investigating partial net returns data (annual and aggregated), CDF curves, and stoplight charts provides useful insights into the adoption potential of the different weed management systems.

Aggregate partial net returns over 2019-21 under no-till cover cropping were significantly higher compared to conventional tillage at College Station. With no-till cover cropping and strip till systems showing comparable economic feasibility to conventional tillage, conservation tillage practices can be a fitting alternative to conventional tillage systems in irrigated cotton production in Texas. However, the opposite was found at Thrall where conventional tillage provided the highest aggregate partial net returns from 2019 to 2021 compared to no-till cover cropping. CDFs and stop light charts affirm the results from ANOVA analysis of partial net returns. At Thrall, LI provided higher average cotton and grain sorghum yields compared to HI from 2019-21. Savings in seed and technology costs along with herbicide and application costs explains the higher partial net returns in cotton:sorghum:cotton sequence. But when used under continuous cotton sequence, LI resulted in weed seedbank buildup and significant decline in annual weed control over three years (Vulchi et al., 2023). This is due to the absence of residual herbicides and the lack of MOA rotation over time.

With glyphosate resistance already existing in the natural weed seedbank, using only one effective MOA each year increases the chances of evolving resistance to an effective MOA in a short time period. Crop rotation also increased the diversity of herbicides, providing greater weed control, higher cotton yields in the following year and consequently higher partial net returns, especially at Thrall. The LI with sorghum turned out to be most cost effective compared to other herbicide programs and cropping sequence systems. Under no-till cover cropping, using LI under cotton:sorghum:cotton rotation provided relatively higher weed control (60%) compared to using it under continuous cotton (10%) by the end of the third year (Vulchi et al., 2023). However, with widespread atrazine resistance in Texas, LI + cotton:sorghum:cotton rotation could become unsustainable in the long run. On the other hand, although using HI under cotton:sorghum:cotton rotation was more expensive, this system provided the best weed control across all tillage types and locations. Higher partial net returns and lower risk were observed in simulated data for LI under both locations, primarily attributed to their cost savings. Data was collected only from 2019-21, only one rotation cycle was available to study the effects of different management strategies on yield. Therefore, cost savings of the weed management systems drove the adoption potential of weed management strategies than crop yields.

Farm-level adoption decisions can also be influenced by economic considerations relating to input uses and investment decisions as well as government programs and policies (Bergtold et al., 2019). Herbicide resistance modeling studies can estimate how long a new herbicide molecule can be efficacious before weeds can evolve resistance under different production practices (Busi et al., 2020). Combining stochastic economic feasibility analysis with herbicide resistance modelling can provide valuable insights into looking at the profitability of new herbicide molecules before evolving resistance in major weed species similar to Livingston et al. (2016). Future research can address this issue.

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